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Residential water demand management: Provision of benefits and impacts on circularity at the example of the city of Hamburg

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Abstract

The thesis deals with residential water demand management measures and to what extent such measures can provide benefits for Hamburg and increase the circularity of Hamburg's water system. The city of Hamburg and in particular Hamburg's water sector present the case for this thesis. Climate change and a growing water demand, due to population growth and a slight increase in the per capita water consumption, pose challenges to Hamburg's water sector, requiring reactions. Against this background, water demand management measures for households are considered throughout the thesis.

Following a case study research design, reviewing literature, and conducting semi-structured interviews serve as the research methods. Complemental to this, the concept of circular water economy and transition theory constitute the theoretical background for this thesis.

The specific extent of water demand management measures related to circularity and provision of benefits could not be determined. However, the thesis outlines the variety of benefits such measures may bring to Hamburg. These include climate mitigation, climate resilience, contributing to a secure water supply, and potentially offsetting the need to build new infrastructure to meet growing water demand. Furthermore, such measures may close the identified gap of measures, that aim to avoid and reduce water consumption in the Hamburg water sector and thereby, represent important means to increase its circularity.

Limiting the potential and the value of residential water demand measures for Hamburg is an identified path dependence between the pipe infrastructure and a specific needed amount of water consumption. Moreover, a dominating mindset in the water utility has been identified that focuses on supply-oriented solutions and neglects the multitude of benefits of reducing water consumption. Similarly, the concept of circular water economy is mainly perceived with regard to the recovery of materials and recycling of water. Therefore, to promote residential water demand management measures, this thesis argues for a mindset change that acknowledges the value of such measures for circularity and considers the full benefits they may provide.

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Abbreviations

BREEAM: Building Research Establishment Environmental Assessment Methodology

DGNB: Deutsche Gesellschaft für Nachhaltiges Bauen

GWRS: Greywater recycling system

OUR: Outdoor use restrictions

RWHS: Rainwater harvesting system

SDG: Sustainable Development Goal

TUC: Total use constraint

UN: United Nations

WDM: Water Demand Management

WFD: Water Framework Directive

1 Introduction

Climate change, population growth, environmental pollution, and a shift to more resource-intensive consumption patterns pose major challenges for the water sector. Over the past 100 years, water use has increased sixfold and is further growing by about 1% each year. Climate change influences the distribution and availability of water resources and aggravates water stress in already affected regions and will create water stress in some regions which were not previously affected (UN Water, 2020). Both, developing and developed countries need to find solutions and strategies to meet these challenges, which is critical for a sustainable future (UN Water, 2020; WWAP, 2019).

Against this background, water demand management, which mainly deals with the use and consumption of water, has gained increasing attention. It acknowledges water as a scarce and valuable resource and stands in contrast with traditional supply-oriented solutions, mainly relying on expanding infrastructure to meet growing water demands (Lallana et al., 2001). Similarly, the concept of circular water economy, which adopts circular economy principles to the water sector, has recently been developed as an approach to address the above-mentioned challenges (Ellen MacArthur Foundation, 2019). Using the example of Hamburg, which experiences a growing water demand and is affected by the consequences of climate change, this thesis investigates to what extent water demand measures for households can provide benefits for Hamburg and increase the circularity of Hamburg's water system. In addition, this thesis uses transition theory to examine barriers and reasons why water demand measures for households in Hamburg are not applied more often and how such measures can be promoted. To address these issues, literature was reviewed and semi-structured interviews were conducted.

The upcoming problem analysis first provides a basic understanding of the general functioning of the water system and presents challenges to the water system in more detail. This is followed by presenting the case study Hamburg with its specific water-related challenges as well as the municipal water utility Hamburg Wasser with its activities and strategies in Hamburg.

2 Problem analysis

The following chapter provides an understanding of the relevant problem areas for this thesis by firstly presenting the broader context. For this, the fundamentals of the natural water cycle are introduced which are followed by climatic and non-climatic challenges to the water system in a linear economy. Besides that, the Sustainable Development Goals are described and the concept of circular economy is shortly presented as a potential means to counteract challenges in the water sector. After that, the problem analysis narrows the focus to the city of Hamburg serving as a case study. Thereby, specific challenges to Hamburg's water sector are outlined as well as current response measures by the water utility.

Combined, the provided information forms the basis for developing the Research Questions for this thesis**.**

2.1 Fundamentals of the natural water cycle

The natural water cycle, also known as the hydrological cycle, describes the water cycling system on earth without human activities. Thereby, water is constantly moving and changing its state between liquid, vapor, and ice just within seconds or over millions of years. The sun, as the driver of the water cycle, heats ocean water which partly evaporates as vapor. Together with water evaporated from soil and transpired water from plant leaves, vapor is carried into the atmosphere by rising air currents. As the steam rises cooler temperatures cause its condensation into clouds which are then due to air currents moved around the globe eventually, falling out as precipitation. Some of it falls as snow, which either accumulates as glacial ice or flows overland as meltwater when temperatures reach the melting point. Most of the water returns to the ocean or to the land where gravity causes it to flow over the ground as surface runoff. These runoffs create streams resulting in rivers or building lakes. Large quantities of runoff infiltrate into the ground forming aquifers, which retain water for a long period. Another part of the groundwater remains near the land surface and can flow back into surface waters or the ocean as groundwater discharge (Inglezakis et al., 2016; USGS, 2019). Figure 1 depicts the natural water cycle and its main processes.

Figure 1: Natural water cycle (Inglezakis et al., 2016)

2.2 Linear economy

In contrast to the sustainable nature of the natural water, cycle stands the linear economy. In the current economic system person-made capital, human capital, and natural capital all contribute to human welfare. These three capitals support or enable the production of goods and services. Thereby, person-made capital consists of tools, machinery or other goods being used in production. Human skills for research or development activities demonstrate human capital. Lastly, natural capital is comprised of inputs of energy and materials for production, ecosystem services such as nutrient recycling, or climate regulation, which preserve and enable the production, and serves as a sink of waste from production (Barbier, 2002). Following these three types of capital, economic actors are involved in four economic activities being resource management, production, distribution, and consumption of goods and services. Products are manufactured from extracted natural resources, sold, used, and finally discarded. These economic processes can be described by the term linear economy characterized by a "take-make-dispose" pattern, which has dominated the economic development of the last 150 years (Ellen MacArthur Foundation and McKinsey & Company, 2014).

2.2.1 Linear water system

Typically, the water sector follows a linear "take-use-discharge" strategy derived from the "take-make-dispose" terminology presented prior.

Therein, water is extracted from rivers, lakes, streams, groundwater reservoirs, oceans or from human rainwater catchments. Then, water is distributed through pipes and used by industries, municipalities, agriculture, and the environment which represent the four traditional categories (Ellen MacArthur Foundation, 2019). This stage includes consumptive and non-consumptive uses. Non-consumptive uses encompass activities after which wastewater is available for recycling or reuse (Ibid.). For instance, water that is used in homes for different appliances and consequently supplied to a wastewater treatment plant and discharged to groundwater or surface water system. By doing so, water is not removed or "consumed" from the system. In contrast, consumptive uses describe activities and applications where water is removed from the surface water system. Such use constitutes agriculture as water evaporates and is transpired by plants (Arthur & Saffer, n.d.).

At last, non-consumptive used water is either directly or via water treatment facilities discharged to the basin where it can be used downstream or is lost due to evaporation or infiltration for example (Ellen MacArthur Foundation, 2019). The different stages of a linear water system are depicted below

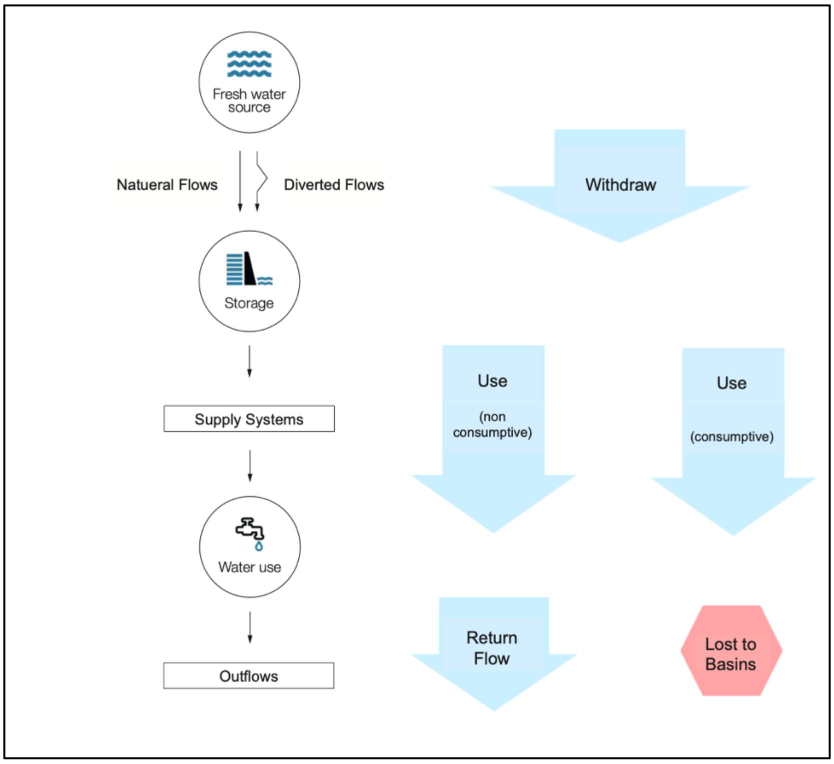

Figure 2: Linear water system (Ellen MacArthur Foundation, 2019: 7)

This linear approach to water management and use is predominant, leading to a number of (environmental) problems (Brears, 2020). With water being mostly endlessly used and disposed of, such a linear model in the water sector has restrained the quality and the availability of water resources, while also degrading the environment. This has severe impacts on the quality of life but also jeopardizes the functioning of entire ecosystems humans depend on (Ibid.).
Hence, the linear water system stands in contrast with the natural water cycle where the resource water circulates through different stages naturally building a closed and functioning system.
The linear water sector is further particularly vulnerable to specific challenges and future developments, which are presented in the following (Ibid.).

2.3 Challenges to the water sector

There are multiple challenges to the water sector. These can be divided into climate change-related challenges and non-climatic challenges.

2.3.1 Climate change-related challenges

Climate change has a significant impact on the water cycle by changing the availability, quality, and quantity of water. Through climate change, water-related extreme events such as droughts and floods occur more often and at a higher intensity leading to less predictable and reliable water availability. As a consequence, more frequently too much or not enough water is available. For instance, during severe droughts, water availability and sources may disappear or become more vulnerable to pollution as high pollution concentrations are reached more quickly. Additionally, groundwater can be over-extracted to compensate for the loss of surface water supplies (UN Water, 2020; Delgado et al., 2021).
In the event of a flood, effluent discharge which can contain increased concentrations of nutrients, chemicals, suspended sediments, pathogens, and oil can contaminate soil, groundwater, and surface water (Müller et al., 2020). Floods can also lead to damage to the water and sanitation infrastructure and thus, for example, create an overflow of sewerage systems leading to sanitation problems and contamination (UN Water, 2020). Even worse, devastating floods can cause substantial damage to entire cities and can kill people. Such an event, for instance, occurred in the summer of 2021 when floods destroyed entire villages and caused the death of over 100 people in Rhineland-Palatinate and North-Rhine-Westphalia (WDR, 2021). Additionally, rising water temperatures and associated lower dissolved oxygen levels can have a negative impact on water quality by reducing self-purification capacity. Such

conditions also enable the formation of harmful algae blooms and demonstrate favorable conditions for pathogens.
Furthermore, reduced river flows in summer are projected as the summer precipitation decreases whereas winter precipitation increases (UN Water, 2020). Thus, river flow droughts are expected to occur in much more frequency and intensity, for instance, in France, Germany, and the United Kingdom (EEA, 2021). Such a change in water availability in rivers demands more artificial water storage, such as dam augmentation. This becomes particularly important against the background of increasing water demand during heat waves and warmer summers potentially exceeding the capacity of the water grid (UN Water, 2020).

2.3.2 Non-climatic challenges

The main non-climatic challenges consist of a combination of population growth, more resource-intensive consumption patterns, and socio-economic development (WWAP, 2019).
With regard to population growth, in 2017, 7,6 billion people lived on the planet with an increase of 1 billion people from 2005 to 2017. By 2030 it is projected to reach over 8,5 billion people and 9,7 billion by 2050 (UN, 2017a). Naturally, this growth will increase the demand for water significantly but will also lead to an incremental degradation of the water quality due to increased pollution and eutrophication. In 2021, over 2 billion people lived in areas where water is considered a scarce resource and over 3,4 billion people did not have access to sanitation facilities that are sufficiently managed. According to the UN (2021), due to population growth, both will worsen in the future.

Another essential aspect related to population growth concerns the food production. To feed such a larger population, food production needs to increase by 60% by 2050 (FAO, 2018). Against the background that agriculture consumes over 70% of the total freshwater worldwide massive increases in water consumption are to be expected (UN Water, 2020). Such increases in agricultural production will also affect the water quality as nutrient runoff from agriculture, containing primarily nitrogen and phosphorous, demonstrates a major source of water pollution. In addition to this, phosphorous fertilizers made from phosphorous rocks are essential for global food security. However, phosphorous rock is a finite and non-renewable resource found only in a few countries around the world with the largest reserves, around 70% of the whole phosphorous rocks worldwide, located in Morocco. This makes its global supply vulnerable to geographic conflicts and fluctuating prices. Globally, phosphorous recovery is only carried out to a small extent (Ryan et al., 2016).

