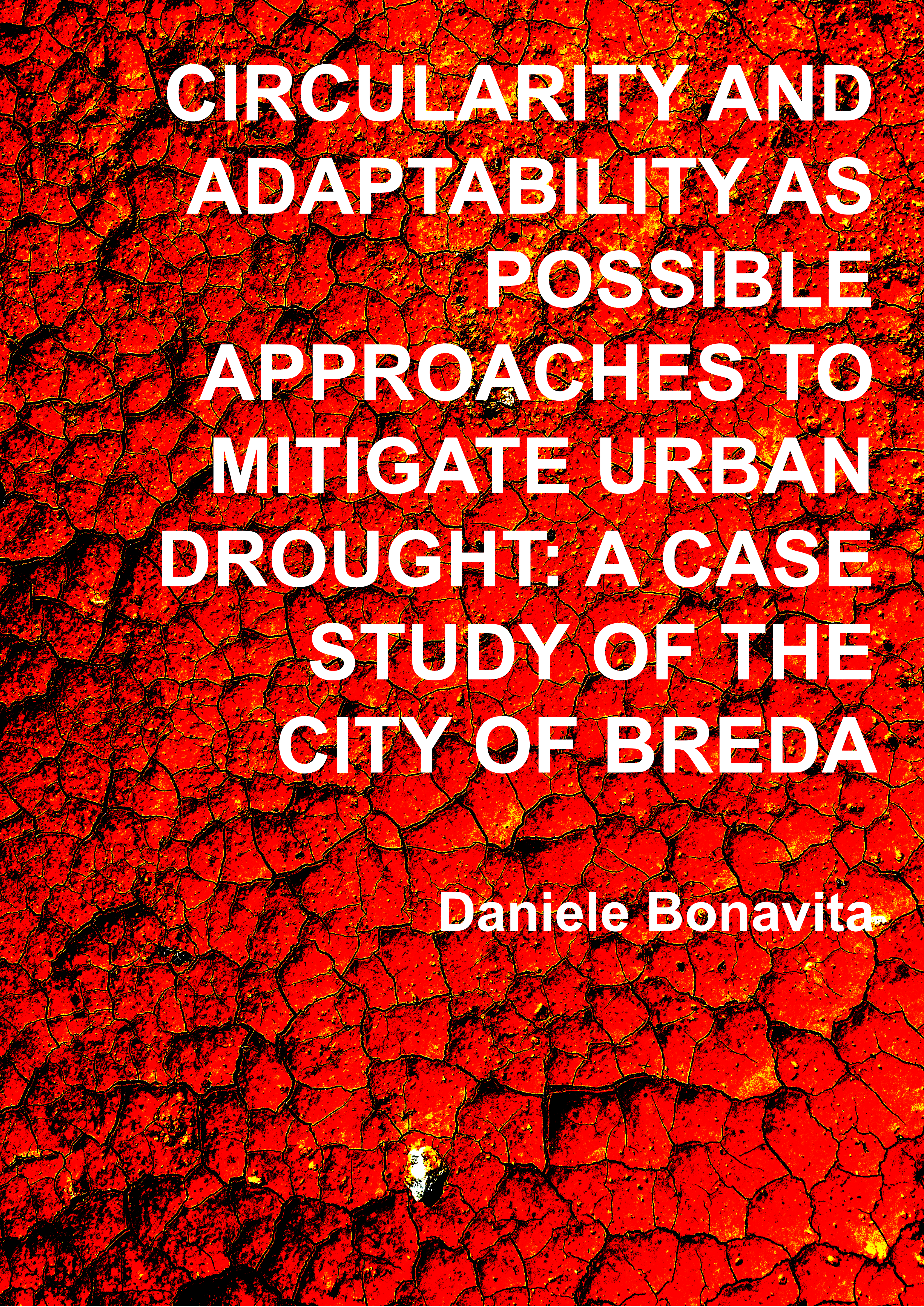

CIRCULARITY AND ADAPTABILITY AS POSSIBLE APPROACHES TO MITIGATE URBAN DROUGHT: A CASE STUDY OF THE CITY OF BREDA

Daniele Bonavita

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CIRCULARITY AND ADAPTABILITY AS POSSIBLE APPROACHES TO MITIGATE URBAN DROUGHT: A CASE STUDY OF THE CITY OF BREDA

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"[...] all history is nothing but a continuous transformation of human nature."
Karl Marx, The Poverty of Philosophy.

ABSTRACT

From 2018 to 2020, the city of Breda (NL) faced drought, with significant economic losses and water scarcity problems. The water board within which the city is located began to consider new possible water management practices, due to the unsustainability of the current ones. This study aims to investigate how a change of the current paradigm can improve the current approach in water management, shifting from a linear to a water management circular approach, and from command-and-control to adaptive. Starting from the case scenario of Breda, the study considers how through the reuse of management wastewater treatment plant effluent and stormwater, and the application of sewer mining units, it may affect the circularity and adaptability of the system. Then, based on Breda's experience, an attempt is made to investigate the concepts of circularity and adaptability.

To be able to understand the current water situation and approach in the city of Breda, a water balance for the year 2020 was drafted. The water balance for 2020 for the city of Breda shows a positive value of 50 mm/year. The definitions of circularity and adaptability for a water management system were determined, and for each of the concepts a framework has been developed, to assess the level of circularity and adaptability before and after the interventions. Then, a workshop with local experts in the field was organized. Different strategies of interventions were proposed to them, in order to evaluate their suitability. Then, a final strategy was formulated, where wastewater effluent is employed as irrigation water for agriculture in the south of the municipality, stormwater discharge into wetlands to recharge aquifers and three sewer mining units in the rural area of Breda. These interventions showed a positive effect on the water system, since the volume of water stored in the system has increased, giving an overall better performance of the circularity and adaptability indicators. Moreover, the final strategy shows a better water balance of 100 mm/year. This research aims at creating a better understanding of concepts like circularity and adaptability. The study shows that there is a potential for re-using water to enhance the overall performance of the water system under certain conditions.

ACKNOWLEDGMENT

It seems unbelievable to me that the punk kid I used to be, who spent hours being yelled at by teachers in high school, for homework not done, for failing tests, and for all those hours I spent hanging around simply admiring empty days, is now getting an engineering degree. Just sort of inconceivable at times.

During the past year, I felt that it was almost impossible, and very often I was on the edge of giving up. Every time I had to achieve a goal, I failed. I failed the midterm and green light meetings, I had to change my supervisor, I had to change the thesis multiple times. I was obsessed with finishing, and I had so much anxiety about being late. I had a goal, and I was not getting it. Then I realised that my approach was completely wrong. I shouldn't have focused on the objective, but rather on the process. I was not adapting and accepting the changes in my environment. I had goals that were not feasible for the situation I was in, for the person I am and for the people around me.

This reflection is the same I made on this project. Is not about having a goal and pursuing it with all the energy and resources, but rather understanding, within the system boundaries, which could be the most suitable solution, instead of pushing our limits. This has perhaps been the biggest difficulty I have had in recent years in engineering education. Many times, when talking about complex problems such as global warming and resource exploitation, the approach has always been merely technical. I personally believe that this technical approach, to always seek efficiency, and use science to justify progress, is one of the causes of the problems mentioned above. The solution is not to improve the current system, but to change it.

Nevertheless, I am deeply grateful to have had the fortune and privilege of being able to attend TU Delft. I wouldn't be here if it weren't for all the sacrifices my parents made. There have been many and I wanted to thank you, Mom and Dad. Thank you for all these years when you were able to provide for my education without me having to think about the financial aspect. It is a fortune that not everyone has, and I am more grateful than ever.

I would never have been able to graduate without my supervisor's support and understanding along all the thesis process. I want to deeply thank Maurits Ertsen, who with all the patience, followed me step by step, always kind and helpful. Thanks also to all the friends who constantly supported me in different ways. Thanks to those who took the time to discuss with me about capitalism, science, technology, society and human nature. Thanks to those who took the time to check my papers and correct my English over and over again. Thanks to everyone who, during the last two years of Covid-19, made the pandemic an experience full of beautiful moments. Thanks to those who still want to hear me complain, and be there to listen to me.

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1 INTRODUCTION

Cities are under pressure from global warming, steady population growth, migration from rural areas to urban centres. These developments challenge the traditional urban paradigm [1]. In what concerns both energy and materials, contemporary cities seem unsustainable for two reasons: the very high pressure they exert on resources and the large amount of various emissions that they generate. Cities consume large amounts of material and then return to nature various forms of solid waste, wastewater, and air emissions. Thus, they contribute to the intensity of material flows and to the increase of the quantity of material in circulation in drawing on natural resources. Resources being consumed are rarely put back into circulation from where they were taken [2]. In particular, the urban water system is one of the main systems in the urban environment that needs to be explore new approaches in order to face the forthcoming effects of climate change, including the problem of drought and urban flooding, progressive uncontrolled urbanization and the decay of current infrastructure [3][4].

1.1 BACKGROUND

In the summer of 2018, which was the driest summer since 1976 [5], the Netherlands was hit by an extreme drought. The same happened in 2019. A year later, February 2020 happened to be the wettest February in over a hundred years. Therefore, the expectations were very optimistic for the coming spring and summer to previous years level, after the drought of the past two years. However, the summer of 2020 was the third consecutive year in which the Netherlands was hit by an extreme drought, resulting in several negative effects on (ground)water, ecosystems and soil [6]. The effects of the drought were particularly strong in the south of the country, with above-average water deficits [7]. As such, in the last years, the municipality of Breda has suffered from drought events too - also with many economic losses in the agricultural industry. Therefore, the Water Board of Breda is looking for new approaches to manage water in the area, related to the upcoming challenges caused by global warming.

According to climate forecasts, global warming would have a wide variety of effects on the climate system, including changes in storm track activity and more intense and serious extreme weather events. However, little is known about when and how global warming would impact the predictability of the atmosphere, and therefore our ability to provide reliable weather predictions [8][9]. Moreover, there are different sources of uncertainty, like lack of data, incapability to predict future demand and supply, and unreliability about natural and physical processes of water cycle in the face of changing environmental, economic, and technological settings [10].

Today, the "conventional" approach is rooted in the "command and control" paradigm that claims to have complete knowledge of the system's behaviour [11][12]. However, the improvements in complexity science showed that complete comprehension of system behaviour and full power over system performance is impossible [13]. An adaptive approach aims to improve the capability of the water system to cope with a wider range of environmental variations. Long-term, adaptive management should develop the flexibility to adjust system configurations, such as switching to different crops and lifestyles, or allocating water quotas to different uses. Water systems with intrinsic degrees of freedom, capable of adapting to new environmental and social situations, should be the goal of system architecture [12]. After the occurrence of drought events, for the Breda's water board it was more evident that the current water management of the area is not suitable for facing water shortage. At the moment, the water in the area is not kept for (re)use, but discharged towards the North Sea.

The traditional linear approach of managing water - sometimes called the *take, make, waste* approach - is proved to be inefficient [14], since it leads to water stress, and uses resources such as energy and chemicals in an unsustainable way. Water is extracted from aquifers or water bodies above the rate of replenishment and then treated to make it potable. Next, water is consumed in urban areas by residents and industries, or in rural areas by farmers. Then, water is discharged into the sewers, treated at the wastewater treatment plant, and then disposed of. It is inefficient to disperse nutrients into the aquatic environment, thus losing resources that can be reused for a variety of purposes. Different methods are required to accomplish economic, environmental, and social sustainability. A toolkit consisting of stormwater management/rainwater harvesting, water conservation, water reclamation and reuse, energy management, nutrient recovery, and source separation, allow a closed-loop urban water and resource management systems to be settled and implemented [14].

However, even with this toolkit, it is still difficult to identify a unified perspective on what adaptivity and circularity mean in the context of water management.

Circularity is often related to circular economy. Regarding circular economy, there is no unified method to measure its value [15]. In fact, the European Environmental Agency (EEA) also admits that standardized metrics and monitoring tools are missing in order to assess and support the paradigm shift towards a circular economy at different scales ranging from company, nation to European level [16]. In addition to the generally underdeveloped state of implementation of circular economy models, their application in water management studies is even more scarce [17].

The same can be said for the concept of adaptivity. One obstacle in achieving broad adoption and relative success of this concept when adopted is the lack of a clear and precise definition of what adaptive management of water is. Furthermore, adaptive water management has been criticized as not living up to its aspirations, in suffering from problems in translation from research to practice [18]. In addition, different nation states will find different approaches to implementing adaptivity, they might be at different development stages, hence will gain different benefits [19].

In short, there are reasons to change the urban water management practices in Breda. Then, it is worth exploring different approaches. Two interesting concepts to investigate are circularity and adaptability.

1.2 PROBLEM STATEMENT

The recent drought that happened between 2018 and 2020, has challenged current water management practices in the south of the Netherlands. The unexpected rise in temperature and lack of precipitation affected especially the agricultural sector, which faced large economic losses. In addition, the recent events made the municipality of Breda questioning its current water management practices. With global warming becoming more intense, Breda's water management has new challenges to face. A linear approach has been proven to be inefficient, since it leads to a waste of resource in Breda, with the water entering the municipality (from the rivers, precipitation or extracted freshwater) being discharged into the North sea. Similarly, a "command-and-control" concept can no longer be applied due to the increase of uncertainty. Therefore, a transition is needed to successfully manage water, in order to face new critical issues such as water scarcity [14]. A circular and an adaptable approach might mitigate future drought impacts and uncertainties in Breda – and possibly in urban areas in general. However, little is known on how to apply those concepts, as they only begin to be integrated into the vocabulary of water management. As such, it is still difficult to understand what these terms actually mean and what it means to shift to new paradigms.

1.3 RESEARCH OBJECTIVE

The research is focused on the concepts of circularity and adaptability in the context of the municipality of Breda, in the southern part of the Netherlands. The objective of this research is to investigate how circularity and adaptability can be applied in Breda's water system through the introduction of sewer mining and different management of stormwater and wastewater treatment plant effluent. This research will analyse how these interventions can contribute to a better performance in terms of circularity and adaptability of the city of Breda.

1.4 RESEARCH QUESTIONS

Based on the research objective, this research postulates the following research question: *"How do sewer mining, stormwater management and effluent reuse contribute to making the water management in Breda's municipality more circular and adaptive?"*.

Following sub questions have been defined to aid answering the research question:

- What are the definitions of circularity and adaptability referred to a general system and to a water system?
- What is the water balance of the municipality of Breda?
- How adaptable and circular is the current system?
- How does the municipality benefit in terms of circularity and adaptability trough the implementation of sewer mining technology / different management of wastewater treatment plant effluent / stormwater?
- Which of the different strategies applied to the municipality result to an overall better performance for the municipality and how?

1.5 STAGES OF THE RESEARCH METHOD

This section will describe the applied research methods of this study. The different stages of the study are explained one by one below. The different stages help to answer each sub questions.

1.5.1 STAGE 1: CASE STUDY / DATA (chapter 3)

The city of Breda, between 2017 and 2020, suffered from drought, and with it came several problems in water management. Since the existing water management practices are unsustainable, the water board of Breda started to examine other options. In order to evaluate the current paradigms and management, this phase of the research methodology gathers relevant data for the municipality of the city of Breda. The useful data involve five main streams: wastewater treatment plant effluent, stormwater, precipitation, evaporation and drinking water consumption. This step provides a precise definition of each flow. This has been achieved by research of papers on the subject, resulting in a set of clear definitions of each flow to be analysed. Afterwards, the data of the municipality of Breda have been collected by consulting different sources (which includes the Water Board of the city of Breda). Then, the flows have been mapped, to create a quantitative picture of the flow and a general qualitative assessment. The quality parameters were developed later according to the necessary criteria for reuse.

The required time frame of the data is daily. During the process of data collection, it was evaluated, if it was possible to have this type of data and with what accuracy. Moreover,the intended time frame was evaluated whether or not it was suitable for the site and its functionality.

1.5.2 STAGE 2: METHOD / TOOL (chapter 2)

It is necessary to develop the circularity–adaptability framework to assess the current system. A framework consists of a set of prescriptions regarding how knowledge should be produced and implemented in order to achieve specific desirable outcomes in terms of natural resource management [18]. Frameworks must be able to define an overall perspective, and at the same time, be able to give a guideline on how to evaluate ideas in practice.

In order to develop a complete methodology to assess how circular and adaptable a water system is, a few steps are necessary. The first step is the definition of the terms mentioned above – on two levels; general, or applicable to any system, and specific to water management. Secondly, the characteristics for each term have been assessed. Thirdly, a series of metrics within each characteristic have been suggested to evaluate the degree of circularity and adaptability in the management system.