Other challenges to the water sector constitute urban areas and the increasing urbanization primarily in low and middle-income countries. By 2050, it is expected that an additional 2,5 billion people will live in urban areas (UN, 2018a). The aspect of urbanization is important since cities have a big impact on the water cycle as significant amounts of water are extracted from groundwater or surface sources which can exceed the natural recharge capacity of the water sources. Because of a high proportion of pavement flood risks are significantly higher. Furthermore, polluted water sources in and around the city are also more concentrated due to untreated or not sufficiently treated wastewater (Delgado et al., 2021).

In addition, cities are of essential relevance in the global economy accounting for the vast majority of the world's gross domestic products. Thus, they do not only constitute a high concentration of people but also of assets. As a result, disruptions in water services have severe implications for the domestic economy (Damania et al., 2017).

Rising income levels as well as economic growth impact the water sector. The OECD predicts the world economy to grow four times by 2050 compared to 2012, leading to an expected increase in water demand of 55%. Thereby, particularly manufacturing (+400%), thermal electricity generation (140%), and domestic use (+130%) demonstrate the main drivers of increased water consumption (OECD, 2012). In addition, almost three billion people will belong to the middle classes by 2050, mainly from today's emerging markets (HSBC, 2012). As a result, food consumption patterns are expected to change towards more water-intensive food, such as meat and dairy products (Ibid.).

Finally, the water sector is a major consumer of energy, particularly in form of electricity. Different water processes such as wastewater treatment and desalination, are energy-intensive and accounted for 4% of the global electricity consumption in 2014. For many municipalities, water and wastewater facilities are the largest energy consumers. Failure in energy supply also often means a failure of the water treatment processes which demonstrates the strong dependency of the water sector on energy (OECD & IEA, 2016).

2.4 Sustainable Development Goals

In view of the global challenges described above but also related to poverty, peace, inequality, justice, and prosperity, the United Nations General Assembly presented 2015 the "Agenda for Sustainable Development" (UN, 2015: 5). This agenda entails 17 interlinked Sustainable Development Goals (SDGs) and 169 related targets aiming "to achieve a better and more sustainable future for all" (UN, n.d.).

Remarkably, water is an important factor in achieving almost all SDGs by contributing positively to a sustainable economic, social, and environmental development. For instance, the availability of sanitation and clean water is essential for prosperity and development of societies. Moreover, water is vital for producing food and energy and is used in the vast majority of industrial processes (Delgado et al., 2021). The importance of water is also reflected in SDG 6 which is fully dedicated to water: “Ensure availability and sustainable management of water and sanitation for all”. SDG6 is among others targeted to:

“*achieve universal and equitable access to safe and affordable drinking water for all* (Target 6.1) (UN, 2015: 20),

“*improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally* (Target 6.3) (Ibid.: 20),

“*substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity*” (Target 6.4) (Ibid.: 20).

In the context of circular economy as a main theoretical concept for this thesis, SDG12: “Ensure sustainable consumption and production patterns” is relevant. Therein, among others, is formulated to achieve:

”the sustainable management and efficient use of natural resources” (UN, 2015: 26) and to “*substantially reduce waste generation through prevention, reduction, recycling and reuse”* (Ibid.: 26).

2.5 Circular economy

Applying the concept of circular economy to the water sector can contribute to achieving multiple objectives of the SDGs, particularly of SDG 6 and SDG 12 (Delgado et al., 2021). Many important international institutions consider a shift to a water system that is based on the concept of circular economy as a huge opportunity to provide safe water and wastewater services and to meet current and future challenges (Ellen MacArthur Foundation, 2019; IWA, 2016; Delgado et al., 2021).

There are multiple definitions of circular economy existent, whereas the Ellen MacArthur Foundation provides one that is extensive and widely used. Accordingly, a circular economy is *" restorative or regenerative by intention and design*" (Ellen MacArthur Foundation, 2013: 7), creates value decoupled from finite resource consumption and associated environmental impacts, maximizes resource use, eliminates use of toxic chemicals, and prevents the generation of waste. In addition, the circular economy approach aims to depend on renewable energies and uses ecosystems and biodiversity (Ellen MacArthur Foundation, 2013; 2015). In chapter 4, circular economy and in particular, circular water economy will be explained in more detail.

2.6 European Green Deal and Circular Economy Action Plan

In an European context, the relevance of circular economy becomes visible through the Circular Economy Action Plan (CEAP) being one of the main pillars of the European Green Deal. The European Green Deal comprises a set of policy initiatives presented by the European Commission in December 2019 with the main goal of reducing net emissions of greenhouse gases in the European Union to zero by 2050 (EC, 2019). The CEAP provides an agenda to create a more environmentally friendly and competitive Europe in active participation of different actors (EC, 2020). Specifically aimed at the water sector, the CEAP aims to "*facilitate water reuse and efficiency*" (EC, 2020: 15) and also wants to promote improvements with regard to wastewater treatment and sewage sludge (Ibid.).

Besides, the European Ecodesign Directive constitutes a framework to set eco-design requirements for specific groups of energy-related products including water-using equipment. The directive's primary goal is to reduce the energy use of products but it also aims to decrease other environmental impacts by considering, among others, material and water use (EC, 2009). In March 2022, as a measure of the European Green Deal, the European Commission presented a proposal for a regulation on ecodesign for sustainable products, extending the scope of the Ecodesign Directive. The regulation proposes mandatory minimum eco-design requirements for all products on the European market. These requirements for the specific product groups would be defined in separate delegated acts which, for instance, include requirements to improve resource use and efficiency and reduce environmental impacts. In addition, the regulation would enable member states to provide incentives for consumers to favor sustainable products (EP, 2022).

2.7 Case study Hamburg

After contextualizing water and associated challenges and processes from a broad perspective, the case of Hamburg is introduced, which this thesis deals with. For this purpose, general information about the city of Hamburg is given first, followed by the water situation in Hamburg. This is closely related to the municipal water utility in Hamburg, which is examined in more detail.

2.7.1 General information about Hamburg

Hamburg, officially called Free and Hanseatic city of Hamburg (Hamburg Stadt, n.d.), is with 1,8 Mio. inhabitants the second-largest city in Germany after Berlin (StBA, 2021). It is located in northern Germany at the mouths of the rivers Bille and Alster and the river Elbe. Hamburg is, at the same time, also a federal state bordering Schleswig-Holstein to the north and Lower Saxony to the south (see figure 3). The climate is permanently humid in Hamburg with 804 mm of precipitation per year (CLIMATE-DATA.ORG, n.d.).

Covering an area of 755,09 km^2 Hamburg has a density of 2.453 per km^2 (Statistisches Amt des Bundes und der Länder, 2021b). Hamburg is of national and international importance as a trade, transport, and service center and is one of the most important industrial locations in Germany. It is home to the third-largest harbor in Europe and a hub for aviation and renewable energies (Hamburg n.d.). With a gross domestic product per inhabitant of 64,022 Euro in 2020, Hamburg shows the highest GDP per capita of all federal states in Germany (Statistisches Amt des Bundes und der Länder, 2021a).

Hamburg has recorded major population growth in the past years with an increase in population of 8,5 % between 2011 to 2020 (Statistisches Amt für Hamburg und Schleswig-Holstein, 2020). Further growth is forecasted to reach 2 million inhabitants in 2030 (Statistisches Amt für Hamburg und Schleswig-Holstein, 2022).

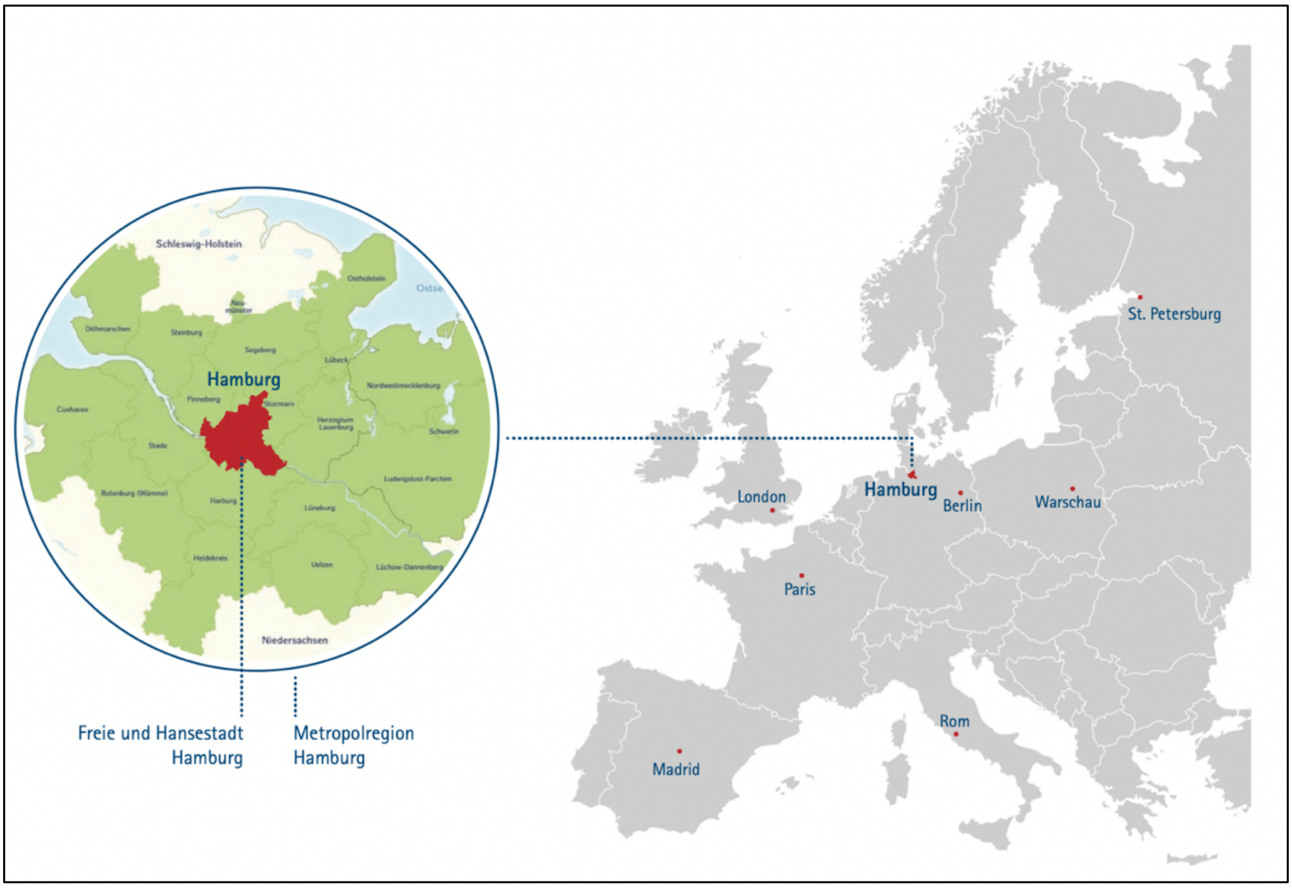

Figure 3: Geographic location of the city of Hamburg (Handelskammer Hamburg, 2020)

2.7.2 Water situation in Hamburg

Hamburg Wasser is the municipal provider of drinking water and wastewater services in Hamburg city and for some parts of the metropolitan area of Hamburg. With more than 2000 employers and a turnover of 644 Mio. Euro Hamburg Wasser supplies 2,2 Mio. people (Hamburg Wasser, 2021b). The following table presents key operating figures of Hamburg Wasser from 2020.

Table 1: Key operating figures of Hamburg Wasser, based on (Hamburg Wasser, 2021d)

Volume of treated wastewater	146 Mio. m^3
Volume of total raw water abstraction	119,9 Mio. m^3
Water consumption per capita per day (Excluding industry, but including small businesses)	144 liter

Amount of water meters	1,15 Mio.
Length of pipe network	5317 km
Length of sewerage network	5989 km

Hamburg's drinking water supply is based exclusively on groundwater extraction. These groundwater resources are located in Hamburg, Lower Saxony and Schleswig-Holstein and are regulated through specific water rights. All wastewater is supplied to a single wastewater treatment plant located in the harbor, treating around 350000 m^3 daily (Hamburg Wasser, n.d.c). Hamburg Wasser as a public municipal service provider is obligated to ensure sustainable and long-term safeguarding of the increasing water demand on the one hand and the drainage of the city on the other (Hamburg Wasser, 2021b). This means that Hamburg Wasser has to prioritize the provisioning of these services over potential monetary benefits. Municipal service providers are allowed to generate profits which are then transferred to the respective municipality (Schäfer, n.d.).

2.7.2.1 Non-climatic challenges to the water sector in Hamburg

From 1980 to 2010, Hamburg experienced a significant drop in water consumption per capita and per day, which decreased from 151 liters to 108 liters[1].

One of the most important reasons for this huge decline, in addition to the introduction of water-saving sanitary fittings and household appliances, was the obligation to install residential water meters (Bürgerschaft der Freien und Hansestadt Hamburg, 2016). However, since the 2010s, a trend toward rising water consumption has been discernible (Hamburg Wasser, 2014). For instance, the water consumption per capita increased from 139 liters per day in 2017 to 144 liters[2] in 2020 (Hamburg Wasser, 2021d). There are numerous reasons which have contributed to this development. These reasons include that a trend to more single or smaller households, which is associated with higher water consumption, is visible (George, 2016). Moreover, different behavioral changes and consumption patterns have been observed. For example, the number of private free-standing and in-ground pools has increased in the past years in Hamburg. In addition, particularly for younger people a trend towards more frequent and longer showers can be monitored. Specific effects of the Corona pandemic are also considered to be relevant,

[1] Excluding small businesses as consumers

[2] Including small businesses as consumers. From 2017 Hamburg Wasser includes small businesses in the water consumption per capita per day data provided by the environmental declaration report

such as more frequent hand washing, or due to home office and school attendance, more cooking and cleaning (Liehr & Lüdtke, 2021).
Furthermore, as outlined, Hamburg is a city with a growing population impacting the total water consumption. Based on a water demand forecast from 2016 assuming a dynamic population increase, the total water demand of households is anticipated to increase by 2,3% by 2025 (Liehr et al., 2016). This forecast does not include various factors that were difficult to predict as, for instance, the Covid-19 pandemic. Consequently, the exact increase will most likely vary.
However, certain is that Hamburg Wasser expects total water demand to increase over the next few years. That is why Hamburg Wasser is currently looking for new well sites for groundwater abstraction (Hamburg Wasser, 2022b). Related to this, elevated salt concentrations in deep groundwater pose a challenge for increasing drinking water production (Hamburg Wasser, 2021d). Currently, Hamburg Wasser tests new process methods for the extraction of drinking water from salty water resources (Hamburg Wasser, n.d.a).

2.7.2.2 Climatic challenges to the water sector in Hamburg

Hamburg is affected by the consequences of the climate change in different ways. Due to climate change, increasing periods of drought and heat and precipitation deficits occur, leading to higher water consumption with water demand peaks. For instance, June and July 2020 created such peaks with warm temperatures with multiple days over 30 degrees and 14 days without any precipitation. During this period, Hamburg Wasser could barely meet the overall water demand (Hamburg Wasser, 2021c). Forecasts to which exact extent the frequency of droughts and heatwaves will increase in Hamburg are difficult to make as, among others, the total amount of greenhouse gas emissions in the coming years and decades is unknown. What all scenarios have in common, however, is that the number of such events is increasing. Overall, the annual average temperature is anticipated to rise by 1 to 1,4 degrees which may also result in higher water consumption (DWD, 2021).

In addition, other extreme weather events such as storms, heavy rain, and flooding occur more frequently and cannot be fully absorbed by a potentially overloaded sewer system (Hamburg Wasser 2021c). For example, heavy rain can briefly increase the volume of wastewater to be handled by more than 20 times compared to the volume during dry weather. This can create overloading of the sewerage network, eventually resulting in overflows causing pollution of the environment (Hamburg Wasser, 2021c). Furthermore, future sea-level rise, as the Elbe transmits the rise in sea level from the southern North Sea to the Hamburg metropolitan region, constitutes another major climate change-related challenge for Hamburg (DWD, 2021). This challenge, however, will not be further discussed as it is not very relevant in regard to circular economy and water consumption.

2.7.3 Conducted and proposed measures by Hamburg Wasser

Hamburg Wasser is committed to an environmentally friendly, resource-saving, and sustainable provision of services. This promise was formulated together with the city of Hamburg in 2010 and has since been renewed and expanded. As for the period 2021 to 2025, the following goals have been decided:

- Reducing the environmental impacts and finding innovative ideas to limit climate change and meet additional challenges of the future.
- Reduce CO_2 emissions from heat and fuel consumption by a further 1,300 t CO_2
- Increase self-supply with renewable electricity to 85%.

Under these overarching goals, Hamburg Wasser has developed specific targets and associated measures. The following table provides extracts of these, derived from the environmental program from 2020. Thereby, the selection of the targets and measures intends to represent a cross-section to give an overall picture. In total, 39 targets have been formulated for 2020. For 2021, 30 targets were defined. Generally, these targets mostly concur with those in 2020 and are therefore not presented separately (Hamburg Wasser, 2021d).

Table 2: Targets and measures of the environmental program of Hamburg Wasser, based on Hamburg Wasser, 2021d)

Specific target	Measure
Resource-saving groundwater extraction and no increase in salt concentration	Monitoring and adjustments of groundwater abstraction concepts
Reduce operational waste volume and improve the separation of recyclable materials	Development of a concept for waste reduction and prevention
Relief of natural waters	Forecasts of runoff behavior and optimizing management of sewerage network to avoid overflows from heavy rain

Minimize use of hazardous substances	Searching for environmentally friendly alternatives to ferrous sulfate for reliable phosphorus elimination.
Increasing functionality of the moor	blocking of drainage ditches and prevention of nutrient inputs
Energetic optimization of the well pumps	Installation and tendering for new well pumps
Savings of digester gas and waste heat utilization	Connection of a facility to the district heating grid
Expansion of renewable energy sources such as wind energy	Creating the prerequisites for construction measures
Improvement of the energetic use of sewage sludge for biogas	Creating the prerequisites for construction measures
Recovery of phosphor from sewage sludge	Construction of phosphor recovery plant
Informing and raising public awareness of environmental and climate-related issues	15 communication campaigns dealing with environment and sustainability, among others, encouraging environmentally friendly behavior

Furthermore, Hamburg Wasser has developed the “Hamburg Water Cycle“ concept, which aims to close the material cycle in residential neighborhoods. Key element constitutes separate processing of stormwater, wastewater from kitchens, and wastewater from toilets to make the best economic and environmental use of therein contained resources. The concept is currently being applied in newly constructed buildings in the Jenfelder Au neighborhood (Hamburg Wasser, 2022c).

By looking at the different targets and associated measures, it becomes evident that the environmental program is very energy-related and is characterized by a strong focus on technological improvements. Most measures aim to increase the share of renewable energies, improve energy efficiency or deal with resource recovery or recycling. In general, the protection and sustainable management of natural resources is also a major aspect. For example, the conservation of groundwater resources is a central management criterion by Hamburg Wasser, meaning that water abstraction for drinking water must not jeopardize the availability of groundwater in the long term through overexploitation.

In addition, the designation of water protection areas at sites of groundwater abstraction is of major significance. Currently, total groundwater withdrawals at all three sites do not exceed total natural groundwater replication (Hamburg Wasser, 2021d).

However, the environmental program lacks measures targeting water consumers to reduce water consumption. Besides different communication campaigns, no such measures are implemented. The same applies to the planned measures for 2021 (Ibid.).

Thus, considering the increasing water consumption per capita per day and an additional growing total water demand due to population growth, it can be deduced that a gap in measures towards the reduction of water consumption of consumers is apparent. Such measures can be assigned under residential water demand management measures. This term is used throughout this thesis and explained in more detail later. Furthermore, against the background of climate change and associated water peak demands and droughts, such measures could also contribute to decreasing vulnerability to such events.

2.8 Sub conclusion

To conclude, the linear water system stands in contrast to the natural water cycle and is unsustainable. Particularly the linear water system is vulnerable to different non-climatic and climatic challenges. Acknowledging the vital role of water for a sustainable and better future, SDG 6 was formulated which addresses sanitation and the availability of water. In the light of the many challenges, the concept of circular economy is assigned great importance to counteract these. This can be seen reflected in the European Green Deal and the European Circular Economy Action Plan. The water system in Hamburg is also affected by multiple challenges.

Therefore, and against the background that the water utility in Hamburg is committed to a sustainable provisioning of services, different measures are conducted and planned to ensure this and to respond to these challenges. However, a gap in residential water demand management measures is discernible.

3 Problem formulation

Based on the challenges Hamburg faces, the need for responses, and the identified gap in residential water demand management measures, the study raises the question of what benefits could result from implementing such measures for Hamburg, how such measures can contribute to the circularity of Hamburg's water system and why they are not applied more widely in Hamburg. For this purpose, the following main research question and sub-research questions are formulated.

Main research question:

- To what extent can residential water demand management measures bring benefits to Hamburg and increase the circularity of Hamburg's water system?

Sub research questions:

- Which residential water demand management measures exist?

- What benefits and potentials arise for Hamburg when implementing residential water demand management measures and with regard to a circular water economy?

- Which barriers face Hamburg's water system with respect to residential water demand management measures? And how can such measures be promoted?

4 Conceptual framework

The following chapter introduces the theories used throughout this thesis, namely circular water economy and transition theory. It also provides their relevance for this thesis.

4.1 Circular economy

The notion of circular economy stems from various concepts developed decades ago (Kalmykova, Sadagopan, Rosado, 2018). Most notably are: "spaceman economy" (Boulding 1966), "limits to growth" (Meadows et al. 1972), "industrial ecology" (Frosch & Gallopoulos, 1989), "cradle to cradle" (McDonough & Braungart, 2002), and "planetary boundaries" (Rockström et al., 2009). These concepts have in common that they all deal with resources and materials and address their finiteness on the Earth (Kalmykova et al., 2018). Interest in developing a global concept of circular economy has emerged only recently, as can be seen from the most important documents on the circular economy today. Before 2012, the term circular economy was primarily associated with China as it adopted circularity principles at an early stage. Currently, the development of circular economy concepts is concentrated in Europe but also governments outside the EU and NGOs are engaged (Kalmykova et al., 2018). Besides the definition of the Ellen MacArthur foundation on circular economy presented in the problem analysis, the European Commission also developed a noted definition which presents circular economy as an economy "where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized" (EC, 2015: 2).

Until recently, the water sector has barely been included in circular economy discussions. Due to the origins of the concept of circular economy many circular economy initiatives and policies have focused on the solid waste and manufacturing sector (Delgado et al., 2021). In 2016, the International Water Association published a report called" Water Utility Pathways in a Circular Economy" pointing out the great potential of circular economy to make the water sector more efficient and sustainable (IWA, 2016). Following an emerging discussion on the potential relevance of circular economy for the water sector, the Ellen MacArthur developed a whitepaper, named "Water and Circular Economy", setting the theoretical basis of the relationship between circular economy principles and the water sector. In doing so, this whitepaper identifies and provides opportunities for circularity by applying circular economy principles to water systems (Ellen MacArthur Foundation, 2019).

Accordingly, a circular water economy recognizes the full value of water as water is used and provides value in a variety of ways:

1) Water as a service – Water is used for heating and cooling purposes, is part of production and manufacturing processes, and provides sanitation in homes and businesses. In addition, water is essential for maintenance and restoration of most natural ecosystems.
2) Water as carrier – In the natural and built environment, water serves as a carrier of different materials such as particles, chemicals, and nutrients.
3) Water as energy – Water can act as a source of energy to generate hydroelectric energy, thermal energy, for instance, through heat pumps, and biothermal energy through aerobic digestion from municipal sewage (Ellen MacArthur Foundation, 2019).

4.1.1 Circular economy principles in the water sector

According to the Ellen MacArthur Foundation, a circular economy is based on three principles. The specific application of these principles to the water sector is presented in the table below.

Table 3: Application of circular economy principles to the water sector, based on (Ellen MacArthur Foundation, 2019)

Circular economy principle	Application to the water sector
Design out Waste and Pollution	• "*Optimise the amount of energy, minerals, and chemicals use in operation of water systems in concert with other systems.* • *Optimise consumptive use of water within sub- basin in relation adjacent sub-basins (e.g. use in agriculture or evaporative cooling)* • *Use measures or solutions which deliver the same outcome without using wate*r" (Ellen MacArthur Foundation, 2019: 6).
Keep Products and Materials in Use	• "*Optimise resource yields (water use & reuse, energy, minerals, and chemicals) within water systems.* • *Optimise energy or resource extraction from the water system and maximise their reuse.* • *Optimise value generated in the interfaces of water system with other systems*." (Ibid.: 6).

Regenerate Natural Systems	• "*Maximise environmental flows by reducing consumptive and non-consumptive uses of water.* • *Preserve and enhance the natural capital (e.g. river restoration, pollution prevention, quality of effluent, etc.)* • *Ensure minimum disruption to natural water systems from human interactions and use*" (Ibid.: 6).

4.1.2 Circular water economy from a systems perspective

To put circular economy principles in a water systems perspective, the Ellen MacArthur Foundation developed a "water butterfly" diagram, which is shown in figure 4. The diagram divides the water system into a "Nature managed" and "Human managed" half. The nature-managed side presents the natural water cycle as presented in the problem analysis in a simplified form with no human interactions.

The natural water cycle ensures the re-optimization, reuse, and replenishment of water as depicted in figure 4:

- *Re-optimize* refers to the capacity of ecosystems to adapt to the available water resources. Biodiversity and ecosystems need a certain amount of water to exist
- *Reuse* describes the natural treatment capacity of water by flora and fauna, for instance, through wetlands and its resulting opportunity to reuse
- *Replenish* stands for the return of water to the environment (Ellen MacArthur Foundation, 2019).

The human-made water cycle, thus the human-managed half in the figure, is usually characterized by a linear water system. This impacts the circularity of the natural water cycle and leads to an unsustainable water system. A circular water economy with its application of principles offers opportunities presented on the human-managed side to align the human water cycle with the natural water cycle to create a sustainable use of water resources. As a result, both can coexist building a functioning and sustainable water system, as shown in the "water butterfly" diagram below.

This can be achieved through the following measures:

- Avoiding the use of water by rethinking services and products
- Reduce the use of water through water efficiency measures and suited resource management such as leakage detection and water metering (Ibid.)