1.5.3 STAGE 3: ASSESSMENT (chapter 3)

Subsequently, the current system has been evaluated. Before starting to assess the municipality, it has been verified that the data collected are sufficient to be able (according to the framework previously established and the mass balance theory) to measure both circularity and adaptability and the water balance of the system. Then, the water balance of the system has been estimated, highlighting inflows and outflows, and the amount of water that is being held by the system. To calculate the water balance, QGIS 3.10 and Excel 2103 were employed. The two packages are intended to model the water balance on both spatial and quantitative level. Following, Breda's circularity and adaptability have been evaluated based on the framework developed.

1.5.4 STAGE 4: EVALUATION OF DIFFERENT STRATEGIES (chapters 4, 5)

Following the assessment of the municipality of Breda, it was possible to understand, based on the framework, to what degree the entire water system is circular and adaptable. After having identified the parameters that need to improve within the system, it was possible to proceed with the implementation of a new strategy. As stated before, the three interventions that this study investigates are sewer mining technology, wastewater treatment plant effluents reuse and stormwater management. Different possible combinations of interventions have been analysed. Through the evaluation of the framework and the water balance, the study tried to understand which strategy is the most effective and efficient strategy. In order to have a better understanding of the system, a workshop and interview with experts were held to review the various interventions and assess which is the best strategy.

1.5.5 STAGE 5: FINAL STRATEGY AND CONCLUSIONS (chapters 6, 7)

After deciding, based on framework, workshop, and water balance, what is the best combination of interventions for the system, an analysis was carried out of the key findings on circularity and adaptability. Starting from the specific case of the city of Breda, and analyzing its water management challenges, the study explores circularity and adaptability as possible new paradigms. From the study case, the thesis attempts to outline the limitations and possibilities of a circular and adaptable approach for water management.

2 FRAMEWORK

This chapter explains what a framework is and how it is used in this thesis. The concepts of circularity and adaptability are introduced and defined, along with indicators to measure these two terms. Finally, a comparative indicators framework is integrated with the parameters established for the two concepts mentioned above, to evaluate the effectiveness of the strategies that are tested (sewage mining, reuse of stormwater and wastewater effluent) with a comprehensive approach.

2.1 CIRCULARITY

This paragraph analyzes the concept of circularity. The history and context of circularity are investigated, then circularity is defined in regards to the water management field. The indicators that can help translate this concept from theory to practice are shown.

In the last few years it has become increasingly important to be able to change the paradigm from linear to circular, as the current approach has proven to be ineffective and unsustainable. The most visible result is increasing water stress (inadequate water supplies), which is occurring all around the world. Fears about resource use and nutrient dispersion into the aquatic environment are also mounting [14].

2.1.1 CONTEXT AND HISTORY: FROM URBAN METABOLISM TO CIRCULAR ECONOMY

The concept of "circularity" in resource management has not been conceived in recent years, although it is increasingly being discussed [20] [21]. Urban Metabolism (UM) proves to be an important resource that helps to explain how circularity has been conceived and thought in the past.

Urban metabolism is defined as *"the sum total of the technical and socio-economic processes that occur in cities,resulting in growth, production of energy, and elimination of waste"* [22]. In practice, urban metabolism is a scientific model to simplify the description and the quantification of the inputs, outputs and storage of energy, water, nutrients, materials and wastes for an urban region [23] [24].

The intellectual development of urban metabolism can be traced back at least to Marx in his *Economic & Philosophical Manuscripts* of 1844 [25] [26] [27] [28]. The term “metabolism” was used by Marx to describe the metabolic connections that occur between nature and society as a result of human activity. Humans wielded animal and physical labor to modify the Earth for their food and shelter. They changed biophysical processes while supplying the metabolism of human activities in the process. Metabolism took on a specific ecological significance as well as a broader societal connotation in his study. Human beings live from nature, but also modify it to meet their own demands [29]. *“The concept of metabolism, with its attendant notions of material exchanges and regulatory actions, allowed [Marx] to express the human relation to nature as one that encompassed both ‘nature-imposed conditions’ and the capacity of human beings to affect this process”* [29].

However, it was not until 1965 that the term Urban Metabolism was defined. In his essay *The Metabolism of Cities*, Abel Wolman specified and used the term urban metabolism in reaction to declining air and water quality in American cities [30] [22]. In his work, Wolman built a model that enabled him to quantify the inflow and outflow rates of a fictional 1 million-person American city. The method allows the tracking and reporting of natural resources used (mainly water), as well as the waste generated and discharged as a result. Wolman's research points out that the daily consumption of natural resources has physical limits, and the accumulation of waste can and will create problems [30] [28].

Based on Wolman's work, the environmentalist Herbert Girardet drew a connection between urban metabolism and urban sustainability. In his book *"The Gaia Atlas of Cities* of 1996, Girardet coined the difference among a 'linear' and a 'circular' metabolism [31] [28]. With a circular approach, there is almost no waste due to re-used of resources. Girardet defined this as a "natural process", while a 'linear' metabolism is identifiable as an urban process, which has a clear input and output [28]. As cities develop and grow, Girardet believed that by continuing to adopt a linear metabolism in urban contexts will cause an oncoming worldwide disaster [31].
In the past few years, urban metabolism has been linked in different way to the urban water system. Several models have been proposed for the quantification of urban metabolisms [32][33].

Meanwhile, in the early 1970s, there was an increasing focus on the Circular Economy (CE) concept. There is no clear evidence of a single originator of the CE, but contributors include the architect and economist, Walter Stahel, the German chemist, Michael Braungart, U.S. professor John Lyle and his student William McDonough [34]. The pillars of the CE concept include the 3Rs (reduce, reuse, recycle) [35] and the 6Rs (reuse, recycle,redesign, re-manufacture, reduce, recover) [36]. The CE concept is interwoven with various other concepts as well.

Nowadays, when talking about circularity most often it is done by referring to the circular economy. This could be due to the fact that the economy is the main driver of global societies [37].

2.1.2 DEFINITION

Cambridge dictionary defines circularity as *"the fact of constantly returning to the same point or situation"* [38]. In practice it is not possible. Dissipation of resources and energy will always happen. Nonetheless, the goal has to be to make the system as circular as possible.

Due to the lack of a water circularity definition, this study looked at the white papers of Arup, Antea Group and Ellen MacArthur Foundation from 2018 [39], IWA in 2016 [40] and McKinsey Global Institute from 2015. [41]. Following the water, energy, and nutrients paths, the three Circular Economy principles, mentioned below, should be evaluated. The three principles emphasize the importance of taking a systems approach and taking into account the interactions between natural and human-managed systems [42].Water-related human-managed systems include a variety of socio-economic sectors, including urban water, agriculture/food, energy, and industry, with agriculture and industries accounting for the majority of worldwide water withdrawals [43]. Hence, water circularity has to be addressed with a multi-sectoral approach, including all water consumers, rather than a sectoral one. Natural and anthropogenic water cycles should be linked, and symbiotic resource management encouraged, to minimize burden shifting from one sector to the next, as well as from the anthroposphere to the environment [42].

Therefore, based on Circular Economy concepts such as reduce, reuse and recycle, and the analysis of the flows of the materials from Urban Metabolism, it is possible to define circularity applied to a generic human-made water system.

A circular anthropocentric water system is defined as: *a water system of closed loops which aims to reduce the consumption of natural resource, regenerate natural capital, ensuring functional environmental flows and stocks and keep resource such as water and by-products of the management system in use.*

From the definition of circularity given for our system, three cardinal principles emerge:

- **Reduce consumption of natural resource**: This involves minimizing fresh water consumption by reusing water and resources. The broader the portfolio of water resources is, including additional sources of water derived from the reuse of other flows, the less reliance must be placed on natural resources.
- **Keep resource in use**: Focuses on closing the water and water-related materials and energy loops within the system. It can be accomplished by boosting resource yields and extraction, and by increasing recycling and reuse of water. Re-circulation of resources to close the loops involves adequate quantity of the reused resources and appropriate quality to meet the domestic demands, as a result, the number of resources extracted from nature would be reduced.
- **Regeneration of natural capital**: Reducing anthropogenic water consumption, preserving and enhancing ecosystems, and guarantee minimal disturbances from human interactions and consumption to sustain functional environmental flows and stocks. A circular model aims to re-balance the natural capital and move towards the natural hydrological cycle.

2.1.3 INDICATORS

Based on the previously given definition of Circularity for a water system and the three principles identified, several indicators to evaluate system circularity could be developed.

Table 1: Circularity Indicators.

Principle	Indicator	Metric
Reduce consumption of natural resource	Volume of freshwater (groundwater and surface water) used for consumptive and non-consumptive purpose	volume % (-)
Keep resource in use	Reclaimed wastewater treatment plant effluent	volume % (+)
	Reclaimed stormwater	volume % (+)
Regeneration of natural capital	Water restored as groundwater	volume % (+)
	Water restored as surface water	volume % (+)

Each principle identified in advance has been given an indicator and an assigned measurement metric. As can be seen from the Table 1, the metrics refer only to a quantitative level (by indicating with the symbol + an increase in circularity with an increase in volume %, and with the - a decrease in circularity with an increase in volume %).

2.1.4 LIMITATION TO ASSESS CIRCULARITY

Currently, the definition of circularity is often associated with the one of circular economy, although it is not the only one. Yet, although much has been written in the field of circular economy and in recent years it has become increasingly popular within the political and governmental sphere (first with Germany in 1996 with the integration of Circular Economy within national laws [44], then with Japan [45] and China [46] in 2002 and 2009 respectively, until 2015 with the Circular Economy Strategy by the EU [47]), there is still difficulty in identifying a single perspective on what is circular economy. There is still no unified method to measure its value [15]. In fact, the European Environmental Agency (EEA) also admit that standardized metrics and monitoring tools are missing in order to assess and support the paradigm shift towards circular economy at different scales ranging from company, nation to European level [16]. In addition to the generally underdeveloped state of implementation of circular economy models, their application in the water management studies is even more scarce [17].

Moreover, circularity and sustainability have gained popularity in the last decades among academics, business, and politicians. However, the distinctions between the two definitions are unclear. The link between the notions is not explicitly stated in the literature, which blurs their conceptual outlines and limits the effectiveness of employing the techniques in study and practice [48]. Hence, there is often an overlap between the concepts of sustainability and circularity.

The most relevant limitation to assess circularity is the lack of academic writings about the topic of circularity in the water management sector. So, it was necessary to rely on the circular economy framework to draw insights into what circularity in water management means. In addition, the definitions given and the indicators can be considered as belonging to the field of sustainability as well. This, as explained above, is due to an interconnection of the two concepts, which although different, can be considered similar (e.g., greater circularity of water makes the system more sustainable, vice versa a more sustainable system involves the reuse and recycling of energy, materials, etc. - such as water).

2.2 ADAPTABILITY

The notion of adaptability is presented in this chapter. The history and context of adaptability are examined, followed by the definition of adaptability in regards to the water management field. The indicators that can help translate this concept from theory to practice are shown.

2.2.1 CONTEXT AND HISTORY: SHIFT OF PARADIGM

With the advent of global warming and its impacts, together with an increased awareness of the consequences of man's anthropogenic activities on nature, the current models of society are being questioned. The current management and consumption of resources is inefficient, which is why the actual approach has been brought into discussion.

A water management paradigm is a collection of assumptions regarding the nature of the system to be managed, the management goals, and the methods for achieving these goals. The paradigm is held by an epistemic community of water management operators, and it manifests itself in artifacts like technological infrastructure, planning methods, legislation, and engineering techniques [49].

The water management approach is evolving. Over the last several decades, a slew of new findings have begun to cast doubt on the fundamental assumptions that underpin traditional water management, which places a premium on technical solutions and command-and-control methods [49]. Correspondingly, more voices have advocated the need for a radical change, for a paradigm shift in water management [50] [51] [52] [53]. The arguments differ in content and emphasis, but not in the core aspects of the required paradigm change, which include: a transition forward into collaborative decision-making and participatory management; decentralized and more flexible management approaches; the adoption of iterative learning cycles as part of the overall management strategy; increased focus on human behavior management using "soft" measures and issues and sectors becoming more intertwined. The major aspects of transition may be stated as a need for a more integrated and adaptive approach to water management [49].

For a long time, the concept of adaptive management has been debated in the context of ecosystem management [54] [55] [56]. Adaptive management assumes that predicting main future's variables and their impact on an ecosystem is intrinsically difficult. The improvements in complexity science showed that complete comprehension of system behaviour and full power over system performance is impossible [49].

2.2.2 DEFINITION

An adaptive approach aims to improve the water system's capacity to function in a wider variety of environmental conditions. Although technological infrastructure is not meant to completely protect a water system from varieties of different environmental conditions, socio-technical measures are used to ensure that a water system's standards are maintained even when it is exposed to it.

However, the notion of adaptive management is complex and difficult to summarize in a few words [57]. Adaptive management may be defined as a learning strategy to managing ecosystems and natural resources in the face of uncertainty.

In the following study, an adaptive water management system is defined as *a system that succeeds in adapting to new boundary and environmental situations while still managing to satisfy the required needs*.

2.2.3 INDICATORS

To detect emerging issues and combine policy execution and adaptive responses to new insights, integrated water management necessitates a cross-sectoral approach [49]. Dynamic water systems are complex systems, including human, environmental and technical components. This thesis aims to investigate how an adaptive system can increase the water security of the total system to be able to mitigate drought problems and uncertainty in the future.

Water security and adaptive capacity are inextricably linked in the sense that obtaining the former may necessitate the development of the latter. Enhancing water security obviously necessitates improving adaptive ability in the face of extremely unknown and unexpected events, such as global climate change impacts [58].

In Tab.2, the first three indicators hint the capacity of the system to be independent by external sources and securing diversified options to meet the water consumption demand. If abrupt changes occur, it is possible that the current water extraction and consumption scenario could change dramatically. In such a context, a system that succeeds in re-generating its own resources (water) and securing its independence, managing to endure over time. A diverse and branched system allows for less vulnerability to changes [59]. This feature is pointed out in the table in the last indicator. The indicator represents the diversification capacity of the network. In fact, it indicates the diversity of treatment capacity that does not count on the main central treatment plant.
Significantly, the first two indicators are relevant to emphasize how much water is claimed and stored, and not to indicate the renewable water already present and the current storage capacity of the system. This is because, while there are renewable volumes of water and storage capacity in the system, they have not been sufficient to address the drought problem. The framework serves to understand how circularity and adaptability can improve the present condition (then focusing on the relative improvement).

Table 2: Adaptability Indicators [60]

Indicators	Metrics	Unit
Water resources availability	gained renewable surface water + gained renewable groundwater + additional imported water desalinated water, reclaimed water (as applicable) per year	m^3/yr/cap
Additional water storage capacity	Total volume of additional water stored in water reservoirs (m^3) expressed as a multiple of average daily demand	No. days
Diversity of water source	Contribution of alternative sources (all sources excluding the largest source) by volume to total available water resources	%
Water treatment capacity	Total treatment capacity not relying on a central structure	%

2.2.4 LIMITATION TO ASSESS ADAPTABILITY

The first limitation faced to assess adaptability is the lack of a clear and precise definition of what adaptive management is. Furthermore, the framework has been criticized as not living up to its aspirations, in suffering from problems in translation from research to practice [18]. In addition, different nation states will find different approaches to implementing adaptivity, since they might be at different development stages, hence will gain different benefits [61].

Along with adaptability, flexibility and robustness are arising terms which promote a new approach to technologies and infrastructure to ensure the sustainability of water systems despite new challenges such as global warming and rapid urbanization. However, it is frequently unclear in the literature what these technologies and infrastructure are. Furthermore, despite their distinctions, flexibility, adaptability, and robustness are frequently used interchangeably. There is no agreed upon single definition of these terms. For these reasons, it is possible to identify general characteristics from flexibility and robustness in the framework proposed for adaptability [62].

In addition, adaptive management is a cross-sectoral approach, spilling into several fields such as governance style, socio-technical solutions, infrastructure, finances and risk, etc. Therefore, a major limitation of the framework assessment is to investigate only one perspective of the entire field.

2.3 COMPARATIVE INDICATORS FRAMEWORK

Along with the framework discussed above (circularity and adaptability), a comparative indicators framework is introduced in this chapter to assess which one the strategies may be the most appropriate, not only regards circularity and adaptability, but also from an economic, social, and governmental perspective.

By aggregating various policy objectives, a comparative indicators framework might aid the decision-making process [12]. It is a strategy for evaluating options based on many, often clashing criteria and then integrating them into a single overall evaluation [63]. Each criterion is given a relative importance in the final evaluation, which depicts its relative relevance in the given scenario.

Table 3: Comparative indicators.