- Reuse water wherever possible: this includes collecting and using wastewater that has not been treated yet and also involves the reuse of rainwater and greywater (wastewater without fecal contamination)
- Recycle water: that involves water that has been treated and is used for non-potable uses (no drinking water quality required) such as irrigation of gardens or of agricultural land (Brears, 2020)
- Replenish water which means the return of water to the basin (Ellen MacArthur Foundation, 2019)

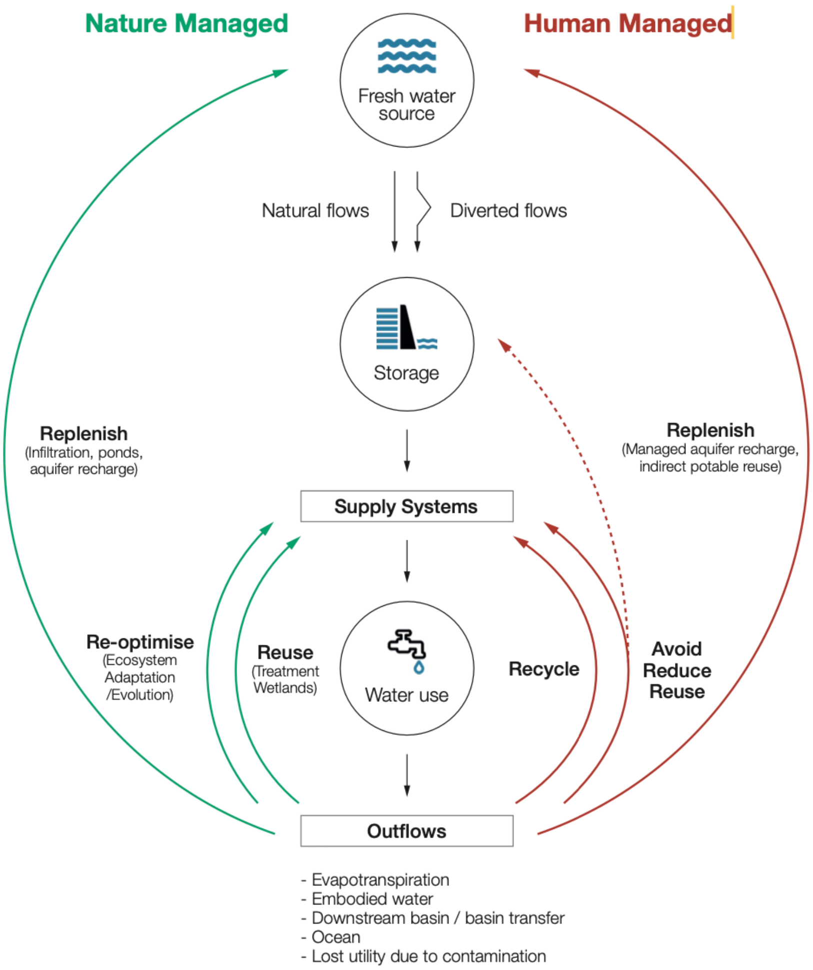

Figure 4: Water butterfly diagram in a water system (Ellen MacArthur Foundation, 2019: 13)

To summarize, by adopting the circular economy principles to the water sector and mimicking the natural water cycle, a circular water economy avoids water use wherever possible, reuses water and other resources. In a circular water economy, the efficiency of water and other resources are improved, waste and pollution are minimized, and natural systems are restored

(Delgado et al., 2021; Ellen MacArthur Foundation, 2019). The concept of circular water sets out the larger context of residential demand management measures. This is because such measures mainly deal with avoiding and reducing the use of water, as will be presented in chapter 6 and can therefore be assigned under the concept of circular water economy. As such, this thesis provides for the importance of residential water demand measures for circularity but also discusses their interaction and relation to each other.

4.2 Transition theory

Transition theory emerged in the 1990s as a reaction to large-scale societal changes and the increasing notion of sustainability. Since then, transition theory has been further developed and applied to many different disciplines (Loorbach et al., 2017).

Loorbach et al. (2017: 605) define transitions, as a "*process of change from one system to another via a period of nonlinear disruptive change*". To achieve such a substantial change in a socio-technical system, an interplay of changes at different levels and in different sectors is needed that support each other and interact. Fundamental in transition theory is that systemic changes occur in regimes which can be described as "*a dominant and stable configuration in a societal system*" (Ibid.: 606). The term socio-technical is intended to stress the path dependence of dominating technologies with, for instance, institutions, routines, and culture, thus expressing the strong influence of technology on society and vice versa. For example, the dominance of technologies does not only result from economical advantages but also from roles, ways of thinking, and routines. Thus, rules play an important role in stabilizing systems (Geels & Kemp, 2007).

Over time, path dependencies can lead to cumulative advantages through self-reinforcing mechanisms for products, technologies, and organizational practices that limit the scope of alternatives and possible actions. Path dependence and the specific advantages that can result are fundamental for systems to develop. However, path dependencies can become problematic when the system gets disrupted so that the established ways of operation are not efficient or desired anymore. If a system is unable to change from the current path a lock-in is present. A lock-in can be described as a situation where a change to alternative practices or technologies would entail high costs or is even impossible although this would be better from a technical, economic, or environmental point of view (Apajalahti & Kungl, 2022).

In a transition perspective, the regime interacts with external factors, meaning the broader societal context, but also with innovations and upcoming novelties. Changes in the landscape and the development of new innovations lead to a state where regimes experience pressure, destabilization, and disruptive system changes (Loorbach et al., 2017). In particular, landscape pressures can lead to internal problems within the regime, such as technical problems or declining economic returns, which may raise doubts among key actors. This can reduce the regime's resistance to change creating opportunity windows for niche innovations (Turnheim & Geels, 2012).

The figure below depicts the different levels in systems and shows the dynamics of transitions.

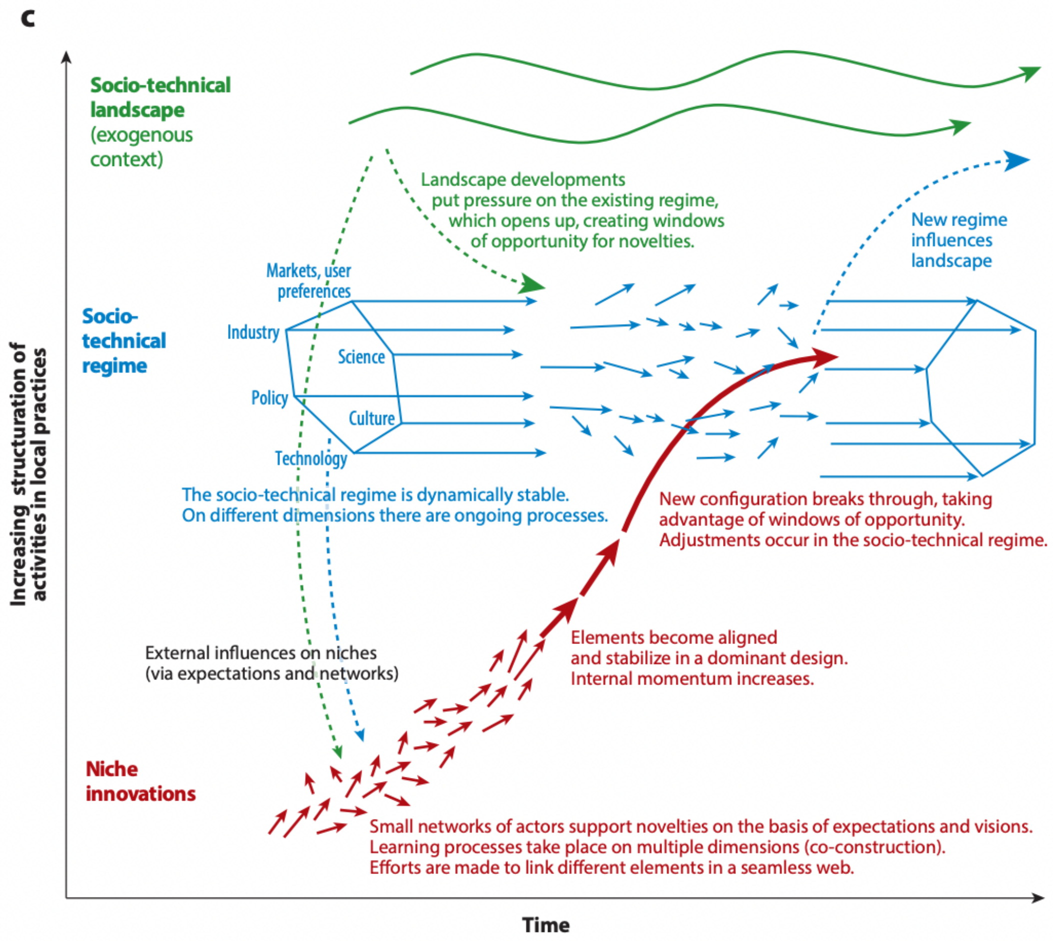

Figure 5: Multi-Level Perspective in transition theory (Loorbach et al., 2017: 606)

The water sector including Hamburg Wasser can be assigned to the regime level. Transition theory helps to understand and determine relations of the water sector to the socio-technical system but also provides guidance to identify path dependencies in the sector and thereby defining barriers of change towards the application of more domestic water demand management measures and improved circularity.

5 Methodology

The following chapter presents the research design and describes the applied research methods to collect data. At the end of this chapter, a figure is shown which gives an overview of the following analysis chapter and the used and applied research methods and theories.

5.1 Research Design

The research design presents the framework for collecting and analyzing. This thesis follows a case study research design. A case study does not constitute a research method as selecting a specific case does not provide any data. A research method needs to be applied to the case to collect data (Bryman, 2012). According to Bryman (2012: 66), a case study "*entails the detailed and intensive analysis of a single case*". Flyvbjerg (2006) points out that using a case study in the beginning of the research can be applied to develop the research question, which the case study design has been used for in this thesis. Following initial research and analysis of the case has helped to generate the research question of this thesis. However, a case study is not just utilized during initial research but also for answering the research questions throughout the thesis (Flyvbjerg, 2006).

The selection of the case for the research is of great importance. Therefore, the purpose of the case should be understood. Besides that, it should become clear, how the case helps to answer the research questions. Thus, in case study research design, different types of cases can be distinguished (Bryman, 2012). Yin (2009) differs between five types of cases consisting of: *critical, extreme, representative, revelatory,* and *longitudinal*. For instance, a *revelatory* case provides the opportunity for a researcher to analyze and observe a phenomenon which could not be investigated before. In contrast, the *extreme* case offers observations that are unusual and far away from the respective mean (Seawright & Gerring, 2008). A combination of characteristics of different case types is also possible.

The case Hamburg constitutes a *representative or exemplifying* case. As such, it "*exemplifies a broader category of which it is a member* " (Bryman, 2012: 70) and can "*provide a suitable context for certain research questions*" (Ibid.: 70). Like the majority of major cities in the world, Hamburg experiences population growth and needs to deal with associated challenges in regard to increasing water demands. Furthermore, Hamburg is also impacted by the consequences of climate change.

Moreover, the case was selected as the city of Hamburg and in particular the Hamburg water utility provides a large range of accessible information sources that can be analyzed. That includes, most notably, the comprehensive environmental and sustainability reports, but also Hamburg water demand forecasts or other websites and media articles.

In case study research design, the possible or, according to other considerations, impossible generalization from a single case study is controversially discussed (Flyvbjerg, 2006). This thesis will not enter this discussion, but it needs to be stressed that acquired knowledge also does not need to be generalized to contribute to a research field. Rather, using "*the force of example*" (Ibid.: 228) can also provide valuable insights and findings for a broader perspective (Ibid.).

5.2 Methods

This project is based on a mixed-method approach consisting of semi-structured interviews and reviewing literature. Through the latter, secondary data is generated whereas primary data is obtained through semi-structured interviews.

5.2.1 Literature review

When reviewing literature, the researcher does not only summarize but also engages critically with the literature including analytical, exploratory, and interpretational understandings (Bryman, 2012). The selection of information sources aims to reflect a wide range of information types to collect a variety of data to be analyzed. These include scientific papers, publications from NGOs, financial institutions and governments, books, and online media. Notably, also all documents associated with the selected case. The literature was mainly retrieved from the AAU library, Google Scholar, and Google search.

5.2.2 Semi-structured interview

Usually, semi-structured interviews employ a mixture of open-ended- and closed questions which are accompanied by follow-up questions (Adams, 2015). The interviewer can vary from the pre-formulated questions set in the interview guide to adapt to the course of the interview and ask further questions depending on the responses of the interviewees (Bryman, 2012). Particularly in mixed-methods research, semi-structured interviews can be a useful research method to provide additional and in-depth data to other research methods (Adams, 2015). It can generate data about how the interviewees experience their world and how they view certain topics. When analyzing the data retrieved from the interview, this personal perspective has to be taken into account. Additionally, the questions asked by the interviewer are critical for the outcome of the interview (Brinkmann & Kvale, 2018).

Unfortunately, it was not possible to conduct an interview with an employee of Hamburg Wasser. There was initially no response to e-mails. After the initial call, it was agreed that an employee in the field of water demand management would respond. After this did not happen, several calls were made to Hamburg Wasser with the result that the responsible experts were too busy and therefore not available.

The other interview partners were selected to gain insights and knowledge from other water utilities from cities with similar characteristics concerning the water situation, challenges, and development status. Thus, to learn and generate data from other perspectives and also possibly, to compensate for the interview with Hamburg Wasser, which was not possible. An interview guide was developed prior to each interview and can be found in the Appendix. The questions concentrated on the use and limitations of residential WDM measures in each utility, current challenges and how to overcome them, and the role of circular water economy. The table below shows the different interview partners.

Table 4: Overview of interview partner, own table

Name	Organization	Position
Dr Gesche Gruetzmacher	Berliner Wasserbetriebe (Berliner water utility)	Director of the division: Central tasks and drinking water quality of the water supply
Lærke Lil Munck Daverkosen	Showroom Energy & Water (Initiative of the City of Copenhagen & HOFOR)	Project coordinator at the showroom
Martin Skriver	HOFOR (Copenhagen water utility)	Water supply and planning of waterworks

5.3 Overview of the analysis

Finally, the following figure illustrates the structure of the upcoming analysis and shows the research method and theory relevant to each section of the analysis.