Indicators	Metrics	Unit
CAPEX	Capital expenditure or is the money an organization/ a corporate entity/ public administration spends to buy, maintain, or improve its fixed assets, such as buildings, vehicles, infrastructure, etc.	€
OPEX	Operational expenditure is an ongoing cost for running a product, business, or system	€
Cost recovery of water	cost water new paradigm water management	new cost
Investment	Ease of finding investors/investments for such a project	0-10
Regulation	Ease of apply the strategies from a regulative point of view	0-10
Social Acceptance	How the adoption of this new strategy is perceived	0-10
Water Balance	Amount of water entered into the area boundaries and that outflow from the area in a year	mm/year

The CapEx (initial investment costs) and OpEx (maintainance and operational cost) represent the economic indicators for the strategies. Moreover, one more indicator regard the economic is the new price of the water compared to the actual one, which is 0.10 €/m^3 for water intended for agriculture and 1 €/m^3 for drinkable water [64][65]. The investment and regulation indicators explore how feasible the proposed strategies might be. The social viewpoint investigates how socially accepted a new proposal is compared to the current model of managing water. For the last three metrics mentioned, the water board of Breda was asked to assign a score ranging from 1 to 10, where 1 indicates an extremely negative value and 10 an extremely positive value. Lastly, the water balance generated by a new strategy is listed as an indicator.

However, the comparative indicators framework misses an essential feature, which is sustainability or an environmental indicator. When it comes to environmental indicators regarding engineering projects, the most suitable one is definitely LCA (Life Cycle Assessment) [66]. LCA is a structured and internationally standardized method for quantifying the potential environmental and human health impacts associated with a good or service from its resource consumption and emissions [67][68]. It considers the entire life-cycle of the object under analysis, from the acquiring of raw materials to end-of-life management, including manufacturing, distribution and use [67]. It is often applied as a decision support tool to provide an effective and efficient contribution towards greater sustainability of goods and services [67][68]. As shortcoming as this is, the study and analysis of the LCA of each intervention would go beyond the scope of this thesis. It is nevertheless recommended to anyone wishing to implement circularity and adaptability of the system through the interventions proposed in the preceding paragraphs, to integrate LCA indicator into the indicators.

3 EXISTING SYSTEM

This chapter explores the water balance for Breda and how it was calculated. First, the chapter shows the current water balance and the assessment of the current system based on the framework. Then, it investigates three factors: the area under study, the flows involved in the urban water system and the time frame with which the water balance has been assessed.

The necessity for (high-level) flow integration to address concerns of recycling, re-use, and sustainability is driving interest in modeling the urban water cycle. With the definition of water balance is a physical process of mass conservation that tracks the movement of water in a defined area in a previously decided time interval [69] [70].

Water balance analysis is a valuable method for determining the current state and changes in the supply of water resources. Additionally, water balance assessments facilitate water management decision-making, by evaluating and enhancing the validity of visions, scenarios, and approaches.

3.1 WATER BALANCE

The water balance calculated for the municipality of Breda in 2020 results in a positive water balance of +47.38 mm/yr for the entire area. For more in depth details regarding calculation, see Appendix A, from Tab.1 to 6.

Table 4: Monthly water balance.

Month	Monthly water balance (mm/month)	Monthly water balance (Mm^3/month)
January	15.69	1.43
February	84.08	7.66
March	1.13	0.13
April	-64.32	-5.86
May	-75.28	-6.85
June	42.13	3.84
July	-19.53	-1.78
August	-43.61	-3.94
September	5.67	0.52
October	42.16	3.84
November	11.95	1.09
December	47.29	4.31

Compared to other years, it seems that water balance is lower, but it must be remembered that during spring there was a water deficit of -170 mm and during summer, especially in the south of the Netherlands, there was even a water deficit of -280 mm [71]. In line with what has been stated previously at the national level, the driest months in 2020 were in the periods between April-May and July-August. In Tab.4 the water balance for each month is shown. Overall, the water balance calculated is consistent.

Following, Fig.22 and 2 show the water balance for the year 2020. For a complete view of the maps produced on QGIS 3.10 and the water balance maps for each month, proceed to Appendix B, from Figure 1 to 26.

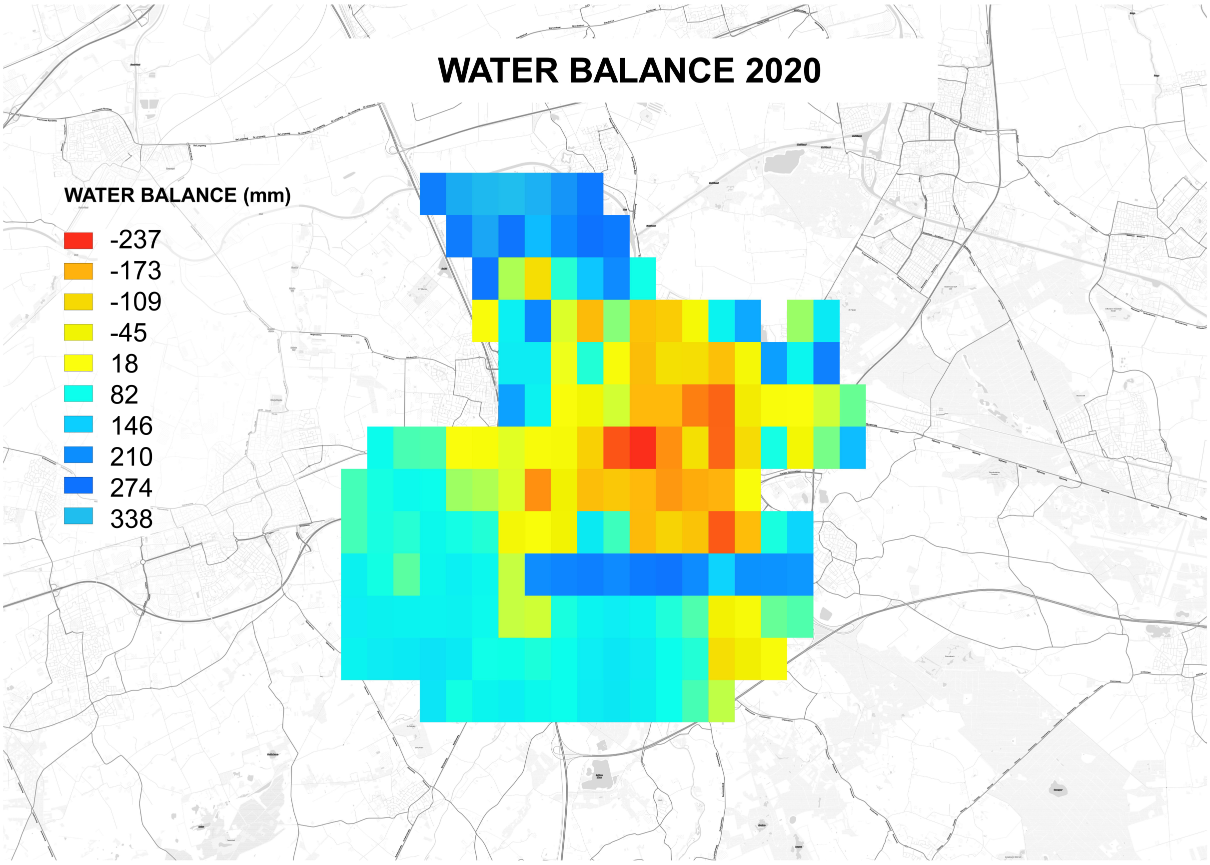


Figure 1: Representation of the annual water balance for the municipality of Breda, through QGIS 3.10.

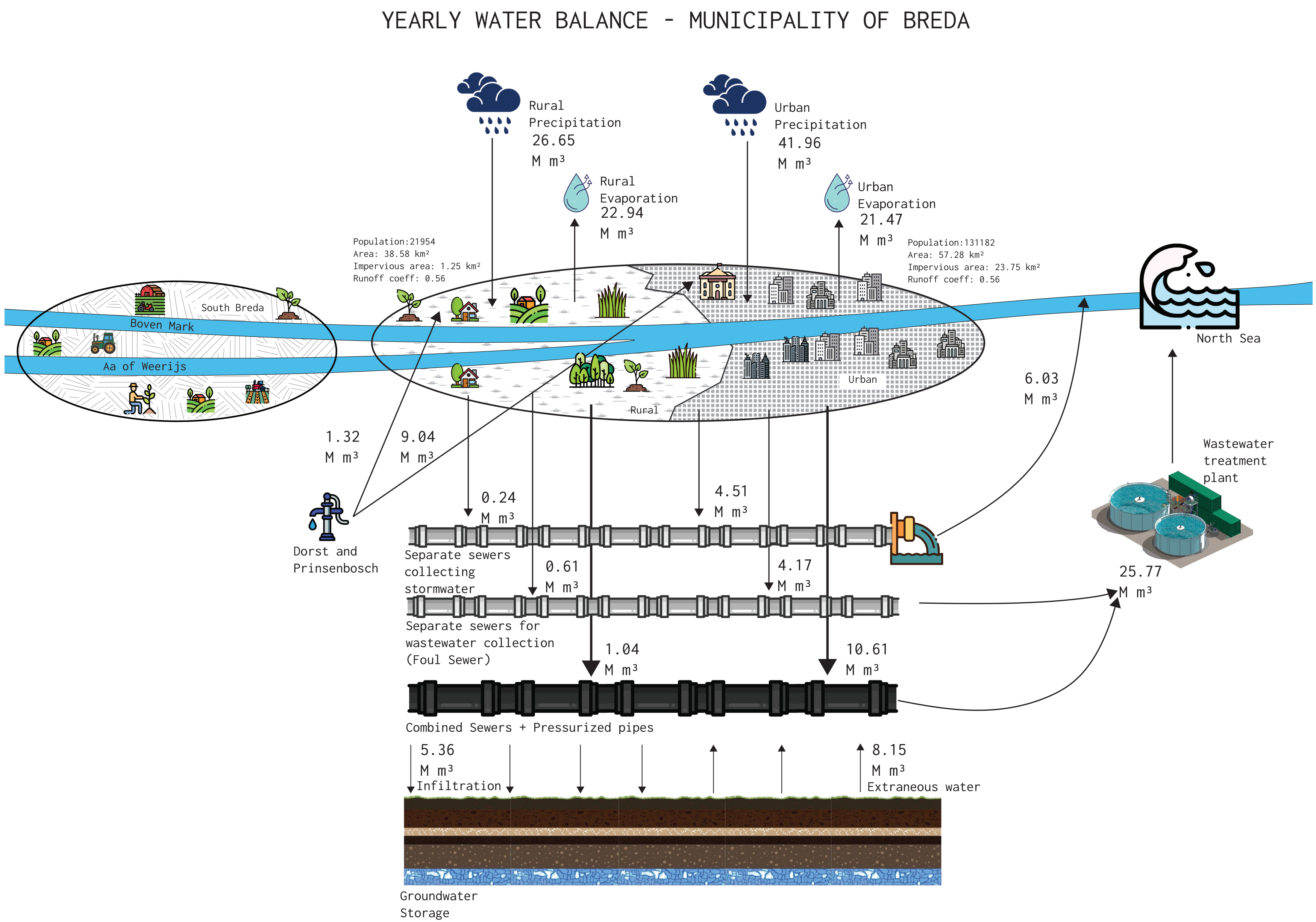


Figure 2: Conceptual map of water balance and different flows and their interaction in the system under study for the municipality of Breda, 2020.

3.2 ASSESSMENT OF CURRENT WATER SYSTEM

Through the developed framework, it is analyzed and observed how circular and adaptable the current water management system is. Tab.5 and 6 show the current state of the water system.

Table 5: Circularity in the actual water system.

Principle	Indicator	Metric
Reduce consumption of natural resource	Volume of freshwater (groundwater and surface water) used for consumptive and non-consumptive purpose	100%
Keep resource in use	Reclaimed wastewater treatment plant effluent	0%
	Reclaimed stormwater	0%
Regeneration of natural capital	Water restored as groundwater (Mm^3)	0%
	Water restored as surface water	0 (Mm^3)

Table 6: Adaptability in the current water system.

Indicators	Metrics	Unit
Water resources availability	gained renewable surface water + gained renewable groundwater + additional imported water desalinated water, reclaimed water (as applicable) per year	0 (m^3/yr)
Additional water storage capacity	Total volume of additional water stored in water reservoirs (m^3) expressed as a multiple of average daily demand	0 (No. days)
Diversity of water source	Contribution of alternative sources (all sources excluding the largest source) by volume to total available water resources	0%
Water treatment capacity	Total treatment capacity not relying on a central structure	0%

The comparative indicators framework has not been included, since it has been designed to help decide which strategy is the most feasible.

It is possible to note from the tables above that the current water system shows a linear and rigid model of water management. Water used by industries, private citizens and agriculture relies solely on the exploitation of freshwater from aquifers. All wastewater collected at the wastewater treatment plant is discharged north of the city into the Hollands Diep, a river that is part of the Rhine and Meuse estuary. The only way water is restored is through the natural process of rainwater infiltration. The system is fragile since it relies solely on a single source of sustenance and cannot store water to cope with unforeseen events. In addition, relying solely on the central water treatment plant, it lacks modularity and the ability to diversify its existing portfolio of treatment technologies.

3.3 SYSTEM BOUNDARY

Breda is a city and municipality located in the southern part of the Netherlands, in the province of North Brabant. The focus of the thesis is mainly on the municipality of Breda. Two rivers enter the city, the Boven Mark and the Aa of Weerijs, to then combine and become the Mark. The Mark is a river which rises in the north of Turnhout, Belgium, in the municipality of Merksplas. It passes through Hoogstraten before crossing the border with the Netherlands. Then flows as Bovenmark through the city of Breda, where it merges with its main tributary, the Aa of Weerijs to form the Mark.
As The Mark, the Aa of Weerijs is a river that originates in Belgium, from the confluence of the Grote Aa (in Wuustwezel) and the Kleine Aa (in Brecht). In Breda the river enters the canals of the city, continuing to flow together with the Bovenmark under the name Mark. The width of the Aa or Weerijs varies from 5 meters at the border with Belgium to 15 meters at Breda. The stream valley is approximately 3 kilometres wide [72].

The research area is characterized by sandy soils. Sandy soil is normally dry and tends to be considered as a light soil, due to their high portion of sand and little clay. These typologies of soils are characterized by fast drainage [73].
Although sandy soils have a low pH and are of poor nutrient content, in the North Brabant there is intensive land use by farmers. The naturally poor sandy soils of Brabant have been enriched by agricultural fertilizing. A form of land use in the south Brabant is high-quality crops. These crops consist of horticulture (flowers, vegetables, fruits and small-scale arable farming) and tree cultivation (avenue trees, shrubs, woodland planting stock, conifers and perennial garden plants). One disadvantage of high quality crops is high water requirements, which means additional groundwater extraction. Besides, land use for intensive grassland and animal feed is significant in the area. Livestock farming consists largely of dairy cattle, partly of pigs and poultry. The animal feed consists of grass (grassland) and for the most part maize [74].

For the following study, it was proposed to consider as system boundary the Breda municipality area. This is because, in the municipality, due to a high rate of housing, there is a strong consumption of drinkable water and consequently production of wastewater (also due to the strong urbanization that has made the soil impermeable).

Depicted in Fig.3 the study area is shown. It is possible to notice that the area under consideration can be divided into two different level of urban tissue: the city centre of Breda, which is highly urbanized, and the southern part of the municipality, where there is a greater presence of green areas, including the Mastbos forest and presumably agricultural fields.

(a) Breda's municipality bounded by white outlines

(b) Different urban tissues in contrast: urban and rural.

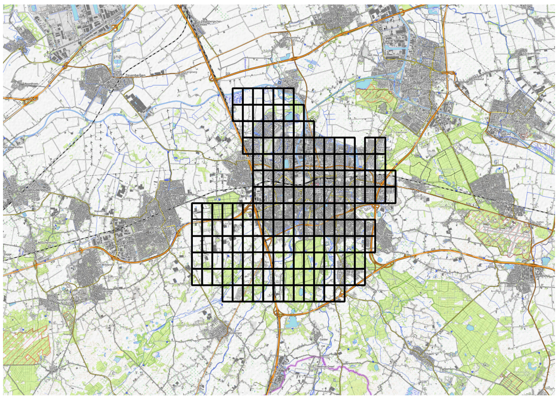
Figure 3: Area of study: Breda's municipality. [75]

This distinction is significant as different spatial patterns have different quantity and quality of flows. The main difference lies in the pavement, which generates a different runoff pattern [76]. In addition, population density varies within the boundaries, and consequently the demand and consumption of water. In the urban part there is a high concentration of inhabitants, while in the rural one, the population density decreases significantly.