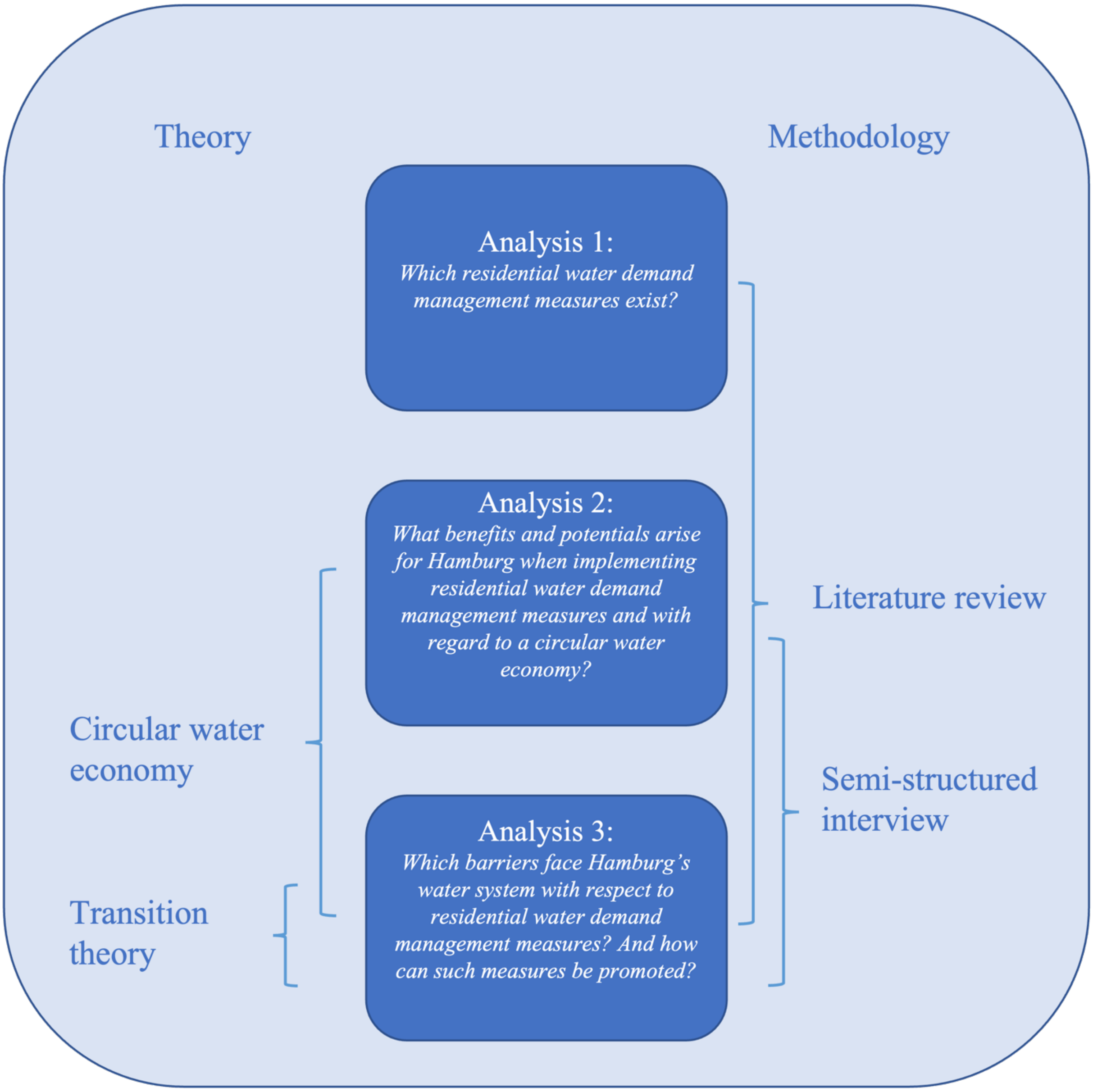

Figure 6: Analysis structure and relevant research methods and theories, own figure

6 Analysis

The analysis is structured into three sections based on the formulated three sub research questions. The sections tackle the matters raised in each sub-question using data collected from reviewing literature and semi-structured interviews.

6.1 Which residential water demand management measures exist?

The following section deals with residential water demand management measures. For this, the term water demand management will first be explained and how it is reflected in the Water Framework Directive. This is followed by providing a wide range of different residential water demand management measures which are shortly described.

6.1.1 Water demand management

Water demand management (WDM) "*refers to the implementation of policies or measures which serve to control or influence the amount of water used*" (Lallana et al., 2001: 11). WDM comprises changes in technologies, culture, and the behavior of people that save water and protect the water quality for all users, including nature (Baroudy, 2005; Brears, 2020). Related to this, measures of WDM are intended to make better use of existing water supplies and infrastructure with a focus on overall reduced water usage and consumption.

This means, that rather than extending water supply infrastructure or increasing the number of bore wells to meet growing water demand in the first place, WDM applies measures such as water leakage detection, incentive schemes and water pricing, irrigation management and methods, and regulations for reduced water consumption. This contrasts WDM from water supply management following a structural engineering approach (GWP, 2012; Stavenhagen et al., 2018)

6.1.2 Water demand management and the Water Framework Directive

In Europe, the Water Framework Directive (WFD) shapes policies of WDM and thus also of residential WDM measures. Adopted in 2000, the directive provides the legal basis for a set of policies to be planned and implemented by the member states. The main objectives are to achieve in all waters a good ecological status and to address the challenges associated with water scarcity, water quality degradation, and the management of costs resulting from water supply services (WISE, 2008). To do so, the WFD promotes among others, demand management strategies and measures (Stavenhagen et al., 2018).

For instance, specific pricing policies shall be implemented, which will be more explained later on (EC, 2014). However, non-price WDM measures are mostly supplementary measures that can be selected to achieve the objectives set out in the WFD. This includes, among others, educational programs or the promotion of water-efficient technologies (Ibid.). Thus, incentivizing water utilities to promote water conservation is not at the core of the WFD.

6.1.3 Residential water demand management measures

Consumers in the human water cycle, as presented in section 2.2, are manifold. Due to the focus of this thesis, only measures being suitable for residential use are considered. Therefore, the water use at a micro-component scale is relevant consisting of domestic water uses indoors and outdoors such as drinking, showering, washing, toilet flushing, and garden irrigation (Giurco et al., 2008). Reviewing a variety of residential WDM measures shows that residential WDM measures can be divided into the categories of non-price and price measures. In the following, different measures of both categories will be shortly described.

6.1.3.1 Non-price measures

Water-efficient appliances:

The uptake of water-efficient devices offers huge potential to save water as a substantial share of household water consumption is consumed through appliances. In Europe, household appliances with the highest average water use percentage are toilets and showers with each over 30%, followed by taps and washing machines with around 10%, and dishwashers with 3%. Outdoor water consumption, for instance for garden irrigation, averages 3% but consumption shows huge variations between income levels and areas (BIO Intelligence Service, 2009). The overall aim of water-efficient appliances is to conserve water without limiting the level of service. Typically, appliances such as low- / dual-flush toilets, low-flow showerheads, faucet aerators (devices that reduce the flow of water on tips), and more efficient washing machines and dishwashers are installed to reduce water consumption (Brears, 2016). The Ecodesign Directive is the most important legislation dealing with the freshwater reduction of water-using products in the European Union (Dige et al., 2017). The newly proposed minimum eco-design requirements for all product groups are extending the scope of the Ecodesign Directive. Thereby, water-saving devices can become the norm throughout the European Union as it applies to all product groups. Consequently, this regulation on ecodesign for sustainable products will be decisive for appliances in the future (EP, 2022).

Nevertheless, there are also other means which can promote the uptake of water-efficient devices. Water utilities can offer rebates to customers who buy water-efficient devices to encourage the uptake of such devices and thus accelerate the replacement of old water-consumptive appliances (Bello-Dambatta et al., 2013). Certification and labeling schemes such as DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) or BREEAM (Building Research Establishment Environmental Assessment Methodology) can also promote the uptake of water-efficient devices as they reward points for reduced water consumption (BREEAM, 2019; DGNB, 2018). Nationwide, regional, or local building codes, setting thresholds on water consumption or requiring the installation of water efficiently certified appliances, can constitute another means (Dige et al., 2017). For example, the building regulations of England and Wales stipulate that water consumption per capita per day for people in new homes must not exceed 125 liters (Andrewartha & Scott, 2018).

Information and awareness campaigns:
Information and awareness campaigns aim to generate an understanding of water as a scarce resource and seek to change the behavior of households. The provision of information to households about the benefits of water-saving thereby is very important to increase the success of such campaigns (Bello-Dambatta et al., 2013). For these purposes, water utilities can use various tools and formats. For instance, these can consist of internet and social media campaigns, commercials on public transport, advertisements, newspaper articles, and public events with workshops (EPA, 2015).

Decentralized supply systems:
Installing a decentralized water supply to houses constitutes a means to reduce water abstraction needs and thus relieves pressure on the water utility for water supply (EA, 2010). The most commonly used decentralized water supply systems include rainwater harvesting system (RWHS) and greywater recycling system (GWRS). RWHS involves capturing rainwater from the surfaces on which it falls as for example pavements and roofs and then subsequent collection in tanks (EA, 2010). Rainwater harvesting can substitute the water supply for non-potable end uses including WC flushing, garden watering, and washing machines. As these uses account for significant domestic water consumption, the usage of rainwater harvesting can lead to high water savings (Alias et al., 2017). Greywater is wastewater that originates from sources apart from toilet flushing and kitchen sink. In GWRS, greywater is stored in tanks and can then be used for different purposes as applicable for RWHS. Common features of both systems are a

tank, a pump or use of gravity to enable transportation of the water, and a distribution system to transport the water where needed. However, both systems can vary respectively in their complexity and scale. Particularly, GWRS can contain an advanced treatment process due to the amount of organic matter contained in greywater and depending on the ultimate purpose of usage (EA, 2011).

Water meters:

The installation of water meters constitutes an important measure. Through water metering, end-consumers are aware of the amount of water they use, and water meters make potential water savings through water-efficient devices visible. In addition, water meters are necessary for charging consumers for the used amount of water and are thus important for designing water tariffs (Brears, 2016). Over the last two decades, smart water meters have been introduced offering new opportunities for water conservation (Cominola et al., 2015). Smart meters generate additional data by creating an information flow between the water network and the water. They are also capable of generating real-time or near real-time data (Nguyen et al., 2018). This helps the water utility to gain insights into individual water consumption. The data can also be used for customized awareness strategies but also enable different pricing and tariff options. The customer can benefit from the data as smart meters can show when and where water was consumed so that they can monitor and optimize their water use (Brears, 2016).

Water restrictions:

Restrictions on water use are usually temporally applied in acute water shortages. Such programs can ban or restrict specific types of water use or demand total water use reductions. Examples of such types of water use include the filling of swimming pools, garden irrigation, and washing of cars (Icon Water, 2006). Countries often establish a "water hierarchy" that determines priority use, with urban water supply prioritized over garden irrigation and agricultural use (OECD, 2015). Besides outdoor use restrictions (OUR), the amount of water used by each household can be restricted, which is also called total use constraint (TUC) (Alias et al., 2017). However, TUCs are usually applied in places with temporal extreme shortages, such as in Southeast Queensland (Seqwater, 2017).

6.1.3.2 Price measures

In contrast to non-price measures, price measures are not as manifold. Water price and water tariffs constitute the main measures under this category.

Water price:

The WFD has introduced in Article 9 the cost recovery principle for water price management (EC, 2014), implying a "user pays principle" (EC, n.d.a). Therein, it is formulated that water users shall pay a price for the received water service which completely reflects the costs of the water services provided. This means that the price covers costs resulting from infrastructure investments, environmental costs, operation and maintenance costs of water supply and treatment (Bello-Dambatta et al., 2013). The underlying idea behind this is "*that water-pricing policies provide adequate incentives for users to use water resources efficiently*" (EC, 2014: 21) so that users consume less water if they pay the real costs for the water service (Bello-Dambatta et al., 2013). This can be expanded to the idea of price mechanism in the water sector which refers to that consumption would decline when prices rise (Alias et al., 2017). When aiming to manage water consumption through pricing, the factor of price elasticity of demand is important which is "*the measure of the relationship between a change in the quantity demanded and a change in its price*" (Dige et al., 2017: 57). With regard to the water sector, it constitutes a measure of how the water demand responds to price changes (Ibid.).

Water tariffs:

Water utilities can apply different tariff structures to customers. Thereby, pricing based on the water consumption requires the installation of a meter which even allows a wide range of tariffs. Widely used are single volumetric tariffs, increasing blocks tariffs, and two-part tariffs (Brears, 2020). Single volumetric tariffs charge a steady price on the actual volume of water used by each household. Increasing block rates use a tiered billing structure where different rates are charged for different blocks of consumption, having a low rate for the first block and a higher rate for each subsequent block. Two-part tariffs consist of a component that has a fixed charge and a component with a variable charge based on the volume of water consumed. With no water meter available, consumers pay usually a flat rate which is a rate regardless of their actual consumption. This type of tariff does not provide any incentives to reduce water consumption (Meran et al., 2020).

6.1.4 Sub conclusion

To conclude, water savings in households can be achieved through different measures which are summarized in the figure below. Many reductions in household water consumption result from behavioral changes (Abu-Bakar et al., 2021). These changes can be triggered through non-pricing measures such as information and awareness campaigns, but also pricing measures can promote such changes and incentivize water-saving behavior. The use of water-efficient appliances which can be promoted through different means is also of major importance for reducing residential water consumption. Moreover, the installation of water meters enables the introduction of a variety of pricing measures but can also serve as a means to change behavior. Water utilities can directly implement water-saving measures as it applies to pricing measures or can incentivize the application of such measures as the use of water-efficient appliances is depending on the water user. All of this raises the question of what benefits such measures can bring for Hamburg and with regard to the circularity of the water system.