Breda's population counts 184,069 inhabitants in 2020 [77]. As just mentioned, the population density is not evenly distributed. To analyze this, it is important to study the spatial distribution of inhabitants. For this purpose, the software QGIS 3.10.14 was used. First, the raster map of the population of the Netherlands, for 2020, was downloaded from Public Services on the Map (PDOK) website [78]. Consequently, the raster file was clipped for the two macro-areas, so as to obtain the population density for Breda. However, on QGIS, when one clips a raster with a mask layer, if a cell (dimension of 0.54 km^2) is cut by the vector layer, the cell is not taken into account. Therefore, 17% of the total populations were not considered, and the total number of inhabitants counted for the area are 153,137. On the one hand, population reduction leads to an increase in the flow value per cell. On the other hand, the reduced population does not interfere with the total volume of the flows, allowing the water balance calculations.
Then, when it was divided further into urban and rural areas, a further cut to the population happened, reduced by 2,814 citizens. The urban part counts 130,897 inhabitants, while the rural one only 19,426. The two sub-areas boundaries are displaced in Fig. 4(a), while in Fig.4(b) the grid cell is pictured and in Fig.5 shows the population density in the area by the raster file.

At the north-west side the wastewater treatment plant can be identified in Fig.6, where all the wastewater from the municipality and from part of the region goes to. This means that the effluent of the treatment plant does not affect the urban water quality. Further explanations about the wastewater plant system are given in chapter 3.6.2.

(a) Urban and rural division of Breda Municipality.



(b) Raster grid for Breda's population.

Figure 4: Area division and grid representation of the raster file.

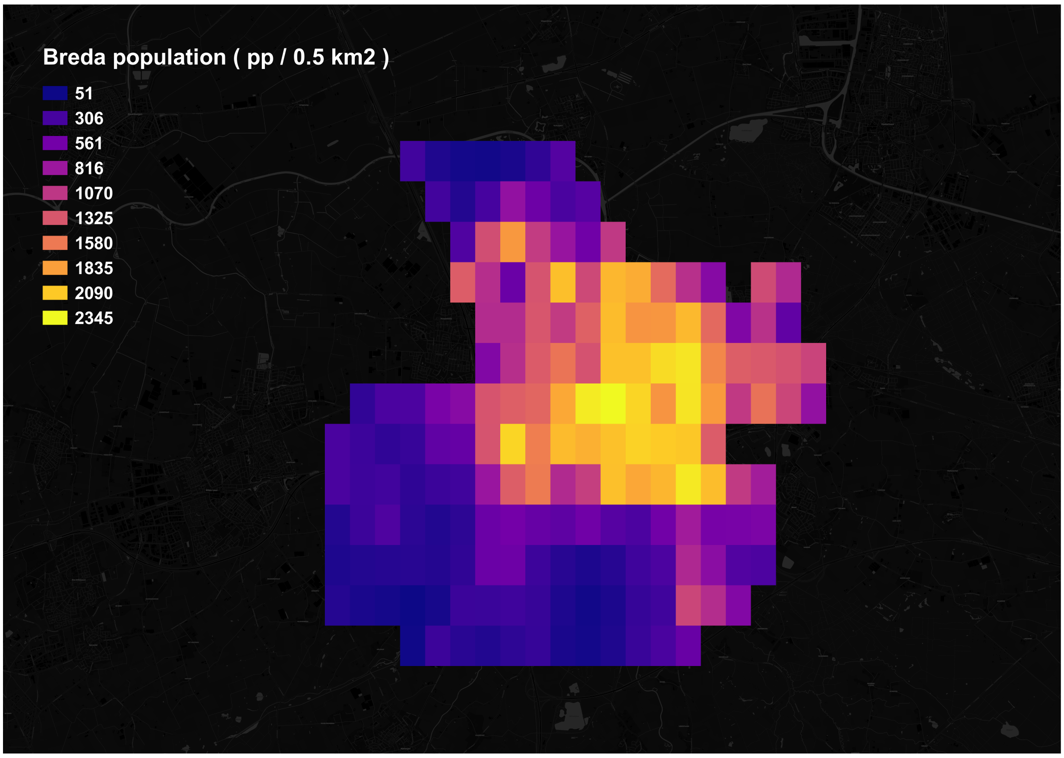


Figure 5: Population density for the two sub-areas of Breda.

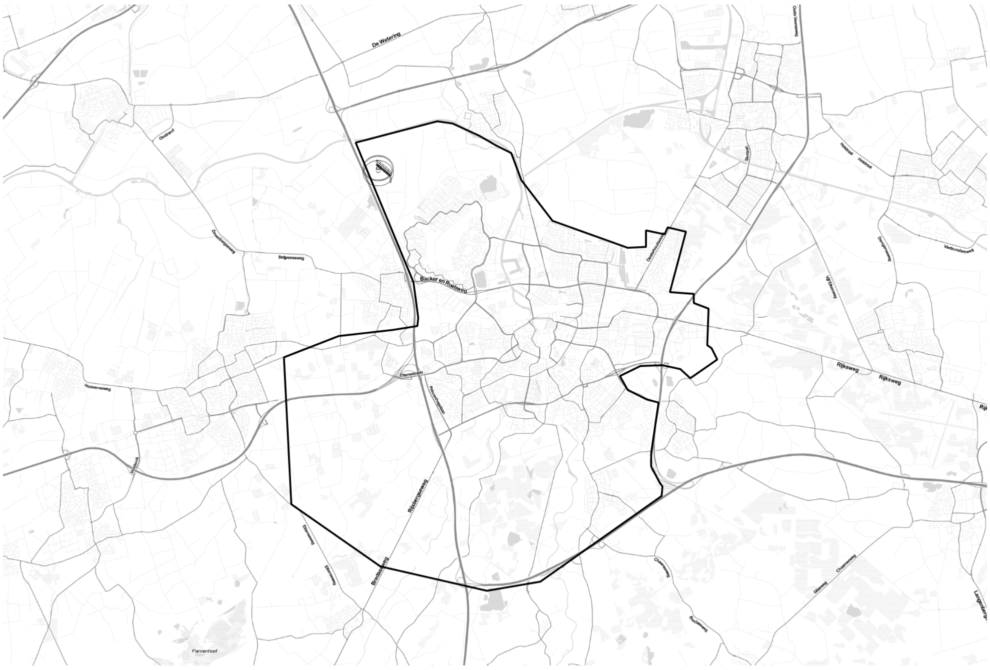


Figure 6: Wastewater Treatment plant located at the north west of the municipality.

3.4 FLOWS

Existing approaches often fail to account for both ‘natural’ and ‘anthropogenic’ flows, resulting in an inadequate assessment of the solutions’ water output and impacts on the urban water cycle [79]. In this study it was accounted for both ‘natural’ hydrological flows (evaporation, stormwater, groundwater infiltration, etc.) and ‘anthropogenic’ hydrological flows (piped water flows) in order to comprehend the ‘whole urban water system’.

The water balance for a given time frame can be expressed as the fluctuation of the storage volume equal to the sum of the inflow minus the outflow [69]. This principle of mass balance is the one who guides the calculation of the water balance.

In this study, the water balance for the different areas (urban and rural) was calculated through Eq.1.

$$S = P + W_{in} - EV - WWTP_e - SSS_{sw} \tag{1}$$

Where S is the storage, so the supplement or the deficit of water in the area; P is the total precipitation, W_{in} is water intake, EV is the potential evaporation, $WWTP_{\text{e}}$ is the wastewater treatment plant effluent, which comprehend part of the extraneous water and stormwater, and ultimately SSS_{sw} the stormwater who flows out of the boundary through the separate sewer system.

A list of flows and terminologies regarding the flows involved in the water balance calculation are given below in the Tab.7.

Table 7: Definitions of the flows.

Flow	Definition	Reference
CSO overflow	Overflows, during wet weather, of combined wastewater and stormwater. CSOs happen when flows in the wastewater collection system exceed the capacity of that system. The term "CSO" is also sometimes used to denote a pipe that discharges those overflows.	[80]
Dry weather flow	Average daily flow to a waste water treatment facility during a period without rain	[81]
Evapotranspiration	The loss of water from the soil through both evaporation and transpiration from plants.	[82]
Extraneous water	Water that has infiltrated into the sewer system but should not be there, such as groundwater seeping via leaks, unlawfully discharged drainage water, or rainwater running into a sewage canal.	[83]
Groundwater	Water contained under the ground's surface, located in the spaces between soil particles and in the cracks of sand, gravel, and rock; a natural resource and source of water for drinking, irrigation, recreation, and industry.	[84]
Imported Water	Water carried into a management area through a pipe or other channel.	[85]
Precipitation	Stage of the water cycle when water vapor molecules become too large and heavy to remain in the atmosphere and fall to the ground in the form of rain, snow, sleet, hail, etc.	[82]
Separate Sewer flow	When there is a separate water system, rainwater is collected separately from wastewater. Rainwater is usually discharged without treatment into rivers, canals or ponds.	[86]
Stormwater	Runoff generated when precipitation from rain and snow melt flows over land or impervious surfaces and does not percolate into the ground.	[82]
Surface Water	Water that is on the Earth's surface, such as in a stream, river, lake, or reservoir.	[87]
Wastewater	Water that contains unwanted materials from homes, businesses, and industries; a mixture of water and dissolved or suspended substances.	[82]

3.5 TIME UNIT OF ASSESSMENT

Once the different flows needed for the water balance have been identified, it is necessary to understand which is the time frame they should refer.

Due to the strategic/planning aspect of such activity, most urban water cycle models operate on a daily time step, if not even hourly. The choice of time step, on the other hand, entails (concealed) assumptions that may have a major impact on the model's performance. Then, the choice of time step is calibrated according to the scope of the research.

Since the purpose of this thesis is to evaluate different strategies, such as stormwater and wastewater effluent management, the time-frame proposed is daily. Even if smaller time steps increase model accuracy (e.g., 15 min, 1h), the decision for a daily time scale is based on the desire to capture variations in the water balance, though avoiding the need to include more difficult and complicated interactions that occur at finer time intervals, which might be necessary for example if the thesis was focusing on the problem of flooding. Moreover, collecting finer data was not always possible. Therefore, the decision to work with daily spans also comes from the fact that, not having accurate information regarding the hourly data and having to make assumptions, it is likely that the magnitude of the error in the scaling down will rise, and the data will be highly inaccurate.

3.6 DATA COLLECTION

This paragraph discusses the various data needed for the purposes of this thesis and how it was collected and processed.

The required data are listed in Table 8 below, following the data type, unit of measure, and source.

Table 8: Type of data.

Data	Unit	Source
Demand and Supply of Water	m^3/d	[64]
Evaporation	mm/d	[88]
Groundwater storage	m^3	calculated
Infiltration	m^3/d	calculated
Runoff coeff.	-	calculated
Runoff	m^3/d	calculated
Precipitation	mm/d	[88]
Wastewater treatment plant effluent	m^3/d	[65]
Separate Sewage Discharge Stormwater	m^3/d	calculated

3.6.1 DEMAND AND SUPPLY OF WATER

The data regarding water consumption for the municipality of Breda was provided by the company that manages the drinkable water network in the Brabant region, namely Brabant Water [64]. The company works to provide fresh water for all purposes, such as household consumption, agriculture, industry and so on. The data provided comes as yearly data of water consumption by 2016, and are referred to the whole Brabant region. Following, Tab.9 shows the water consumption data.

Table 9: Water consumption for Brabant region [64].

Distribution of water in 2016 (Brabant region)	m^3/yr	%
Household	108,587,246	62.7%
Agriculture	9,778,678	5.6%
Commercial	38,984,704	22.5%
Other	10,583,108	6.1%
Unsettled	5,374,162	3.1%

Tab.9 is helpful to understand how water distribution occurs in the region. It is clear, based on the table, that the largest water consumption comes from citizens, followed by industries and other unspecified activities. Then, based on population density, the water consumption for the area of interest was calculated.

To be able to calculate the water consumption of the area of interest, 2020 water consumption data has been collected. For 2020, the drinkable water for the municipality of Breda was extracted in 3 diversified zones. Dorst with 10.5 Mm^3/yr, Prinsenbosch with 5 Mm^3/yr and Ginneken with 0.4 Mm^3/yr [64]. However, out of the 15.59 Mm^3 extracted every year, only 10.5 Mm^3/yr are being employed for the municipality of Breda [64]. Then, assuming that the total water consumed in the city of Breda is 10.50 Mm^3/yr [64], out of a total of 150,324 citizens in the QGIS raster file, it is possible to calculate the average water consumption per citizen. Therefore, the water consumption per capita was multiplied by the number of inhabitants in the rural and urban areas of the municipality, in order to obtain the quantities of water consumed per citizen. The groundwater extraction points are indicated in Fig.7.

As can be seen from Fig.7, one of the extraction points (Ginneken) is located within the perimeter of the study area. Therefore, the water extracted in Dorst and Prinsenbosch , which represent 97.48% of water consumption, is considered inflow in the system.

The water demand is expressed as m^3/year. Since it was previously decided to work with a daily time-frame, it is necessary to change the unit of measure, in order to express the water consumption in m^3/d/citizen.

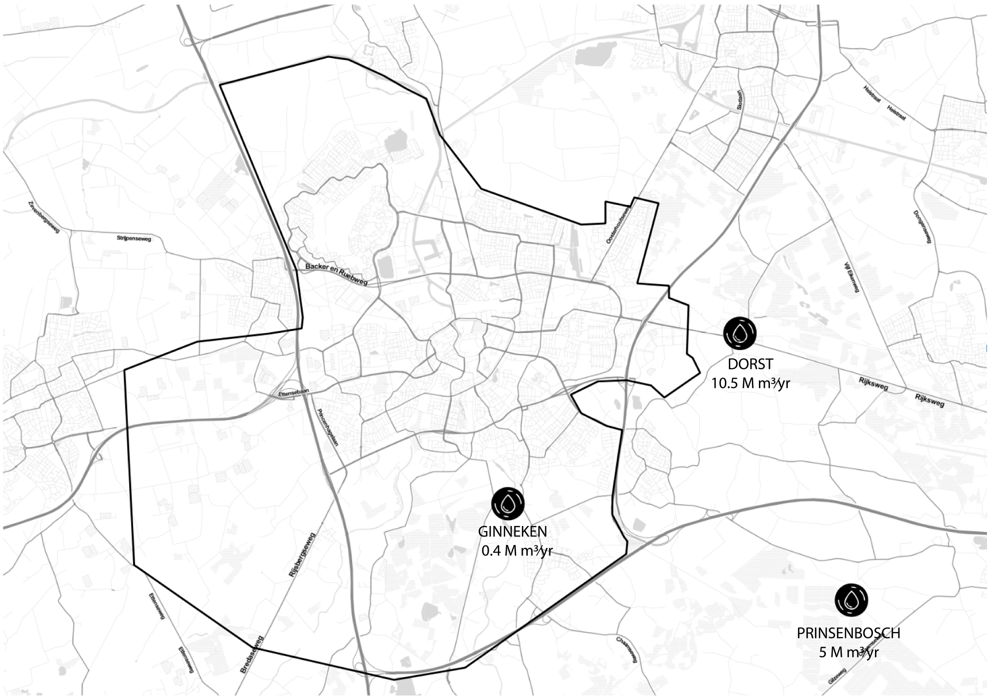


Figure 7: Extraction groundwater area for Breda's municipality. [64]

As can be seen from Fig.7, solely one of the extraction points (Ginneken) from the aquifers is located within the perimeter of the study area. Therefore, only flows from Dorst and Prinsenbosch, which represent 97.48% of water consumption, are considered as inflows for the calculation of water balance.

The water demand is expressed as m^3/year. Since it was previously decided to work with an hourly time-frame, it is necessary to change the unit of measure so that the consumption of water is expressed on a daily basis (m^3/d/citizen).

The water consumption has a seasonal fluctuation influenced by a diverse variables as the weather circumstances, the different demand by the industries, the behaviour of the consumers and the agricultural harvesting conditions [89][90][91] [92]. The peak factor for Brabant Water overall is roughly 1.7. On a hot summer day, the total consumption is a factor 1.7 higher than on an average day. The peak factor can differ between different areas. The peak factor in urban areas is around 1.6. In rural areas it can go up to 1.8-2.0 [64]. Knowing that, it was decided that for the rural area a peak factor equal to 1.9 and for the urban area equal 1.6 was set. Rising temperatures lead to greater consumption of drinking water [92], nonetheless no information could be found on the mathematical relation between how temperature impacts drinking water consumption. Therefore, in this study, the mean annual temperature was considered as the threshold, where below the temperature variation does not affect water consumption. Above the threshold (which is, based on KNMI data, 12℃) a linear correlation between temperature increase and consumption increase was assumed. Tab.10 shows the different peak coefficients for each temperature range for both rural and urban areas.

Table 10: Direct relationship between temperature and peak coefficient.

T (°C)	Peak Coeff. Urban	Peak Coeff. Rural
12-15	1.1	1.1
15-18	1.2	1.3
18-21	1.4	1.5
21-24	1.5	1.7
24-28	1.6	1.9

As for the difference between rural and urban areas, there was no different approach in calculating water consumption. The total water consumption by each area was made by multiplying the total number of inhabitants by the daily water consumption per capita. As shown in Tab. 9, 62.7% refers to consumption by households, while only 5.6% refers only to agriculture and the rest mostly goes for commercial purposes. Clearly, these are the percentages referring to the entire Brabant region, and they are not representative of the study area. Therefore, since the main consumption comes from household and commercial, it was assumed a linear relationship between number of people and water consumption.

This approximation, as much as it may be a limitation, allows one to have an insight into the water consumption in the areas of interest. It should be added that if only temperature is taken into account, a range of other equally important variables are not considered, such as relative humidity or radiation intensity [93]. Additionally, the year under consideration, 2020, was particular due to the advent of the COVID-19 pandemic. With the COVID-19 lockdown impacting the livelihood of people, changes in hygiene and water consumption behaviour occurred at global scale. Especially hygiene habits have been the most affected by the pandemic. Activities as hand washing, showering, sanitising and domestic cleaning have increased during that period [94]. Nonetheless, these assumptions make it possible to get a better idea of the fluctuation in water consumption by the municipality and the distribution along the areas.

3.6.2 WASTEWATER TREATMENT PLANT EFFLUENT

The Nieuwveer wastewater treatment plant is located in the north of the city, just above the urban area. The treatment plant does not only collect wastewater from the municipality of Breda but also from other villages nearby. Fig. 8 shows the pathway for the wastewater towards the treatment plant in 2013.

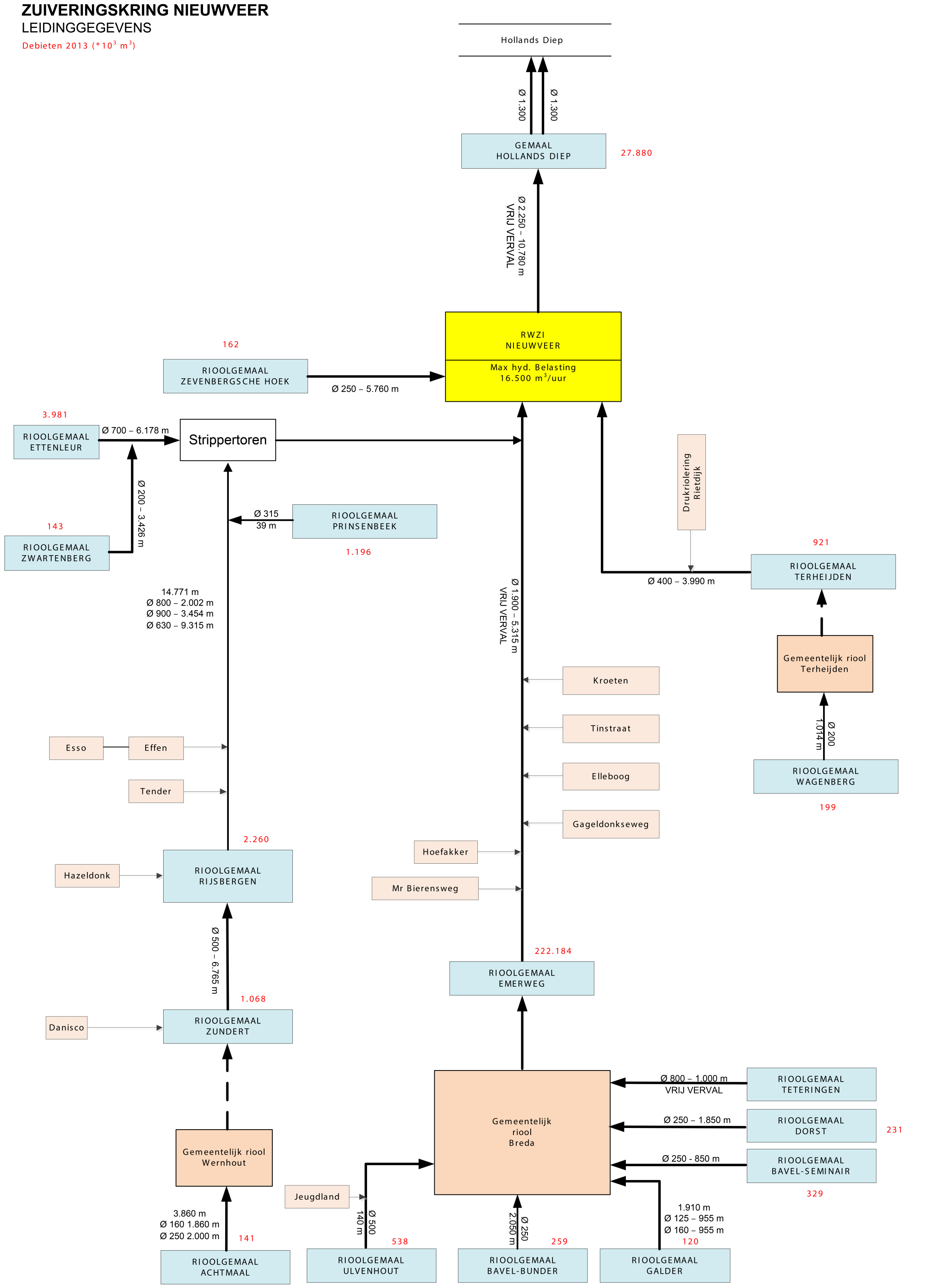


Figure 8: Nieuwveer wastewater treatment plant scheme for 2013. Written in red the annual flow in 10^3 m^3.[65]

The Water Board of Breda provided the daily data regarding effluent volumes from the wastewater treatment plant for 2020. In order to calculate the wastewater production by each area, the percentage of Breda municipality wastewater production was calculated, compared to the total amount that is discharged towards the plant. Breda discharges 95% of the total effluent of the Nieuwveer. Based on that, as has been done previously for water consumption (paragraph 3.6.1), the total effluent was divided by the total population of the municipality and then multiplied for the amount of population of each area.

3.6.3 PRECIPITATION

Precipitation data were obtained from the Royal Netherlands Meteorological Institute (KNMI). KNMI is the Dutch national weather forecasting service, with 51 meteorological stations all over the Netherlands. The closest station to the area of interest for the data is station number 305 "Gilze-Rijen", which is located east of Breda.

The discrete data from the weather station was then extended for the entire area of interest. Two different types of precipitation are calculated. Net precipitation and total precipitation. Net precipitation is referred to the precipitation over the impervious area. The impervious area over the municipality of Breda is total 25 km^2, of which 23.75 km^2 for the urban area and 1.25 km^2 for the rural ones. Total precipitation was calculated over the total area for each zone.

In order to reduce the complexity of the work, it was decided to extend the data of station 305 (for both precipitation and evaporation) to the whole area of interest. This procedure has evident limitations. By spatializing the data homogeneously, possible meteorological variations in space are not taken into account. Notwithstanding, if the data were spatialized through different methodologies (e.g., Thiessen polygons or IDW interpolation), there would be other limitations regarding the values obtained [95].

3.6.4 RUNOFF COEFFICIENT AND STORMWATER

In order to be able to calculate the stormwater produced over the impervious area during rainfall events, the runoff coefficient had to be assessed. The runoff coefficient, referred as c, is defined as:

$$c = \frac{\text{Total runoff via combined and separate sewage system}}{\text{Total amount on precipitation on directly connected paved area}} \tag{2}$$

c is expressed either as a fraction or as a percentage [96]. Runoff coefficient diversifying for different urban land types.

To calculate the runoff coefficient for the area, first it is necessary to know the percentage in volume of stormwater present in the wastewater effluent. To calculate the volume of stormwater within the wastewater, the Weiß-Brombach method [97] was employed. This method, through the wastewater treatment plant effluent, the water consumption (dry weather flow) and the number of rainy days, can calculate what are the percentages of dry weather flow, stormwater and extraneous water in the wastewater treatment plant effluent. In fact, the sewage of Breda suffers of extraneous water from groundwater. This infiltration is named extraneous water, explained in Tab.7 After having found out the volume and percentage of stormwater present in the effluent, then it was possible to calculate the runoff coefficient, dividing this value by the net rainfall.

The Weiß-Brombach method, also called the Triangle method, was performed on Microsoft Excel 2103, (Fig.9 and Fig.10). The inflow data (daily mean) was first ordered in ascending order, which resulted in a classic S-shaped curve. The sanitary sewage, or water consumption, flow was considered to be constant (annual water consumed divided by the days of the year), this results in a horizontal line in the diagram. The treated yearly dry weather flow volume is shown in the rectangle region below.

The amount of runoff plus infiltration intake is represented by the region between the curve and the horizontal line. In order to separate those two flows, it was supposed that the infiltration flow is at maximum after wet periods. Infiltration inflow, on the other hand, will be significantly lower – and may even be considered to be nil – as long as the sewers are full with storm water, because water will also exfiltrate in this situation. This model method is fulfilled by a straight line drawn in the figure as illustrated. The number of days with surface runoff (i.e., days with storm events and days immediately after) was calculated using the WWTP data and is graphed from right to left. The straight line begins when it crosses the curve. It goes all the way down to zero at the right end of the figure. Stormwater figures above this line, while infiltration below it [97].

Fig.9 and Fig.10 show the triangle method.

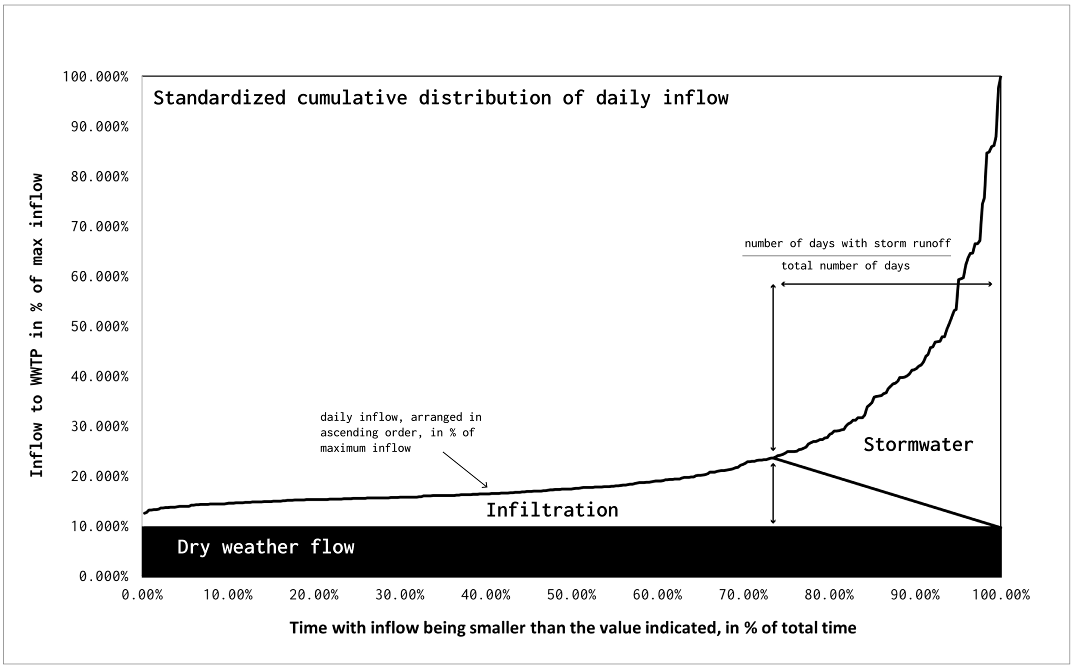


Figure 9: Determination of average dry weather flow, stormwater and infiltration by the “triangle method” in %.

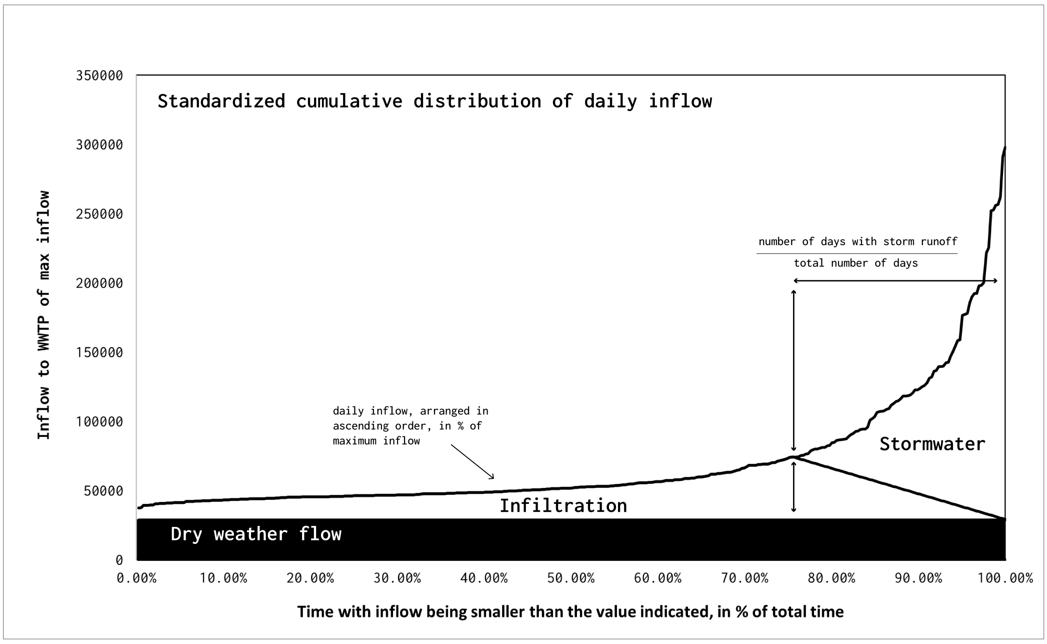


Figure 10: Determination of average dry weather flow, stormwater and infiltration by the "triangle method" in volume.

From the graphs, through trapezoidal rule, the areas of percentage and volume for stormwater were calculated (Table 7, Appendix A). Then, after have determined the volume of stormwater present in the wastewater treatment plant effluent, the runoff coefficient was calculated with Eq.3:

$$c = \frac{V_{runoff}}{p \cdot (0.95 \cdot A_{CSS} + 0.66 \cdot A_{iSSS})} \tag{3}$$

Where c is the runoff coefficient, V_{runoff} is the volume of runoff in effluent in m^3/yr, p is the cumulative precipitation in m/yr, A_{CSS} is the area served by combined sewer system and A_{iSSS} is the area served by the improved separate sewer system. Eq.3 assumes that 5% of total inflow of runoff to combined sewers is discharged via CSOs and 33% of total inflow of runoff to improved separate sewers is discharged via their SSOs.

From the equation, the runoff coefficient for the entire area of 0.56 was calculated. Having calculated both the net rainfall and the runoff coefficient, it was possible to calculate the stormwater production flowing into the pipelines on a daily basis.

3.6.5 SEWAGE SYSTEM

The sewage system of Breda consists of a partially separate sewage system and combined sewers. A separate sewerage consists in the separate collection of municipal wastewaters (blackwater, greywater and industrial wastewater) and surface run-off (rainwater and stormwater). During rainy seasons, the separate collection prevents sewer systems and treatment stations from overflowing, as well as the mixing of the comparatively unpolluted surface run-off with chemical and microbiological pollutants from urban wastewater. Stormwater, after it is collected, is directed into water bodies, such as canals. A combined sewage system transports wastewater and urban runoff together to a sewage treatment plant. Fig.11 shows the sewage network of the municipality of Breda.