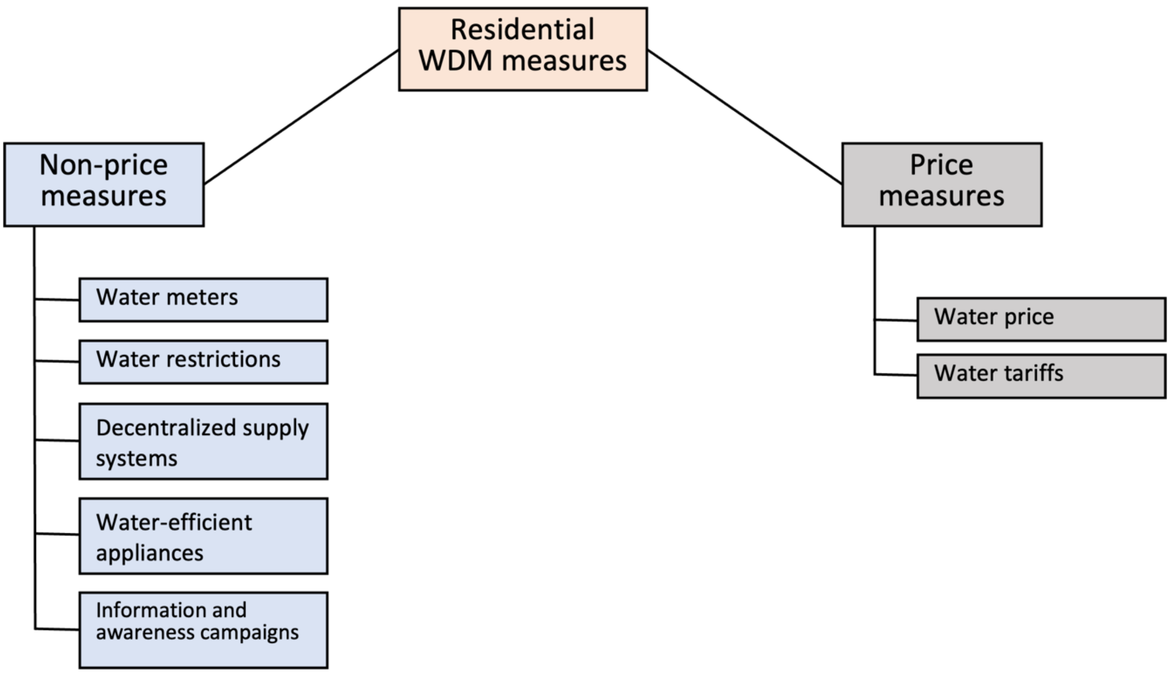

Figure 7: Overview of different residential WDM measures, own figure

6.2 What benefits and potentials arise for Hamburg when implementing residential water demand management measures and with regard to a circular water economy?

In order to answer this sub research question, the huge variety of determinants of household water consumption is firstly presented resulting in specific implications for this thesis. After that, based on a case, the overall potential of WDM for Hamburg will be presented. Finally, the importance of such measures in relation to the circularity for Hamburg will be outlined.

6.2.1 Factors on household water consumption

The complexity of domestic water demand derives from the large variety of determinants on household water consumption. To give an understanding of the different water demand determinants in households, a classification into three factors can be made.
These constitute exogenous (environmental), endogenous (contextual), and behavioral (psychological and social) factors (Abu-Bakar et al., 2021).

Exogenous factors encompass factors with indirect influence on the water consumption meaning that the water consumer cannot control these. Prominent variables demonstrate population, climate, geography, and seasonality. Specific factors under these variables are migration, tourism, precipitation, evaporation, availability or scarcity of water, temperature, or weather conditions (Ibid.). Generally, higher water consumption is associated with increasing temperatures. A British study concluded that a temperature rise of 10% results in a higher per capita consumption of 0,3%. A similar decrease could be observed with a 10% increase on rainy days. Furthermore, garden irrigation is much higher in summer than in winter, while shower water consumption and duration increase in winter months (Manouseli et al., 2019).

Endogenous factors have direct influence on the water consumption. These mainly consist of sociodemographic and socioeconomic variables as well as characteristics of the households. Occupancy and makeup of households have among the biggest influence on water consumption per capita (Makki et al., 2015). A conducted study in Brisbane suggests that households with a small number of residents have a lower water consumption per capita and higher tendency to conserve water (Fielding et al., 2012). In contrast, larger family households with teenagers show higher per capita consumption due to more frequent and/or longer end-use events, such as

showering. The level of education and household income is also a relevant factor. Better educated people have a higher interest in conserving water and participating in water-saving initiatives (Watson, 2017; Makki et al., 2015). Similarly, affluent households have a higher tendency to install water-efficient appliances (Fielding et al., 2012). Related to this, housing owners have a higher tendency to invest in water-efficient appliances than renters (Aprile & Fiorillo, 2017). However, this does not mean that higher educated and higher-income households generally have a lower water consumption, the opposite applies. Such households, usually have more frequent shower uses and a longer shower duration (Makki et al., 2015), and use more water for garden irrigation and for house washing (e.g. cleaning of kitchen, washroom, floor washing) (Hussien et al., 2016). Similarly to this, educated and wealthy people tend to have a larger carbon footprint (Xu & Khalili, 2020).
Furthermore, the presence of water-efficient devices does not necessarily result in less water usage if the users do not curtail their consumption. Offsetting behaviors, such as longer showering when water-efficient showerheads are installed, can diminish the effect of water-efficient devices (Fielding et al., 2012).

Psychological and behavioral factors have huge impacts on household water use and the intention to conserve water. Water-conserving behavior is largely determined by attitudes, norms, and habits. Studies have shown that people in households consume less water when they have a positive attitude towards the environment and water conservation. Assigning value to water and being concerned with how it is used shapes water-conserving behavior (Willis et al., 2011). Water-conserving behavior can include brushing teeth with a closed tap, washing vegetables without a running tap, and avoiding washing with little loads. Awareness, attitudes, and knowledge also clearly impact the level of participation in water-saving initiatives and the motivation to change own habits and routines (Abu-Bakar et al., 2021).

By presenting the different influential factors on household consumption, it becomes evident that the effectiveness of residential WDM measures and strategies depends on the level these factors are taken into account (Ibid.). In addition, the effectiveness also depends on whether multiple measures are combined in one strategy or conducted separately. The example of offsetting behavior in relation to water-efficient appliances demonstrates this relevance. Therefore, it is argued that technology measures (e.g. water-efficient appliances) should be complemented with behavioral and psychological aspects of water consumption (Levin & Muehleisen, 2016). Overall, it can be said that the effectiveness of residential WDM measures is to a large extent case-specific, with achieved water savings that can vary in extent (Bello-Dambatta et al., 2013).

Therefore, to be able to determine the accurate potential of residential WDM measures for Hamburg, all these prescribed factors would be needed to be taken into account which is not feasible in the course of this thesis. At the Berliner water utility, a working group has recently started to determine the effects of different WDM measures on the Berliner water network. This group consists of employees from the communications, finance, wastewater, and drinking water departments, which underscores the complexity described (Appendix, A),

Nevertheless, to demonstrate the potential such measures could have for Hamburg, a study on the long-term potential of WDM measures for households in Wales and England will be presented.

6.2.2 Case example England and Wales

The study was commissioned by Ofwat, the Water Service regulation Authority for England and Wales, and conducted by Artesia consulting, a specialized water consultancy.

The scope of the study is on the potential to reduce water consumption in households in the long term, namely by the year 2065. Thereby, the study analyses the wide range of factors that affect water consumption, such as consumer behavior or the use of water-consuming products, reflecting described complexity of household water consumption resulting from the variety of determinants (Lawson et al., 2018).

To contemplate potentially different developments of factors affecting water use consumption, different scenarios were formed. In each scenario, household consumption is divided into micro-components, meaning the consumption by each residential activity, such as showering, WC flushing, clothes washing, tap use, etc., to determine the resulting impact of different WDM measures (Ibid.).

Following this approach, the scenarios: 1. "Current ambition", 2. "Localised sustainability", and 3. "Regulation and compliance" were developed. The following table provides a short description of each scenario.

Table 5: Description of different scenarios, based on (Lawson et al., 2018)

1. "Current ambition"	2. "Localised sustainability"	3. "Regulation and compliance"
- Progress in public awareness of future water scarcity - Behavior change through product regulations and water labels - More efficient water-using appliances	- Water scarcity considered as an important issue - Water utilities are active in offering WDM measures - Water conscious behavior and purchase of water-efficient appliances	- Usage of tariff structures and behavioral measures - Progress in public awareness of future water scarcity - Strict regulations on water usage and availability

Starting from a per capita consumption of 140 liter per day which was the average consumption in Wales and England in the period 2015 to 2016, the three scenarios are estimated to lead to the following water consumption per capita per day in 2065:

Table 6: Estimated water consumption per capita per day in 2065 for different scenarios, based on (Lawson et al., 2018)

Scenario	Year: 2065
1."Current ambition"	105 l/cap./day
2. "Localised sustainability":	62 l/cap./day
3. "Regulation and compliance"	73 l/cap./day[3]

These water savings derive from the following residential WDM measures assumed to be implemented in each scenario:

Scenario 1: Old toilet cisterns are continuously replaced, water utilities promote behavior change with a focus on shower use duration and tap use, uptake of water-efficient appliances through regulations and labels for showers and washing machines, and rising public awareness leads to a decline of bath use and reduced potable water use for garden irrigation or car washing.

[3] To model such potentials, the study makes assumptions that are not described here but can be found in Lawson et al., 2018.

Scenario 2: 50% of the toilets are equipped with a very efficient water-saving toilet flushing technology, 50% of the toilets use non-potable water for toilet flushing, less frequent shower use and wide use of low flow shower heads, extensive use of non-potable water for dishwasher, washing machine and cleaning, prevalent use of decentralized supply systems particularly for garden irrigation and car washing.
Scenario 3: Due to regulations, only low flush toilets are allowed for retrofits, water labeling demands water-efficient washing machines and dishwashers, water labeling leads to widespread installation of showers using recycled water, less bathing, and regulations promote decentralized supply systems for garden irrigation and car washing (Lawson et al., 2018).

By looking at the different savings potentials, it becomes evident that major water savings might be achieved through different residential WDM measures. A drop down in consumption from 140 l/cap./day in the period 2015 and 2016 to consumptions in 2065 ranging from 105 l/cap./day to 73 l/cap./day emphasizes the vast possibilities. Presenting this study is not intended to indicate any form of replicability to the case of Hamburg, even reality in England and Wales will be different depending on the actions taken in the next years. For instance, assuming in scenario 2 that all toilets use either- non-potable water for flushing or use highly efficient technology can be considered unrealistic from today's perspective.
The scenarios are meant to give an idea of the long-term saving potentials of residential WDM measures which could also be possible for Hamburg.

6.2.3 Potential benefits for Hamburg

Reducing the per capita consumption of water in Hamburg may bring a variety of benefits depending on the strategy and actions taken. Lower consumption results in less water to be pumped from groundwater resources and less wastewater to be treated. Both lead to lower energy consumption. In addition, less energy will be used in the distribution of drinking water and wastewater collection. Eventually, less energy use leads to a reduction of greenhouse gas emissions (Hamiche et al., 2016). Therefore, residential WDM measures may demonstrate an effective complemental strategy contributing to achieving the formulated goal of the climate plan of Hamburg Wasser to cut down emissions by 90% by 2025 compared to 1990. Currently, the climate plan is mainly built on increasing the capacities of renewable energy production and increasing the efficiency of waterworks (Hamburg Wasser, 2020).
Through more efficient fittings and appliances, less warm water will be consumed, reducing the greenhouse gas emissions of households and thus helping to achieve Hamburg's overall

greenhouse gas reduction goals (Waterwise, 2017). Therein, the sector of private households is specifically addressed as an important sector with the main focus on energetic renovation (Freie und Hansestadt Hamburg, 2019).
Remarkably, using less water does not only help to meet climate goals but reduces household water and energy bills and thereby leading to financial relief (Appendix A).

As presented in section 2.7, Hamburg is increasingly affected by water scarcity. Lower water consumption diminishes pressure on the bore wells, the groundwater resources, and the supply network, and thus helps to better deal with long and dry climate periods (Waterwise, 2017). Temporal restrictions on specific water use do not reduce the water consumption in the long term. However, these restrictions can be suitable to better cope with extremely dry and hot weather conditions resulting in high water peak demands that become more and more of a challenge for water utilities (Appendix B). Therefore, residential WDM measures and associated water consumption reductions may constitute a means to increase the resilience against the consequences of climate change in Hamburg temporarily and permanently.
Furthermore, against the background that Hamburg Wasser is presently looking for new potential bore well sites, reductions in water consumption can diminish the implications of a growing population and an associated rise in overall water demand. Thus, together with increased resilience, residential WDM measures may contribute to a secure water supply by Hamburg Wasser.
In addition, such measures may potentially offset the need to build new infrastructure which is very costly and often connected with lengthy and complex approval procedures and environmental impact assessments with public participation. Residential WDM measures may represent cheaper and easier-to-implement alternatives (Appendix A). The existing issue of elevated salt concentrations in Hamburg's deep groundwaters may thereby also be mitigated. Generally, the pressure on the natural groundwater resources and water-related ecosystems could be reduced (Brears, 2020).

6.2.4 Residential WDM measures and circular water economy

As presented in section 6.1, reducing the amount of water being used is a core element of WDM and residential WDM measures. In doing so, such measures may represent vital means of increasing the circularity of the water sector in Hamburg. WDM reflects the principle of "Regenerate Natural Systems" wherein it is formulated to "*maximise environmental flows by reducing consumptive and non-consumptive uses of water*" (Ellen MacArthur Foundation, 2019: 7). The efficiency improvements in water use, for instance, derived from water-efficient appliances, can be found in the "Keep Products and Materials in Use" principle aiming to "*optimize resource yields (water use & reuse, energy, minerals, and chemicals) within water systems*" (Ibid.: 7). Furthermore, WDM also comprises technologies such as decentralized supply systems that enable the reuse of water. Overall, by reducing water consumption, WDM measures reduce pressure and disruptions on the natural ecosystem which is essential as a circular water economy relies on such (Delgado et al., 2021; Ellen MacArthur Foundation, 2019).

However, by looking at the concept of circular economy, it becomes evident that a circular water economy differentiates between activities and their importance to the concept.
In particular, measures that cause people to avoid or prevent the use of water, such as turning off the tap while brushing teeth or reducing the frequency of showering, are assigned great value. A circular water economy would prioritize such measures which avoid the use of water and thereby prevent the generation of wastewater. This has the greatest benefit for protecting the environment and preventing disturbances in nature. It would also generally optimize the use of water as a resource if it were only used when needed (Ellen MacArthur Foundation, 2019). In contrast, the installation of water-efficient appliances focusing on water efficiency improvements, eventually resulting in reduced water consumption, would have a lower value for circularity.
To emphasize this point, a connection to the EU waste hierarchy as part of the EU Waste Framework Directive can be made. Therein, the prevention of waste is the preferred option over the reuse and recycling of waste materials as depicted in figure 8 (EC, n.d.b). Such a prioritization or hierarchy of measures is an important aspect of the concept of circular water economy. In WDM such a hierarchy or prioritization could not be identified. Therefore, when linking WDM measures to circular water economy, a differentiation is needed to assess the importance of the different WDM measures to the concept.
Overall, it needs to be stressed that avoiding and reducing the consumption of water are crucial means to achieving a circular water system. Avoiding and reducing water use are key elements of residential WDM measures. Both come first and second on the priority list of a circular water economy demonstrating the importance of residential WDM measures to this concept (Ellen MacArthur Foundation, 2019).

Figure 8: EU Waste Hierarchy (EC, n.d.b)

By looking at WDM measures from a systemic and fully circular perspective, it can be said that solely applying such measures will not achieve a system that fully reflects the principles of a circular water economy. Residential WDM measures do not cover all activities and actions of the human-made water cycle. For instance, they do not enable the recycling of water as wastewater treatment does not fall under such measures. Related to this, the extraction of resources and the generation of energy from water and wastewater cannot be provided by residential WDM measures. In addition, they do not deal with the use of chemicals and hazardous substances nor is the distribution of water and replenishment of water to the basin part of residential WDM measures. Such measures, as the name indicates, deal with water demand and targets the consumers of water which are only one part of the water system. Furthermore, water constitutes the basis for all life (UN Water, 2020). Consequently, avoiding and reducing water consumption is subject to certain limitations as there will always be water use and consumption and thus also the generation of wastewater. Therefore, other measures and management strategies will also be needed now and in the future.

Nevertheless, residential WDM measures may offer great potential to increase the circularity of the Hamburg water system. Such measures could fill the gap identified in the problem analysis in measures that aim to avoid and reduce water consumption which is so vital in circular water systems. Hamburg Wasser is well-positioned and ambitious when it comes to the recycling of water and the recovery of resources from water and wastewater.

This becomes evident through the planned phosphor recovery plant but also by generating energy from the sewerage sludge which shall further be expanded. All produced wastewater in Hamburg is treated in a treatment plant and thus enables full recycling of the water.
Furthermore, efforts are made to minimize hazardous substances in their operation and the protection and sustainable management of natural water resources are a central matter of Hamburg Wasser, contributing to preserving natural capital (Hamburg Wasser, 2021c).

6.2.5 Sub conclusion

In conclusion, it can be said, that the effectiveness of residential WDM measures is often case-specific due to the huge variety of exogenous, endogenous, and psychological and behavioral factors. The presented study from England and Wales demonstrates the long-term water-saving potentials which can arise when implementing different measures. Applying residential WDM measures to Hamburg may contribute to a secure water supply by alleviating the pressures on the water system caused by population growth and higher per capita water consumption. Related to this, residential WDM measures may also increase Hamburg's resilience against climate change both permanently and temporarily. Furthermore, by reducing greenhouse gas emissions, they may constitute a means of achieving climate goals of Hamburg Wasser and the city of Hamburg. With regard to circular water economy, it can be noted that such measures are important means that contribute to achieving a circular water economy by especially avoiding and reducing water use. Currently, Hamburg and the Hamburg water system display a lack of such measures. That is why residential WDM measures may offer great potential to increase circularity and fill this gap. However, residential WDM measures do not cover all components of the human-made cycle and therefore cannot provide services to potentially create a full circular water system.

6.3 Which barriers face Hamburg's water system with regard to residential water demand management measures? And how to overcome these?

So far, it has been demonstrated that residential WDM measures are not widespread in Hamburg, although substantial long-term water-saving potentials are possible that may bring a variety of further benefits to different actors, including Hamburg Wasser and the city of Hamburg. Therefore, the following section examines why residential WDM measures are not widely implemented by identifying reasons and barriers to this from the perspective of the water utility Hamburg Wasser. Finally, means and changes are presented which could promote residential WDM measures.

6.3.1 Barriers and reasons from the perspective of Hamburg Wasser

One barrier that can be determined is the perception that there is not a strong need for residential WDM measures and a reduced water consumption. Generally, providing a safe supply of water does not demonstrate a challenge (Appendix A, B; Hamburg Wasser, 2021b, d). In addition, a long-term vision setting desired future target values for a specific water consumption per capita, e.g., for 2030 or 2040 for Hamburg, could not be found. Rather, the per capita water consumption reductions achieved in the 1990s, 2000s, and 2010s were highlighted by Berliner Wasserbetriebe and HOFOR, giving the impression that much, if not enough, has been done in this regard. (Appendix A, B).

Having this as a basic understanding reduces the willingness and ambition to promote (many) residential WDM measures by the water utility when mostly only the benefit of reducing the volume of water used dominates the discourse (Dutreix et al., 2014). Other benefits associated with such measures, such as greenhouse gas emission reductions, are not regarded. That is consistent with the fact that Hamburg Wasser does not describe such benefits in their environmental declaration or sustainability report, nor has one of the interviewees made this point (Hamburg Wasser, 2021d, 2021b; Appendix A, B).

However, temporal extremely dry and hot weather conditions leading to water peak demands constitute a huge challenge. In this regard, temporal water restrictions as part of residential WDM measures are conducted and assigned a high relevance. The benefit that an overall lower per capita consumption in the long-term also diminishes some pressure from the water utility in extreme situations is not particularly mentioned (Appendix A, B; Hamburg Wasser, 2021a).

Based on this, it can be deduced that residential WDM measures are specifically considered quantitively, meaning the reduction in the volume of water used and in regard to temporal usage for extreme events. Other benefits associated with such measures are mostly overseen.
Related to this, the interviewees and the reports by Hamburg Wasser indicate that the value, as described in section 6.3.1, of residential WDM measures for a circular water economy is not fully taken into account. A focus on resource and energy recovery technologies for increasing circularity and environmental performance is dictating Hamburg Wasser's environmental strategy (Hamburg Wasser, 2021d). This is complemented by a supply-oriented philosophy, which becomes clear by citing bore well development, as a reaction to the challenges of population growth and climate change (Hamburg Wasser, n.d.a). In general, it could also be concluded that the principles of a circular water economy are not known in the way they are presented in section 4.1. This can be underpinned by looking into the "chapter" "Kreislaufwirtschaft", which translates to circular economy, of the environmental strategy. Therein, only the topics of waste, chemicals, and materials (solid) are dealt with, which can be considered a very narrow view on circularity (Hamburg Wasser, 2021d).

As a utility, Hamburg Wasser is structured according to a largely linear model, i.e., it supplies the volume of water demanded and thus generates, to a large extent, volume-based revenues (Hamburg Wasser, 2022a). Therefore, reductions in water consumption have an impact on such a revenue stream (IWA, 2016). For the year 2021, Hamburg Wasser has generated a net profit of € 39.3 million transferred to the city of Hamburg (Hamburg Wasser, 2022a). Again, when not considering the wide range of benefits of residential WDM measures such measures become less attractive.
Furthermore, the existing pipe network constitutes an infrastructural barrier. Both interviewees from the water utilities and a newspaper article by the former managing director of Hamburg Wasser emphasize that the water pipes are designed for a specific amount of water. If too little water runs through the pipe system, difficulties with the pressure inside the pipe could occur and the pipes would have to be fully flushed regularly. Overall, more effort and higher costs result from the underutilization of the pipe system. (Appendix A, B; Abendblatt, 2013). Here a path-dependency between the volume of water consumption and the existing pipe network or infrastructure network can be identified which could qualify for the criteria of a lock-in, as presented in section 4.2 (Apajalahti & Kungl, 2022).

The pipe infrastructure requires a certain amount of water consumption without which this specific infrastructure would not work. Therefore, this specific water consumption is maintained.

Another difficulty is that it is often complex and not always possible to quantify the benefits and costs that are associated with the implementation of different residential WDM measures. This derives from the variety of factors of influence described in section 6.2.1, and potentially restrained availability of data (Dutreix et al., 2014). Stable and predictable revenues from investments in residential WDM measures can therefore be problematic, which might make such investments less attractive for water utilities and thus for Hamburg Wasser (Brandes & Ferguson, 2004). Related to this, residential WDM measures are often associated with long-term effects as also mentioned by Dr. Grützmacher from the Berliner Wasserbetriebe, contributing to the difficulty of predictability (Appendix A; Brandes & Ferguson, 2004).

6.3.2 Promotion of residential WDM measures

So how could residential WDM measures be promoted? This thesis argues for leadership at Hamburg Wasser that is knowledgeable on the different potential benefits of residential WDM. The leadership is in charge and makes decisions and determines future strategies and policies and thus may be a vital enabler for such measures. (IWA, 2016). The leadership can be supported by collaborations and partnerships with stakeholders outside the utility which could provide expertise in the field of water demand management. Considering the size of Hamburg Wasser, it can be assumed that also in-house staff could have considerable knowledge in this regard and might know about the full benefits. However, knowledge transfer or sharing can be impaired in water utilities by different factors such as hierarchical structures and routines (Sandelin et al., 2019). Changing structures which should also include promoting collaborations across departments in Hamburg Wasser reflecting the complexity of WDM could hence be an important means.

Hamburg Wasser could not only aim to collaborate with universities and NGOs but also with the energy sector. Due to the impact of residential WDM measures on (household) CO_2 emissions, synergies and collaborations could be formed. In addition, energy savings and energy efficiency have been increasingly recognized in the energy sector to meet growing energy demands and reduce CO_2 emissions (Mahi et al., 2021). Thus, learning experiences could be exchanged helping to change the water sector.

Related to this, experience has been made in the energy sector with regard to potentially declining revenues due to energy efficiency programs (Lallana et al., 2001).

Hamburg Wasser, being a municipal service provider, is closely linked to the city of Hamburg which appoints the majority of the members of the supervisory board. The supervisory board advises and supervises Hamburg Wasser's management (Hamburg Wasser, n.d.b). Hence, it is of major importance that the leadership can communicate the full spectrum of potential benefits to the politics. Reductions in CO_2 emissions, resilience against climate change, and contribution to a circular water economy will likely promote the acceptance of such measures. This becomes particularly relevant against the background of potentially decreasing profits due to reduced water consumption (Appendix A).

Profitability in municipal services is assigned a special role in German law, which best can be explained through the following quoatation: "Hier sind dem Gewinnstreben Schranken gesetzt, die der Wirtschaft fremd sind, und es müssen auch Risiken eingegangen, Wechsel auf die Zukunft gezogen werden, zu denen sich die Wirtschaft nicht veranlasst sehen würde" (Schäfer, n.d.: 4). Freely translated, the water supply has priority over profit-making, which is subject to barriers alien to free enterprise and shall make future adaptations that a free enterprise would not do. Consequently, residential WDM measures are legitimated despite potential decreasing profits.
Another aspect that could be addressed is to create a common understanding of the concept of circular water economy and thus being aware of its systemic understanding. This would add value to residential WDM measures and thereby contribute to increasing its application. Having a shared and common framework that serves as guidance is essential for implementing new strategies and enables working across disciplines and scales (Wang & Luo, 2021).

6.3.3 Sub conclusion

Overall, a change in mindsets is needed that acknowledges the full value and benefits of residential WDM measures. The leadership would likely demonstrate a good starting point. Such a mindset change could shift the dominating supply and infrastructural-oriented strategies towards more demand management strategies in Hamburg Wasser and thus would also contribute to its overall circularity.
Assuming increasing pressure from the landscape level through, among others, the consequences of climate change and potential future adjustments in the Water Framework

Directive which could further incentivize residential WDM measures for water utilities, changes in the regime can be expected. New technologies are constantly developing with smart meters being at the forefront enabling new opportunities for WDM (Appendix, A).

To what extent changes in the regime, niche, and landscape level will impact the socio-technical system cannot be predicted or whether even a disruptive change could be achieved.

Transitions are "*fundamentally uncertain and open-ended; surprises and unintended outcomes are to be expected*" and "*depend critically on interpretations and social acceptance*" (EEA, 2019: 27). One significant barrier constitutes the described path-dependency between the pipe network and a specific needed amount of water consumption. At some point, replacement of the existing pipeline network may be required if residential water conservation measures are widely applied and water consumption can be massively reduced. Whether the described changes could eventually lead to this cannot be predicted.

7 Discussion

The following chapter discusses the results of the analysis as well as the limitations of this thesis. At the end of the chapter, the residential WDM measures are briefly considered from a global perspective.

7.1 Results

The analysis has shown that residential WDM measures may provide multiple benefits for Hamburg Wasser and for the city of Hamburg. To which extent however depends on a number of different types of factors and is complex to determine. Therefore, only the overall potential of such measures could be shown for Hamburg. It would have been interesting to develop different scenarios by applying different residential WDM measures and determining their respective impact on the per capita water consumption. In doing so, the most effective residential WDM measures could have been identified for Hamburg.
Beyond that, the CO_2 savings for both households in Hamburg and for Hamburg Wasser could have been calculated which would result from a certain amount of reduced water consumption. This becomes particularly relevant against the background that "*water utilities collectively influence up to 12% of regional total primary energy consumption*" (Ballad et al., 2018: 14). Thereby, the biggest share is attributable to users, heating water. Typically, on a global scale, 1-2% of the primary energy use is accounted for by water utilities (Ibid.). Being able to determine the exact potential effects of residential WDM measures for Hamburg could further support such measures and encourage a mindset change.