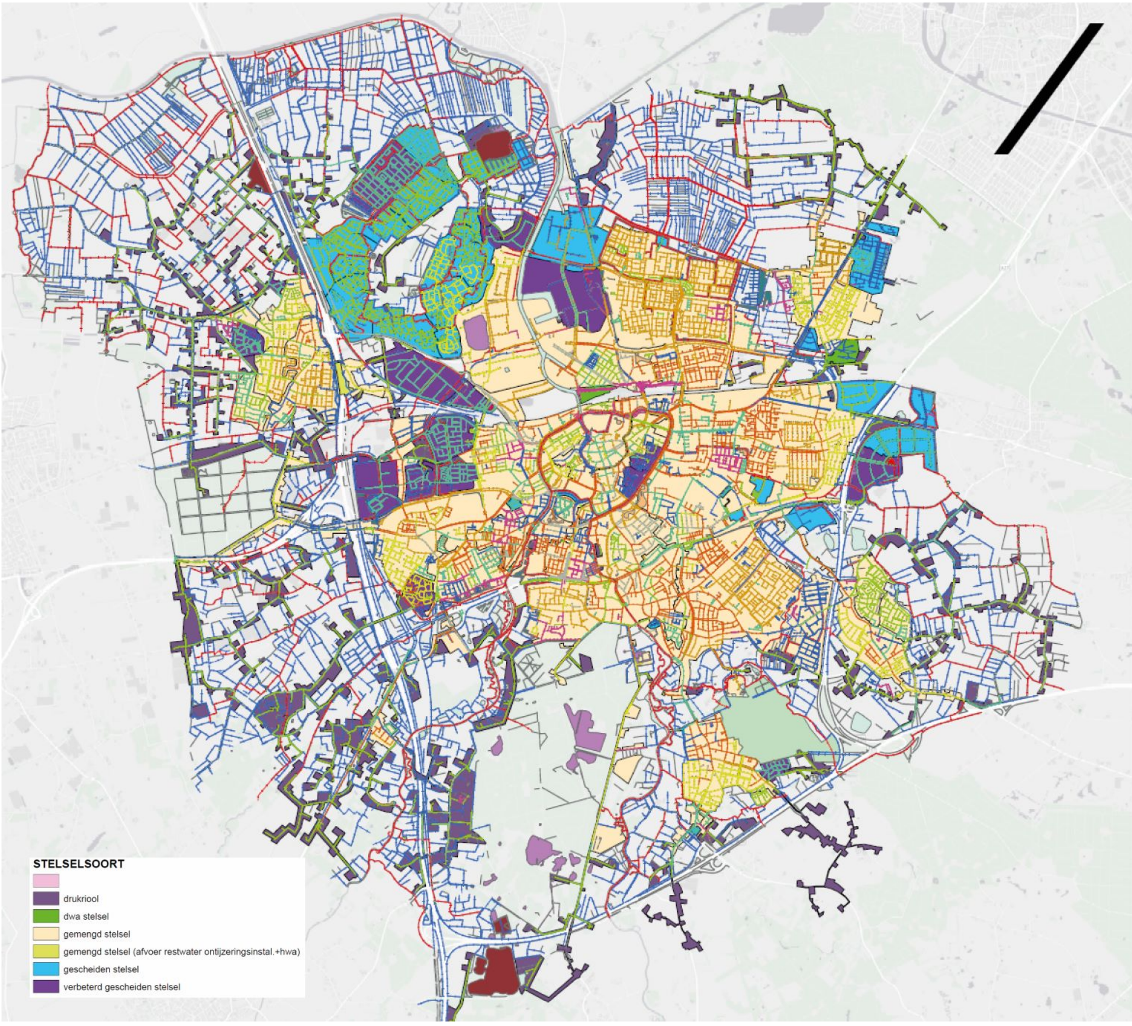


Figure 11: Sewer system of Breda.[65]

From Fig.11 it was possible to estimate, through an analysis of the percentage of color referred to each sewer compared to the entire map, the percentage of separate sewer system (SSS), combined one (CSS) and pressure sewer system (PSS). The separate sewer counts for 45% of the system, while combined and pressure sewer together count for 55%. Henceforth, it was possible to be able to calculate how much stormwater is collected by one sewage and the other.

Once the different percentages of coverage for each network have been established, it is possible to calculate the percentage of stormwater, dry weather flow and extraneous water for each sewer.

3.6.6 POTENTIAL EVAPORATION

As for precipitation, potential evaporation was obtained from the Royal Netherlands Meteorological Institute (KNMI), referred to station number 305 "Gilze-Rijen".

For the study, potential evaporation was used to calculate the water balance and not evapotranspiration, since transpiration (the conversion of water from the liquid to the gaseous state through plant stomata) could not be calculated due to the lack of data and the high complexity of the calculation. In fact, transpiration is influenced by a variety of features, including: number of stomata, number and size of the leaf, light supply, water supply and presence of plant cuticle [98]. In addition, potential evaporation has a higher value, which is more distant from the actual reality of the phenomena [99]. The total or actual evaporation is the same as the potential evaporation, but it is not limited by the amount of water available. As a result, actual evaporation is always lower than or equal to the potential evaporation. The limit of the achievable evaporation is indicated by the potential evaporation [99].

Unlike precipitation, whose values were extended to the total study area, evaporation data were only extended in percent to pervious areas. This means that, if for precipitation the value in mm was multiplied by the total study area (in order to obtain a volume of m^3), the evaporation values were multiplied by the total pervious areas. This is because evaporation processes do not occur (or at least, not significantly) with impervious layers. Knowing the impervious area, to find the pervious area the impervious area was simply subtracted from the total area.

As for precipitation, in order to reduce the complexity of the work, it was decided to extend the discrete data of station 305 (for both precipitation and evaporation) to the whole area of interest.

3.6.7 INFILTRATION

Infiltration is the process by which water on the ground surface enters the soil. To estimate this value, the difference between precipitation and evaporation is multiplied by total pervious areas.

Consideration was also given to the possibility of rainwater that, due to soil saturation, is unable to infiltrate and additional stormwater is generated. To be able to control this, with a simple rule of thumb, the minimum groundwater level of -1 meter was considered from August (therefore 300 mm given a porosity of 33% for sandy soil), given the severe drought that affected the month. Then the precipitation level minus the water released through evaporation was added. Proceeding in this way from day to day it was possible to check the saturation of the groundwater. Through calculations, no land saturation events occurred for the year 2020.

3.6.8 SUBSURFACE STORAGE

The groundwater present in a given area can be defined as the difference between recharge and discharge in the timescales in which these changes occur, varying from days to years [100]. However, the amount of room not occupied by groundwater can be considered natural storage space. Then, knowing how much groundwater is present in the area of study, allows one to understand the amount of storage volume available. Eq.4 was employed to calculate the available storage volume:

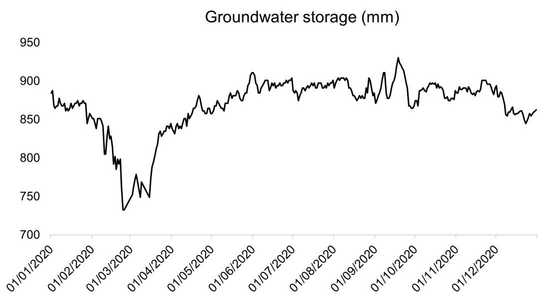
$$V_{storage} = p \cdot (Z_{SL} - Z_{WT}) \cdot A \quad (4)$$

where:

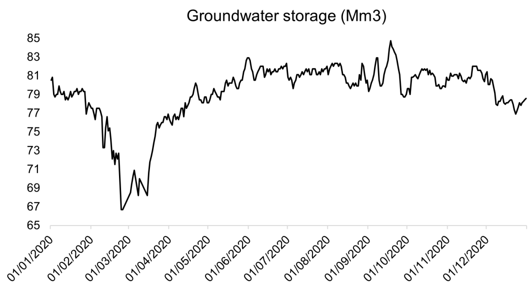
- V: Volume of underground storage (m^3)
- p: porosity of the soil (-)
- Z_{SL}: Surface level (m)
- Z_{WT}: Water table (m)
- A: Area (m^2)

The porosity for sandy soil in the area of Breda ranges between 0.30 and 0.35. Therefore, it was decided to set porosity as 0.33 [101]. Then, for the surface level and the water table level, the values are taken from The Geological Survey of the Netherlands (GDN), an organization which includes geologists, hydrologists and subsurface model developers. Then, for the area is taken the one for the municipality of Breda.

Fig. 12 represents the fluctuation of underground storage in time for 2020 calculated with Eq.4.



(a) Underground storage (mm).



(b) Underground storage (Mm^3)

Figure 12: Available underground storage volume expressed in mm and Mm^3.[102]

From the calculation, the available underground storage ranges from 67 to 85 Mm^3.

3.7 URBAN AND RURAL WATER BALANCE

Based on Eq.1, the water balance for the rural and the urban area was calculated. It follows that in the urban area the water balance is +50.56 mm/yr and in the rural area it is + 42.38 mm/hr, for a positive water balance of +47.38 mm/yr for the entire area. For more in depth details regarding the difference between the water balance in rural and urban areas, see Fig.22 and **??** for the yearly water balance. For monthly water balance see Appendix B, from Fig. 1 to 26.

4 EVALUATION OF DIFFERENT INTERVENTIONS

For many years, societies have been recycling water to restore groundwater aquifers, irrigate landscapes and farmlands and provide an alternative to drinking water for a variety of purposes.

To succeed in improving the water management system in the city of Breda and the surrounding catchment, three different interventions are proposed and analyzed in the following study: sewer mining, wastewater treatment plant effluent reuse and stormwater reuse. This paragraphs explain the different proposals and why they are considered. Following, the water options given by the interventions are shown.
This chapter is a literature review of current knowledge regarding the aforementioned interventions and their possible uses. The concepts from this literature review form the fundamentals used to design the strategy to improve the water management system in Breda.

The chapter first introduce each intervention aforementioned. For each intervention, it is explained its relevance in general terms and related to Breda's context. Following, it is introduced the possible reuse ends of the reclaimed water through the various interventions. These include: agriculture, aquifer recharge through injection wells or wetlands, and stream flow augmentation.

4.1 INTERVENTIONS

The interventions investigated in the study are wastewater treatment plant effluent reuse, stormwater reuse and sewer mining. Following which, its relevance in the Breda water management system is also discussed.

4.1.1 WASTEWATER TREATMENT PLANT EFFLUENT REUSE

Currently, in the municipality of Breda, the wastewater effluent is discharged in the Mark, for then flowing into the North Sea. Therefore, the effluent is dispersed into the aquatic environment. The current management of wastewater does not work in line with problem of drought in the region. The actual reuse of this resource increase the water portfolio of the location.

Freshwater is a limited and fragile resource that is necessary for life, development, and environmental preservation. With the ongoing population growth in the Netherlands [103], the need for water is growing too. In light of climate change and an increasing population, there is a need to find alternative sources of water [104].

In order to address water scarcity and decrease dependence on natural resources, several water utilities have implemented water reclamation (wastewater recycling and reuse) to supplement water supplies, particularly for non-potable applications [105] [104]. Potable water demand involves direct consumption or a high likelihood of direct consumption of the water by peoples. Water for sinks, showers, and dishwashers are among these demands. Non-potable water demand is those for end-users that do not entail direct human consumption and may be satisfied with non-potable water. For a region's long-term growth, future water resource programs must be planned in a reasonable and coordinated manner for all users [104].

The volume of wastewater reuse is determined by the availability of recovered wastewater as well as the demand for it. Normally, wastewater comes from two sources: (i) central wastewater treatment plants (i.e. WWTPs) or/and (ii) decentralized wastewater treatment facilities [106].

For the city of Breda, the treated wastewater suits a variety of application, such as agricultural and landscape irrigation, industrial operations, non-potable urban applications (i.g., toilet flushing, street cleaning, and firefighting), groundwater recharging, recreation, and direct or indirect water supply [107][108][109][110][111]. Modern wastewater treatment technology, which has come a long way in the last century, has assisted in its increased usage. Those techniques can now effectively remove pathogens, suspended solids and organic matter from the water [112], allowing the treated one to be used for a variety of purposes [113].

This strategy of adding value to treated wastewater allows the Breda water management system to become more adaptable to future boundary uncertainties (climate change, governance decisions, etc.). Decentralization of the supply system (reuse of wastewater), reduction of water demand (less water to be extracted from aquifers) and increasing water availability (recharge of aquifers), make the system more adaptable to future uncertainties.

4.1.2 STORMWATER REUSE

The increasing urbanization along with the increasingly impervious surface, such as pavements and rooftops, cause a lot of change to the characteristics of the catchment, which in turn affects the natural hydrological cycle of the area [114].

One of the main challenges for the future will be to improve the management of the water within the urban environment. Currently, in most cities (including Breda), large volumes of water fall onto roadways, rooftops, or simply run out to water bodies via stormwater drains. Furthermore, large amounts of water are only utilized once and then pumped out. Unmanaged stormwater can lead to two main problems. The first one is related to the volume and timing of runoff, which can cause flooding. Flooding occurs due to the rapid overwhelming of the drainage system by stormwater. The other issue is associated with water pollution: stormwater runoff collects natural and man-made pollutants that have settled on surfaces during dry days and carries them to water bodies (such as rivers, lakes, ocean) [115]. Since human activity differs depending on land use, the forms and quantities of pollutants in runoff are strongly connected to specific areas of concern [116].

Thus, stormwater management is essential in the urban environment [114], not only to face the previously mentioned problems, but also as a tool to generate reclaimed water. Over the last years, there has been a growing interest towards adopting water generated within the urban boundary as a resource that can be integrated together with other water sources. In this context, stormwater reuse has risen to prominence as a viable alternative to water supply particularly in the city of Breda.

Although popular in certain areas, stormwater reuse is not widespread yet, especially in Breda [65]. This is due to the fact that stormwater reuse poses a multitude of different problems. Since rainfall is not constant over time, it cannot be considered to be a reliable source [117] [118]. Therefore, it is essential to make water available during dry periods through suitable storage spaces. In addition, if subsurface conditions are suitable, another option is to store stormwater underground. Although, if geological conditions are unfavorable, expensive storage reservoirs are required[119].

This unpredictability character should be taken into account when planning and designing stormwater storage. Moreover, stormwater may also be extremely contaminated, perhaps even more so than secondary treated sewage, depending on its source [118]. As a result, it is critical to develop treatment techniques that are tailored to the intended purpose. When all of these factors are taken into account, the main challenge becomes guaranteeing supply dependability at a low cost when compared to alternative water delivery choices [119].

The notion of "water suited for purpose" should guide stormwater reuse [119]. This enables using water of varying quality depending on the desired application, while lowering water treatment expenses and saving treated water for direct consumption only.

The features of stormwater reuse systems vary a lot from project to project, but most of them contain the same aspects [120] [121] [122]:

- **Collection**: Stormwater collection is the process of channeling stormwater runoff into storage facilities. Generally there are two different ways to collect stormwater [123]. The first method is the traditional one, through drainage systems that transport stormwater to storage facilities, often with treatment at or just before the facility. Another approach to collect stormwater is to build additional facilities to move water from streams in an indirect way [123]. These structures might also function as stormwater storage before treatment. Weirs, for example, redirect flows into stormwater containment and contribute to a significant portion of a city's stormwater catchment, where it is then held for treatment and distribution later on. Stormwater collection is used for a variety of reasons, including urban runoff and flood control [120].

- **Storage**: To balance supply and demand, stormwater is temporarily stored in tanks. When it comes to storage, there are three things to consider: function, location, and capacity. The planner is in charge of determining how the stormwater will be used (e.g., irrigation, recreation, fire fighting, industrial water supply, etc.). A water tank near the end use of the water may be the optimum design in terms of system placement and storage. On-site, below-ground infiltration systems may be considered if the collecting system is designed to delay runoff and/or replenish an aquifer.The type of end use in a specific environment or time period will define the storage system's capacity (e.g., is important to store the volume needed to between peak supply and the highest demand). Moreover, there are also others factors to take into account as the variability of the stormwater quality (e.g, the first flush of a rainfall event result in high levels of pollutants discharged compared to the remaining stormwater), the health and environment values of watercourses which should be preserved and the recharge rate of aquifers and their holding capacity [120].

- **Treatment**: The most difficult aspect of stormwater collecting is stormwater treatment. The level of pathogens and contaminants to be screened and reduced is determined by the intended use. For example, for non-potable purposes only filtration and disinfection as part of the water treatment. Instead, for potable uses (therefore better quality) more steps and processes are needed to treat the water, such as screening, coagulation, disinfection and carbon adsorption [120].

- **Distribution**: Normally, there are two different kinds of stormwater distribution systems.

The first one regards the irrigation of open spaces. This application uses cleaned runoff to watering open spaces such as parks, green spaces, and so on [124]. Another type of distribution, meant for non-potable uses, is for things like toilet flushing, fire fighting or industrial purposes. This system might require extra infrastructure as another pipe network distribution [120].

Stormwater, as mentioned earlier, can be used for a variety of purposes. Mostly, the water is reused for non-potable applications, as it would require more treatment otherwise. The principal aims of water reuse can be distinguished between: residential uses, irrigation of green areas, industrial uses, recovery of aquifer and agriculture [125].

Stormwater in residential areas might be collected and used for a variety of aims, reducing water demand significantly. The sewer system of Breda, already present a separate sewer system, where stormwater is collected separately from wastewater. The collected stormwater then could be stored and reused for different purposes. Indoor usage is more likely to need a continuous supply of water, necessitating a backup water source.

4.1.3 SEWER MINING

Sewer mining is a lesser-known alternative in the toolkit of decentralized wastewater reuse technologies at a medium scale (local-to-neighbourhood) [126]. It is a technology originally initiated in Australia in order to supply non-potable water for urban purposes, such as irrigating in urban green areas, sporting facilities, and even for household applications. It is associated with mobile wastewater treatment units in containers that can treat and deliver reused water at the point of demand in dense urban environments [127] [126].

Sewer mining is gaining popularity as a result of its high-efficiency treatment technique and the little amount of area required for the implementation. It can be placed in situ due to its decentralized nature, bringing it closer to the circular economy concept [127]. Implementing in the rural area of Breda, would further augment the current water management system by reclaiming the wastewater before ending in the treatment plant. The quality of the water been reclaimed, can suit the local necessities of water demand.