It needs to be noted that with residential WDM measures also challenges and limitations are associated. A challenge presents that some residential WDM measures are not suitable or applicable in specific situations. Decentralized supply systems usually require a high level of effort and are very costly if implemented in old buildings. That is why they are often considered in connection with new building projects (Appendix, A, C). In addition, water price as a means to reduce water consumption is controversially discussed (Abu-Bakar et al., 2021). Different studies have shown that the water consumption is inelastic to the water price (Frondel et al., 2021) or fluctuates between elastic and inelastic (Kenney et al., 2008).

Another issue that is being discussed is that as a consequence of reduced water consumption, water utilities are likely to increase the tariffs as a means to generate sufficient revenue. This puts larger families, who tend to be high water users, and low-income households at a disadvantage as water becomes less affordable (Garner et al., 2011). Similarly, water-efficient appliances can be costly so that low-income households might not be able to afford them even though they might gain financial profits in the long run as it also applies to energy-efficient appliances (EP, 2016). Vouchers for both appliances and water and tailored tariffs can counteract these challenges in WDM by fostering inclusiveness (OECD, 2016). This shows the political dimension of residential WDM measures with environmentally oriented parties likely to be more supportive of such measures than socially-oriented parties (Appendix, A). Therefore, the implementation and promotion of such measures are to some degree also dependent on politics, especially when it comes to households. That is why it is so important to work closely with politicians in this area (Appendix, A).

Nevertheless, grounded on the findings of the thesis, a more widespread use of residential WDM measures may provide a range of benefits and increase the circularity of Hamburg by filling the gap of measures aimed at avoiding and reducing water use. In a circular economy, such measures have high priority. As a public municipal service provider, Hamburg Wasser is obligated to ensure sustainable and long-term security of the water supply. In this, residential WDM measures should take on a more important role. Residential WDM measures offer different application possibilities and are often cost-effective as most measures do not require large investments in infrastructure (Lallana et al., 2001).

In order to achieve more widespread use of residential WDM measures, a mindset change is required placing more importance on avoiding and reducing the use of water. Certainly, multi-level changes are needed to enable a potential transition. Transition theory has provided guidance to understanding the relations in the water sector and helped to identify barriers on the regime level with the identified path-dependence. The mechanisms that can lead to such dependence are better explored in transition theory than how to overcome it (Apajalahti & Kungl, 2022). Hence, transition theory lacks guidance in this regard.

Overcoming the path-dependency in Hamburg turns out to be very difficult. For residential WDM measures to become more established and thus higher reductions in water consumption, the pipes would probably have to be replaced at some point. However, given the population growth in Hamburg and the associated increase in total water demand, this would be delayed as pipeline capacity can be assumed to be still high even with a slight decrease in the water consumption per capita.

The replacement of the pipe system would require enormous efforts and costs. Whether that is feasible or realistic remains unclear and difficult to predict so that further research is needed here. When this happens, attention should be paid to the circularity of materials meaning that the old pipes are ideally reused or materials of the old pipes are recycled. Related to this, when implementing residential WDM measures that include the installation of new equipment and appliances, recycling of old equipment should be targeted. For instance, water utilites could offer to take back old appliances as it is partially done with mobiles (T-Mobile, n.d.)

The thesis has outlined the importance of residential WDM measures for a circular water economy. By using this concept, it was possible to look at residential WDM measures from a perspective other than that of the water utility. This has created an understanding that sees residential WDM measures in a bigger picture and emphasizes the need to avoid and reduce water consumption. However, it becomes also evident that residential WDM measures are only one important component to achieving a circular water system. Similar to the waste hierarchy, a hierarchy for the water sector could be developed emphasizing their relevance, as depicted in figure 9. Here, the Water Framework Directive could come into play incorporating these aspects more than it currently does. This would allow more guidance in the decision processes of water utilities.

A possible weakness of the circular economy concept could be that it does not communicate clearly enough that recovering resources and recycling water are only one part of it and that the concept encompasses much more including the prevention and reduction of water use. At least, this conclusion can be drawn from the case of Hamburg.

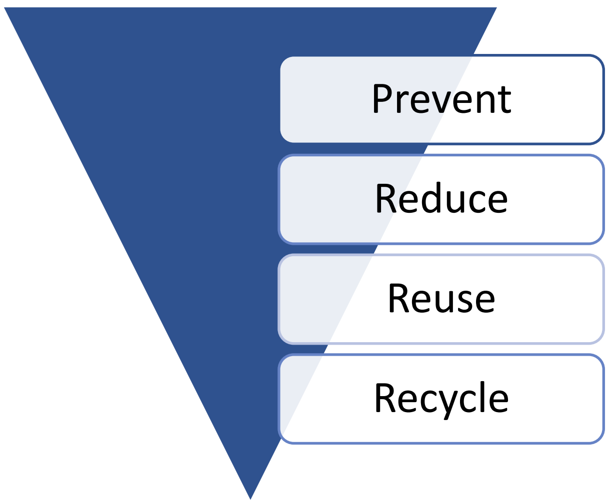

Figure 9: Possible "Water hierarchy", own figure

7.2 Limitations

It needs to be mentioned that WDM measures have been considered in relation to households. The application of such measures, however, goes beyond this. Industry and agriculture are other important sectors where major improvements may be achieved (Appendix, A; GWP, 2012). Changing the sector brings other barriers but also new potential and different measures, that can be implemented under WDM. This entails irrigation management and planning tools and water-efficient irrigation technologies for agriculture and water efficiency management plans for businesses and industry (Price et al., 2017; GWP, 2012). Moreover, residential WDM measures have been considered in the context of a developed country. Developed countries use a variety of technological and management measures which might not be all suitable for developing countries. This is because the technologies might not be available or the institutions might not have the capabilities and skills in order to conduct these measures. Therefore, the potential and barriers of residential WDM measures are different in developing countries (Sharma & Vairavamoorthy, 2009).

As stated in section 5.2.2, unfortunately, it was not possible to conduct an interview with an employee of Hamburg Wasser. This would have enabled to retrieve information and in-depth knowledge which is not available in documents or on websites related to Hamburg. Specifically, obtaining inputs on the exact reasons why Hamburg Wasser does not apply residential WDM measures more widely would have been insightful or whether Hamburg Wasser is implementing measures not being publicly available.

However, it can be assumed that the quality and output of this thesis are not largely affected by this. A huge pool of sources on Hamburg was publicly available and the two conducted interviews with an employee of the water utility in Berlin and Copenhagen could compensate the lack of inputs that would have been obtained in the interview with Hamburg. Both cities and utilities share similar characteristics with respect to challenges and development and in relation to Hamburg. Here, the choice of an exemplifying case as the research design turns out to be helpful.

In addition, both interviewees came to an akin assessment of residential WDM measures. Therefore, likely an interview would have provided some more in-depth knowledge but the results of the analysis and the conclusions may have remained similar.

The case study as the research design can also be discussed in terms of its limitations. For instance, it is pointed out that a generalization from a single case is not possible, so research based on a case study research design does not contribute to scientific development. Additionally, it is argued that a case study provides more room for the researcher's subjective assessment, thereby compromising the validity of the research. (Flyberg, 2006). This can be countered by the fact that bias may also be present in other forms of research and that experience from case studies has shown that a higher tendency toward bias cannot be confirmed (Ibid.). Related to the other point of critique, Flyberg (2006) elaborates that single case studies can also advance science as shown by the single-case experiments of Newton, Bohr, and Einstein. Research designs have their strengths and limitations. The use of a case study research design in this thesis has provided contextual knowledge and insights, addressing the research problem. That proves that the case study is the appropriate research design for this thesis.

As mentioned in the discussion of the results, precise calculations or forecasts on the effects of residential WDM measures could have provided important knowledge to determine the extent of such measures, for example, CO_2 emission savings that could be achieved through a certain reduction in water use. However, given the complexity and the available capabilities, this was not possible in the scope of this thesis. There are certain modeling approaches and software tools available which can provide such knowledge as for instance applied in the study on Wales and England (Lawson et al., 2018). Such tools and modeling approaches could therefore have proven to be valuable research methods.
To finish the discussion and finally broaden the perspective, residential WDM measures are considered with regard to the SDGs.

7.3 Sustainable Development Goals

Climatic and non-climatic challenges are increasingly exerting pressure on the water sector at a global level. Developing countries are even more affected by these challenges (Sharma & Vairavamoorthy, 2009). In this context, residential WDM measures can present important means of contributing to achieving SDG 6 to "*ensure availability and sustainable management of water and sanitation for all*" (UN, 2015: 20). Residential WDM measures can be particularly assigned to target 6.4. Their relevance for this target can be seen reflected in the associated indicators which are "*change in water-use efficiency over time*" and "*level of water stress: freshwater withdrawal as a proportion of available freshwater resources*" (UN, 2017b: 10).

By reducing the water consumption, residential WDM measures relief pressure on water-related ecosystems such as rivers, wetlands, lakes, and aquifers and thereby contribute to target 6.6 with its associated indicator of "*change in the extent of water-related ecosystems over time*" (Ibid.: 11). Furthermore, as residential WDM measures reduce the generation of wastewater they can be considered important for target 12.5 under SDG 12. Target 12.5 is about reducing waste generation "*through prevention, reduction, recycling and reuse*" (Ibid.: 16).

Reducing water use also impacts terrestrial ecosystems and thus contributes to achieving SDG 15 "Life on land". For example, water availability can prevent desertification, which is formulated in target 15.3, or conserves biodiversity as almost all species rely on water (Ibid.). The list of examples could be further extended. Water is the essence of human life and the natural environment and must therefore be used adequately to ensure prosperity of both future generations and the planet (UN Water, 2020). Therefore, water and its availability are critical to all SDGs. Similarly, all SDGs are strongly interconnected. Progress in one SDG will also lead to progress in others (UN, 2018b).

The application of different residential WDM measures differs between developed and developing countries and might be even more limited in the latter (Sharma & Vairavamoorthy, 2009). Still, where water infrastructure might not be sufficient and resources limited, measures, such as building education and awareness on water saving, water efficiency, and the advantages of conserving water, will generate a range of benefits contributing to a sustainable future (Ibid.). Thus, residential WDM measures are not only important for Hamburg but also on a global scale.

8 Future research

This thesis has viewed residential WDM measures mainly from the perspective of a water utility. In doing so, a mindset change within the water utility has been identified as needed to promote residential WDM measures. However, institutions, including water utilities can be affected by bureaucratic challenges such as the organizational culture and trained incapacity which can prevent such a mindset change. Trained incapacity describes that people are educated to use certain tools and methods to achieve goals and progress professionally. This can lead to routines and patterns that are difficult to change. The approach of organizational culture deals with bureaucratic structures and their associated implications. For instance, institutions that are characterized by a clear distinction of responsibilities, uniformity, and hierarchical structures, that restrict knowledge exchange and communication across departments, are impaired to adjust to situations and conditions requiring changes (Aylett, 2011). Building on this, such bureaucratic challenges could be examined using Hamburg Wasser as an example and how they affect the choice of supply- or demand-side measures and how they shape the understanding of the concept of circular water economy.

Moreover, a change of perspective would open different opportunities for research. On the one hand, the focus could be directed to industry and how WDM measures can be applied and further promoted there, and what benefits and potentials could result from this. For this purpose, a specific case where WDM has not yet been widely considered could be suitable. On the other hand, an interesting perspective would be to investigate the applicability of residential WDM measures in a developing country. This could allow to identify limitations and obstacles to residential WDM measures and develop recommendations and means to overcome them.

As discussed, research could be conducted to determine the precise effects of specific residential WDM measures on the water use in Hamburg to select and propose the most effective measures. In addition, other benefits associated with lower water consumption can be explored, such as how much CO_2 emissions can be saved in Hamburg by reducing the water consumption by a certain amount.

Lastly, this thesis raised the issue of how to overcome the described path dependence.
Future research could concentrate on this matter and define changes at the different levels which are needed to achieve this.

9 Conclusion

This thesis has presented different non-pricing and pricing measures of residential WDM. Household water consumption is determined by a huge variety of exogenous, endogenous, and behavioral factors. As a result, the effectiveness of residential WDM measures depends on the level these factors are taken into account but also how they are applied in a strategy, for example alone or in combination with other measures. Therefore, determining the precise water-saving potentials of specific residential WDM measures for Hamburg is very complex. Although this is a cornerstone, the conducted study on Wales and England illustrates that the implementation of WDM measures may lead to major water savings

With regard to the research question: "*To what extent can residential water demand management measures generate benefits and increase the circularity of the Hamburg water system?",* it can be answered that the specific extent of such measures could not be identified for Hamburg. However, the thesis shows that residential WDM measures and associated reduced water consumption may provide a variety of benefits for Hamburg Wasser and the municipality of Hamburg. This includes greenhouse gas reductions, increased permanent and temporal resilience against climate change, alleviating the pressures on the water system, contributing to a secure water supply, and offsetting the need to build new and costly infrastructure. Furthermore, residential WDM measures have great potential to increase the circularity of the Hamburg water system as they may fill the gap in activities and measures that aim to avoid and reduce water consumption. Both activities are fundamental in a circular water economy.

What is limiting the potential for circularity and possible provision of different benefits by residential WDM measures, is a path-dependency between the pipe infrastructure and a specific needed amount of water consumption. This appears as a barrier impeding the broadening of the use of such measures and will be difficult to overcome. In addition, a supply-oriented understanding in the water sector and a recycling and recovery-oriented perception of circularity have been identified, that neglect the importance and the possible benefits of reducing water consumption. Therefore, to promote residential WDM measures, this thesis argues for a mindset change that acknowledges the full value of such measures for a circular water economy and is conscious of the variety of benefits it may provide.

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