The Membrane bioreactor (MBR) and the Reverse Osmosis (RO) unit are the two sub-units that make up the sewer-mining technology. Both are made up of separate packed modules that are linked together to form a small system that is easy to travel. In the membrane reactor, the circulation of the sludge flow balances out the biological solids surrounding the membranes in the MBR. This re-circulation stream is high in dissolved oxygen and delivers extra oxygen to the biological activities in the nitrification zone. This stream also averts sludge de-watering in the filter tank, as well as minimizing membrane fouling by lowering TSS loads at the membrane. The biomass concentration is regulated by the circulation rate, which should not exceed a certain limit [126].

Sewer mining capacity to re-integrate treated wastewater on-site not only increases local water circularity but also boosts the level of the system adaptability. The modular design of infrastructure is an important feature so that it can easily be added and expanded in response to demand, making the system more amenable to being changed [62].

Sewer mining systems can range in size from large to minor. A sewer mining system consists of the following components:

- a connection to the sewer to extract wastewater;
- a system of pipes that transports wastewater from the place of collection to the treatment facility;
- a wastewater treatment facility that generates reclaimed water that is appropriate and safe for the purposes for which it is intended;
- a system to handle the by-products generated by the sewer mining operations [128].

4.2 WATER APPLICATION OPTIONS

Following, a list of four different options to reuse water are presented. These alternatives fit the local necessities, geographical terrain and demand of water.

4.2.1 AGRICULTURE

The reuse of water has been practiced by humans for a very long time, with a multitude of uses. However, by far, agriculture has been the most dominant end use application till now [129]. Usually treated wastewater is being used, since it provides several benefits for the environment and economy.

The resulting reduction in pressure on freshwater sources is one of the most well-known benefits of wastewater usage in agriculture. As a result, wastewater can be used as an alternate irrigation supply [130]. Furthermore, the nutrients typically contained in wastewater allow for fertilizer cost savings, resulting in a closed and environmentally friendly nutrient cycle that prevents the indirect return of macro- (particularly nitrogen and phosphorus) and micro-elements to water bodies. Wastewater may contains source of macro-nutrients (N, P, and K) as well as micro-nutrients (Ca, Mg, B, Mg, Fe, Mn, or Zn) [131]. In fact, wastewater reuse has been shown to increase crop yield and reduce fertilization processes [130] [132] [133]. Especially, for the Brabant region, characterized by a poor quality soil type, with scarce nutrients, the reuse of wastewater will be beneficial. Moreover, wastewater effluent is a reliable and consistent resource over time.

Nonetheless, because of the high potential for health risks and soil pollution, wastewater must be properly treated before being used for agricultural irrigation [134].

Another potential resource to use in agriculture is stormwater. Even if stormwater reuse has become popular in some regions on a modest scale, it is still not a common phenomenon worldwide. As defined before, stormwater is the runoff of rainfall event on the catchment surface, and the quality of the water depends on anthropogenic activities found in the catchment [135]. Additionally, stormwater quality is highly dependent on the local weather and rainfall occurrences. As a result, fluctuation in the quantity and quality of the incoming water is one of the major issues in stormwater treatment and harvesting. Nonetheless, previously statistics might be used as a guide to highlight the spectrum of physico-chemical characteristics and elements found in stormwater [135]. The most common sources of natural pollutants in stormwater are vegetation debris and roadside soils, which also include suspended solids, metals, nutrients, organic matter, and microbes [116].

Since there is a separate sewage system in the city of Breda, rainwater is directly discharged into the canals. Therefore, primary and secondary treatment of the water is necessary in order to be reused.

Therefore, it is important to define what the minimum quality requirements are for wastewater and stormwater to be reclaimed for irrigation purposes. Different guidelines have been drawn over the years and updated several times on the minimum requirements. The most popular and the ones used most by different countries as guidelines are the one from WHO [136], FAO [137] and EPA [138] [134].

Tab.11 shows the parameters and their limits, suggested by the three aforementioned guidelines.

Table 11: Water reuse limit values for agriculture [139] [136][137][138][134] [140]: stormwater [141] and wastewater treatment effluent [65] compered.

Parameters	WWTP Effluent (mg/l)	Stormwater (mg/l)	Agriculture parameters (mg/l)
COD	33.4	32	-
BOD	4.06	5.7	<10
TSS	7.38	17	<10
TDS	632.96	-	450-2000
NH_4	2.18	-	-
NO_2	0.25	-	-
NO_3	7.26	-	-
N-TOT	11.3	2.2	-
PO_4	1.61	-	-
P-TOT	1.73	0.4	-
Cl	18.3	18.3	100
K	0.0002	-	-
Mg	7	-	-
Na	-	-	-
Ca	-	-	-
As	0.0014	-	0.1
Cd	0	0.0003	0.01
Cu	0.00889	0.019	0.002
Cr	0.0007	0.0062	0.1
Hg	0.0000	0.00005	0.001
Ni	0.004	0.0056	0.2
Pb	0.00028	0.018	0.01
Zn	0.0237	0.102	2
Coliform (cfu/100ml)	-	1900	<10(cfu)

4.2.2 AQUIFER RECHARGE: INJECTION WELLS

The growing gap between freshwater demand and supply in many parts of the world has resulted in a plethora of novel ways to make use of the limited water resources available. The problem is to produce enough high-quality water for the desired application. Water shortage is promoting the use of a variety of unconventional water sources, some of which may include chemical and microbiological pollutants, endangering human health [142].

The deliberate practice of recharging water into aquifers for future recovery or environmental applications is known as managed aquifer recharge (MAR) [143]. MAR is an artificial way of replenishing groundwater, as opposed to natural aquifer recharge techniques, in which aquifers are supplied by rain or stream-bank infiltration. It is recognized as a cutting-edge technique for enhancing water quality and storing water in a combined nature-based solution, in which the aquifers contribute as an ecosystem service. Surface spreading, injection wells, sprinkling, and groundwater conservation facilities are all methods of artificially refilling aquifers. MAR features comprehend storage (avoid evaporation, protection against algal blooms), purification (removal of pathogens and micro-pollutants) and preserving groundwater table [142].
Through MAR, aquifers can be recovered using treated municipal wastewater. However, the physical, chemical, and microbiological quality of the water determines whether or not it is suitable for MAR. Water quality is an important consideration, and will be guided not only by the end purpose but also by environmental water quality standards. As such, additional treatment will likely be required for reclaimed water. A risk-based assessment is necessary in order to evaluate the safety of the water [142].

In 2017, near the city of Breda, in Dinteloord, MAR provided a solution to the mismatch between the production of irrigation water and the demand for a 220 ha "high-tech greenhouse" [142]. Fresh groundwater was scarce, and river flows were already on a critical level, thus securing a consistent and sustainable freshwater supply for the peak months of demand (April–August) was a major issue for the greenhouse cluster's growth. Nearby the greenhouse there was a sugar factory, which processed sugar beets in order to produce sugar during the harvesting season (September-January). Normally, the wastewater produced by the factory (1 Mm^3/yr) was treated before being discharged into River Dintel [101]. One third of the factory's wastewater (0.3 Mm^3/yr) was further treated (ultrafiltration and reverse osmosis), and then redirected towards the greenhouse during periods of highest water demand. The first plan was to store the water in an open basins, nonetheless, since it was an unprotected open area, there were some issues regarding water quality preservation for long-term storage due to evaporation, atmospheric deposition, bird and unauthorized people interactions. MAR presented a solution in the shape of ASR (Aquifer Storage Recovery), which could be simply applied on unexploited land surfaces in the area's biological zone [101] [142].

The infiltrated freshwater stayed at a stable position close to the ASR well, as evidenced by the effective recovery of the infiltrated water with negligible admixture of brackish groundwater. Calcite dissolution and pyrite oxidation were observed to alter the quality of the water, resulting in a little but reasonable rise in Ca, Mg, HCO_3, SO_4, Fe, and Mn, according to water assessments. During the analysis, no hazardous viruses or bacteria were found [142] [101].

Nonetheless, stormwater may also be a possibility as a resource. Increasing rainfall patterns offer new possibilities for stormwater-based MAR projects. Distributed stormwater collection (DSC)-MAR projects focus on collecting excess runoff during storms before it reaches a stream.

Several research shows that precipitation severity has increased during the previous century [144] [145] [146] [147]. Greater precipitation generates higher runoff, which results in less infiltration and recharging. Moreover, increased runoff and decreased recharge are additional consequences of extreme urbanization, posing stormwater management challenges [148][149]. Excess runoff can be collected and infiltrated to assist reduce floods and bring groundwater basins back into equilibrium.

These type projects pose two problems of different types. First, stormwater quality is well known for its stochastic nature and often urban models fail to explain its own nature [150]. Accordingly, it is difficult to determine what kind of treatment is needed. There is a risk of over-structuring the treatment plant in order to face the "worst" stormwater in terms of quality. Therefore, a cost-benefit analysis, both economically and environmentally, could be disadvantageous. Secondly, stormwater, unlike wastewater, does not have a distinct rhythm. However, based on historical data and numerical analysis of past events it is possible to at least have an estimation of future rainfall. Nonetheless, if on one hand, according to climate forecast, global warming would lead to more intense and extreme weather events, on the other hands, little is known about when and how global warming would impact the predictability of the atmosphere, and therefore our ability to provide reliable weather predictions [8] [9].

Table 12: Water reuse limit values for aquifer recharge [101]:stormwater [141] and wastewater treatment effluent [65] compared

Parameters	WWTP Effluent (mg/l)	Stormwater (mg/l)	Groundwater parameters (mg/l)
COD	33.4	32	-
BOD	4.06	5.7	-
TSS	7.38	17	-
TDS	632.96	-	568
TKN	3.84	1.9	-
NH_4	2.18	-	1.9
NO_2	0.25	-	-
NO_3	7.26	-	3
N-TOT	11.3	2.2	-
PO_4	1.61	-	1
P-TOT	1.73	0.4	-
Cl	18.3	18.3	32
K	0.0002	-	3.5
Mg	7	-	10
Na	-	-	41
Ca	-	-	100
As	0.0014	-	0.0069
Cd	0	0.0003	-
Cu	0.00889	0.019	-
Cr	0.0007	0.0062	-
Hg	0.0000	0.00005	-
Ni	0.004	0.0056	0.2
Pb	0.00028	0.018	-
Zn	0.0237	0.102	-
Coliform (cfu/100ml)	-	1900	-

4.2.3 AQUIFER RECHARGE: WETLANDS

Another solution to be able to recharge the aquifers, in a more "natural" way are wetlands. Wetlands are areas of marsh, fen, peat-land, or water, permanent or temporary, with static or flowing water, fresh, brackish, or salty. Wetlands can be either natural or man-made infrastructures that receive, transport, clean and store water. The functions of a wetland are many, including: living matter development, increment biodiversity, recreational activities, groundwater replenishment, water purification and flooding control [151] [152]. Not all wetlands perform all functions, and they do not all execute them effectively. The functions of a wetland is determined by its geographic location and size [153].

The study focuses on wetlands as a means to clean the inflow and recharge aquifer. In the Netherlands, the application of wetlands is common, for water purification and retention.

The principal hydrological regulating function of wetlands is groundwater recharging. Groundwater recharge refers to the movement of surface water down through the soil into the zone in which permeable rocks and overlying soil are saturated [154]. Groundwater exchange is significant in wetlands that are connected to groundwater systems or aquifers. They hold water, allowing infiltration to take place over time. As a result, wetlands aid in maintaining the water table's level and exerting control over the hydraulic head. Groundwater recharging and outflow to other bodies of water are both benefited by this [155]. Soil, vegetation, location, volume ratio and water table gradient all influence the amount of aquifer recharged by a wetland. Mineral soils, which are usually located near the boundaries of wetlands, serve as a source of groundwater recharge. Small wetlands with a high perimeter to volume ratio have a large surface area via which water can penetrate into the groundwater [152]. Tiny wetlands as prairie potholes help to replenish groundwater supply considerably.

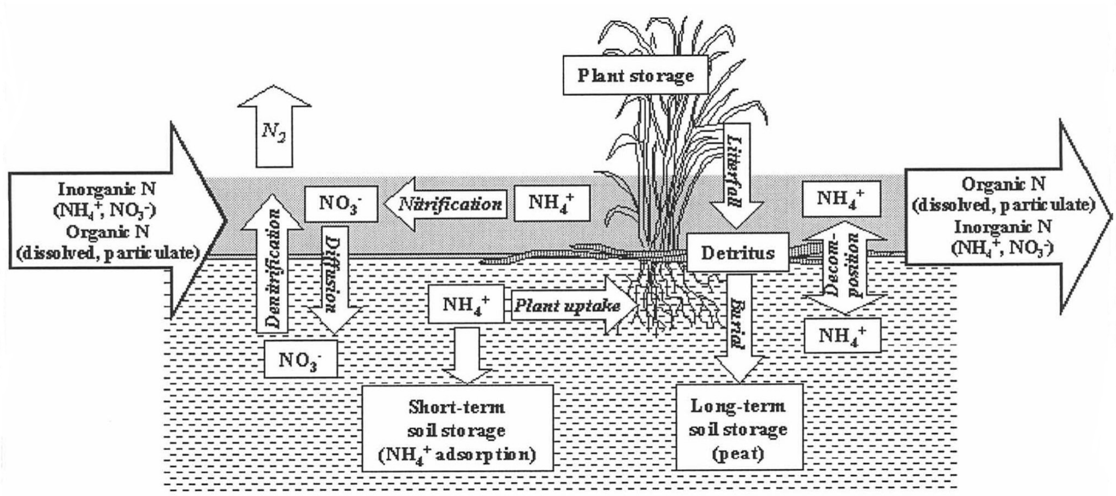


Figure 13: Nitrification cycle in a constructed wetland [156].

If, in the case of injection wells, both wastewater treatment plant effluent and stormwater have to be treated, one for high TDS, NH_4, NO_3 and PO_4 values and the other for high Coliform content (see Tab.12), in this case wetlands can ensure that the water infiltrated into the soil complies with minimum standards required through biological treatment of the entering water. Through the nitrogen cycle, incoming nitrogen is removed through chemical and biological processes [157] (removal rate depends on the type of wetland). Organic nitrogen N is split into smaller organic molecules, both particulate and dissolved. Ammonium (NH_4^+) is either absorbed by the microbe as a nutrient or dissipates back into the ground or water. Therefore, in the aerobic substrate of the wetland (typically localized to the surface water) Nitrosomonas bacteria convert inorganic N (NH_4^+) to nitrite (NO_2^-) first, and then to nitrate (NO_3^-) via Nitrobacter bacteria. Thus, in the anaerobic region of the wetland, normally below the soil surface, denitrification occurs through microbial conversion of nitrate to nitrogen gas (N_2), which is released to the atmosphere [156] [152].

Phosphorus is removed in wetlands through plants and soil microbes, adsorption process by iron oxides and aluminum, precipitation of aluminum and calcium phosphates, and sedimentation of phosphorus adsorbed by organic matter [158]. However, following plant decomposition and cell death, phosphorus is released again into the system [158].

Coliform and bacteria are attached to suspended solids that, after entering the wetland, they remain trapped in the vegetation. Soon after they die due to degradation by sunlight, low pH, protozoan consumption and by toxins secreted by some plants' roots. Wetlands play a significant role in eliminating pathogens from water in this way [157].

4.2.4 STREAMFLOW AUGMENTATION

The past three years of drought in the Netherlands and recent climate change due to anthropogenic activities have destabilized rivers, among other things. Water withdrawals can exacerbate the consequences of seasonal drought, especially when they occur during periods of naturally low flow [159]. The average winter flows in the Netherlands' major rivers have risen, while the average summer discharges have decreased [160]. During the past 3 summers (2018-20) the discharge and base flow of the rivers in the country has declined [161].

The fact that there is less water in the rivers is a problem, not only because the rivers provide water for farmers, but also the watershed biodiversity and ecosystems. As mentioned in section 3.3, the Mark and the Aa of Weerijs flow through Breda, coming from the Belgium boarder. These rivers drying, especially during drought, have devastating effects for people and the environment, including reduced water for agriculture, loss of river transportation corridors, degradation of ecosystem impacting biotic living and abiotic factors, as aquatic habitat for fish and other organisms among others [162][65]. The aim of augmentation is to achieve a benefit, such as improved aesthetics or aquatic or riparian habitat. River flow augmentation may be a cost-effective way to ensure water quality while also providing additional advantages. The additional water will benefit the overall quality of the water of the waterbody and will help to mitigate the effects of low flow drought conditions. Flow augmentation may be necessary to sustain stream flows, improve aquatic and animal habitat, and preserve the aesthetic value of waterways [138].

Historically, wastewater has been handled to satisfy legal standards before being released into a surrounding river, lake, or ocean. An increasing number of wastewater treatment plants increased their standards in order to match quality parameters to recycle water for other applications. Treated wastewater for stream flow augmentation, with the appropriate timed flow, has the potential to enhance stream habitat while also increasing potable water supplies [163] [164]. As mentioned before, this resource is reliable and constant over time, and can implement the local water supply portfolio.

Obviously, to be able to reuse wastewater as a source for replenishment of the river, it is essential to ensure that the recycled water meets the quality parameters, therefore it will not affect the ecosystem in a negative way.

Table 13: Water reuse limit values for streamflow augmentation [162] [165][166]: stormwater [141] and wastewater treatment effluent [65] compared

Parameters	WWTP Effluent (mg/l)	Stormwater (mg/l)	River parameters (mg/l)
COD	33.4	32	-
BOD	4.06	5.7	<20
TSS	7.38	17	<20
TDS	632.96	-	450-2000
TKN	3.84	1.9	-
NH_4	2.18	-	1.9
NO_2	0.25	-	-
NO_3	7.26	-	<3
N-TOT	11.3	2.2	-
PO_4	1.61	-	0.1
P-TOT	1.73	0.4	-
Cl	18.3	18.3	32
K	0.0002	-	3.5
Mg	7	-	10
Na	-	-	41
Ca	-	-	100
As	0.0014	-	0.0069
Cd	0	0.0003	-
Cu	0.00889	0.019	-
Cr	0.0007	0.0062	-
Hg	0.0000	0.00005	-
Ni	0.004	0.0056	0.2
Pb	0.00028	0.018	-
Zn	0.0237	0.102	-
Coliform (cfu/100ml)	-	1900	-

5 PROPOSED STRATEGIES

This chapter explains the various procedures that led to the formulation of the various strategies to be able to increase the circularity and adaptability of the water system in order to mitigate the water management problems in the area of Breda. A workshop was organised with local expertise from both the water board and the drinking water company "Brabant Water", and a single interview was scheduled with an expert on groundwater from TU Delft University. In the different meetings, dichotomous solutions have been presented as a starting point for a discussion on how these proposals can be developed in a real scenario.

The chapter outlines the two strategies that were presented at the workshop and in the interview. Each strategy details, and the different interventions employed, are explained. The study investigates how the interventions are implemented in a real scenario, their feasibility and which are the costs and the expensive. Through the different frameworks, the study examines how the water system has shifted as a result of the system's new water management. Then, based on the interview and the workshop, the two strategies presented thus far are re-evaluated and analysed, exposing limitations and inaccuracies.

The two strategies both employ sewer mining in the same way, but stormwater and wastewater are reclaimed in different ways. These differences, which are explained in the following sections, concern the type of use for wastewater effluent (to enhance river's flow or as irrigation water) and for stormwater the technique (in both cases to recharge the aquifers, first with wetlands then with injection wells). These distinctions bring diverse benefits and consequences, which were discussed in the workshop and interview.

Tab. shows the comparison of the 2 strategies, while an overall summary summary of the two strategies is presented in Tab.15 and 16.

Table 14: Comparison between strategy 1 and 2.

Intervention	Strategy 1	Strategy 2
Wastewater treatment plant effluent reuse	River enhancement	Agriculture irrigation
Stormwater reuse	Wetlands	Injection wells
Sewer mining	Applied in the rural area to reclaim wastewater produce locally	Applied in the rural area to reclaim wastewater produce locally

Table 15: Strategy 1 interventions.

Intervention	Use	Volume	Location	Technicalities	Treatment
Wastewater treatment plant effluent reuse	Enhancement river(s) flow	2110 m^3/hr	Upstream of the river, at the border with Belgium	Wastewater pumped through a pipe	Nitrification and denitrification
Stormwater reuse	Recharge aquifers	830 m^3/hr	Municipality of Breda	Redirect stormwater collected through separate sewer to wetlands	UV treatment
Sewer mining	Reclaim wastewater	8 m^3/hr	Rural area of the municipality of Breda	Collect and treat wastewater from the sewage	-

Table 16: Strategy 2 interventions.

Intervention	Use	Volume	Location	Technicalities	Treatment
Wastewater treatment plant effluent reuse	Irrigation water	2110 m^3/hr	South Brabant, below Breda's municipality	Wastewater pumped through a pipe	-
Stormwater reuse	Recharge aquifers	400 m^3/hr (first 4 months of the year)	South Brabant, below Breda's municipality	Collect stormwater with tanks and pump to ASR location. Then stormwater pumped to groundwater with injection wells.	UV treatment
Sewer mining	Reclaim wastewater	8 m^3/hr	Rural area of the municipality of Breda	Collect and treat wastewater from the sewage	-

5.1 WASTEWATER TREATMENT PLANT EFFLUENT REUSE

Wastewater treatment plant effluent, for both strategies, is redirected to the south of the municipality through a pipe. In the first strategy, wastewater is employed to enhance the river(s) stream flow. In the second strategy, wastewater is adopted as irrigation water for agricultural land.

5.1.1 STRATEGY 1: RIVER ENHANCEMENT

Wastewater is a feasible resource for stream augmentation. Both the Boven Mark and the Aa of Weerijs during the summer of 2020 had a very "low flow" rate [65], respectively reaching minimum flow rates of 0.15 m^3/s and 0.05 m^3/s and an average discharge for the period which goes from April to September of 0.70 m^3/s and 0.37 m^3/s. The measurements of the river's flow have been taken in Oranjeboombrug for the Aa of Weerijs, while for Bovenmark in Duivelsbrug. With the introduction of wastewater treatment plant effluent into the river (for a maximum of 6800 m^3/hr), an increase of stream flow rate occurs.

From Fig.14 and Fig.15 it would seem that nothing significantly has changed from the initial flow rates. Yet, if one zooms into the preceding graphs and compares them, it can be seen that, especially during the driest periods, the amount of wastewater was significant for the increased flow rate. Fig.16 shows the new flow rate for each river if the wastewater effluent would be reused for river enhancement.

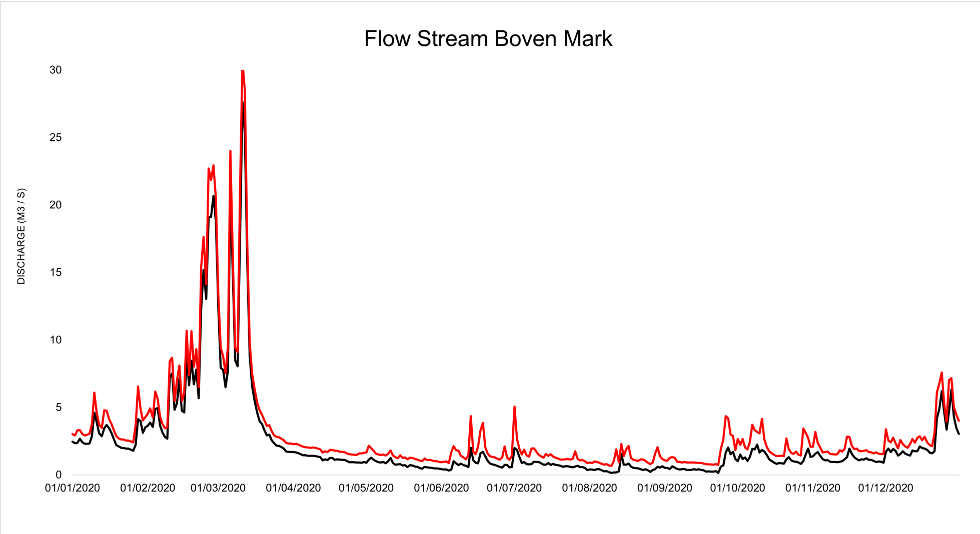


Figure 14: Boven Mark flowrate. In black flowrate of 2020, in red river flowrate increased by wastewater effluent [65].

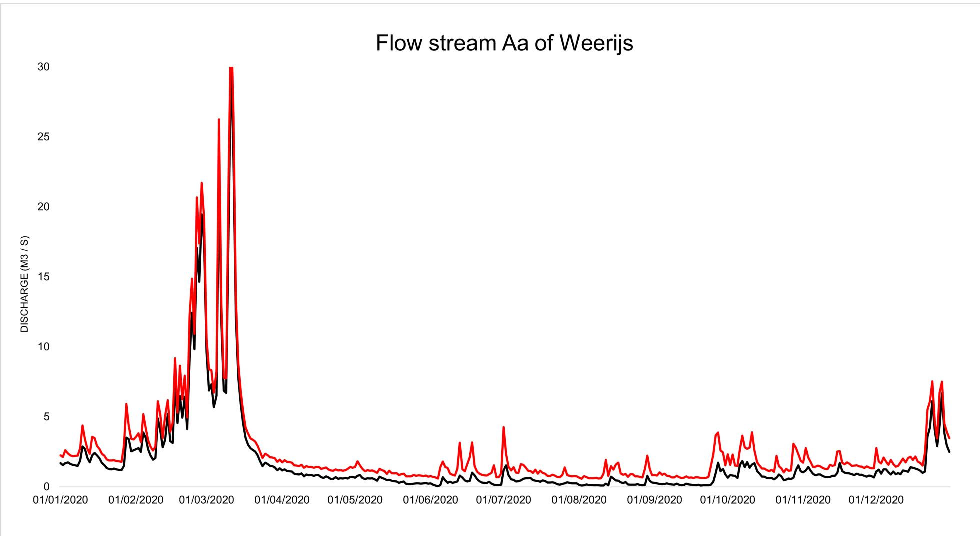
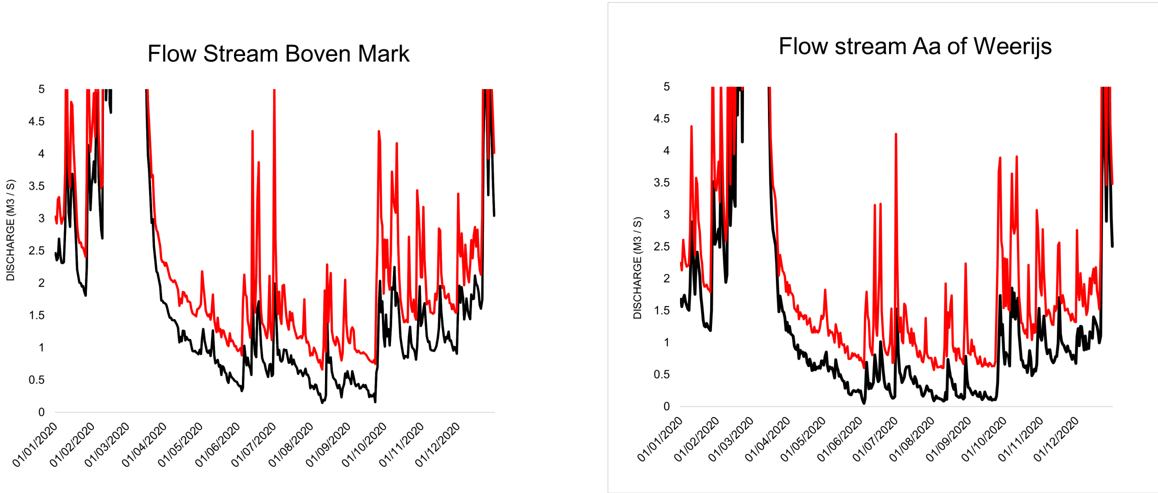


Figure 15: Aa of Weerijs flowrate. In black flowrate of 2020, in red river flowrate increased by wastewater effluent [65].



(a) Boven Mark. (b) Aa of Weerijs.

Figure 16: A zoom on both the Boven Mark and the Aa of Weerijs before and after adding wastewater effluent reuse.

The distance as the crow flies from the wastewater treatment plant to the beginning of the rivers is approximately 10 km. Not having detailed information about the sewer and pipe system below the surface, and not knowing which path the effluent could flow to get upstream of the watercourse, it was decided to consider a distance of 15 km from the treatment plant to the area of interest for reuse.
In order to be able to transport water from point A to point B it was considered to build a pipe. A minimum velocity of 0.3 m/s has to be ensured, at least one hour per day, to avoid any problem to the network. In fact, low velocities enhance the process of sedimentation and accumulation of discrete particles. These sediments can be a source for biofilm formation that results in a determinant element for re-growing and other bacteriological effects. Therefore, for longer residence times, there is a substantial increase in bacteria and chemical reactions. By managing to set a minimum speed at least once a day per pipe, it is possible to avoid most problems. Higher velocity, on the other hand, can accelerate corrosion if the pipe is made of concrete. At bends and turns, fast moving water might damage the system and lead to pitting and other problems. Thus, an upper limit of 2.5 m/s was settled.

Based on the the distribution of wastewater treatment plant effluent showed in Fig.17, values greater than 6700 m^3/hr falls within three standard deviations of the mean, which it means that its occurrence is around 2.34 %. Then, a pipe's diameter of 1050 mm is calculated based on an average flow of 2932 m^3/hr, for a maximum of 6700 m^3/hr. The average velocity settled is 1.2 m/s.

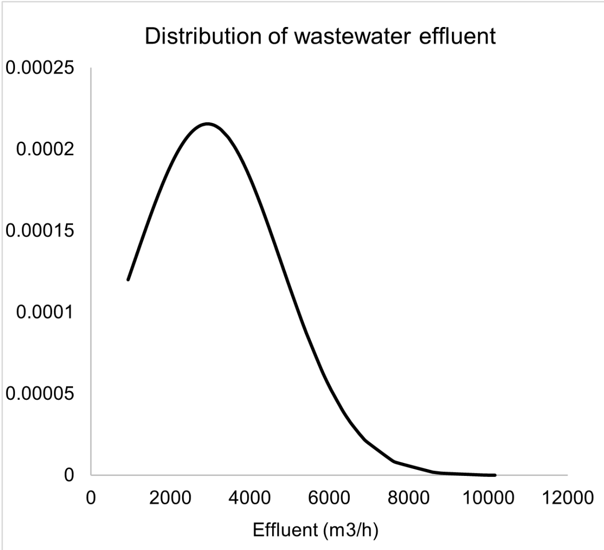


Figure 17: Distribution of Wastewater treatment plant effluent 2020.

It is advisable, through a monitoring and control system, to ensure that in case the flow is greater than the maximum designed flow that the pipe can handle, the control system blocks the excess flow at the inlet and discharge it to the north in the receiving rivers.

In order to transport water from the north to the south, in the basin of the two rivers, it is necessary to install one or more pumping stations. Four pumps with the capacity of 2500 m^3/hr were installed. The different pumps are dispose in parallel. The benefit of a parallel system is to be able to provide greater flow at the same pressure. One pump is needed for normal use, and for maximum discharge three in full operation and one pump not at full power. It is also necessary to underline that having multiple pumps, allows to make up for the lack of one in case of maintenance or malfunction.

As discussed in the previous chapter, treated wastewater does not meet all the parameters to be released into water body areas such as rivers (see Tab.13). In order to meet the required level of nutrients, the wastewater treatment plant should be implemented with a higher capacity to remove both nitrogen and phosphorus.

For each type of proposed intervention, a financial assessment of the investment and maintenance cost is made. For the aforementioned intervention, CapEx and OpEx are shown in Tab.17.

Table 17: CapEx and OpEx for reuse of wastewater treatment plant effluent for river enhancement.

	Nitr/Denitr [167]	P removal [168]	Pipe [169] [170]	Pumping stations [171]
CapEx (€)	6,851,974	7,837,911	7,837,911	9,802,536
OpEx (€/year)	139,836	881,663	45,000	310,812

5.1.2 STRATEGY 2: AGRICULTURE IRRIGATION

For strategy 2, instead of reusing wastewater to enhance the river(s), the flow is directed towards the south of Brabant as irrigation water.

Unfortunately, there is no data on water consumption and its distribution in the area. One could refer to the approach used earlier to calculate the water demand for the city of Breda (paragraph 3.6.1). However, if the percentages of water consumption (Tab.9) can be indicative for the municipality - since Breda is highly urbanised - the same cannot be said for the area in question, where 5.6% certainly does not represent water consumption by the agricultural sector.
Therefore, in this case, the reuse of treated wastewater by the agronomic sector is not based on the desired daily and seasonal needs of water, but designed on the limiting case where all the water discharged from the treatment plant can be used for the irrigation of the fields.

Hence, the reuse of wastewater involves almost all of the water discharged by the treatment plant. The average wastewater treatment plant effluent is 2110 m^3/hr over the year. The designed pipe of 1050 mm works for minimum flow registered 929 m^3/hr to a maximum of 6800 m^3/h. The distance as the crow flies from the wastewater treatment plant to the "ideal" center of the catchment is 10 km [75], where it is conceived that then the water can be transported and distributed to the different farmers who require it. As before, twelve pumps are employed to transport the water.

Treated wastewater is excellent for agriculture, since it contains a variety of macro nutrients such as nitrogen, phosphorus. potassium, micronutrients, calcium, magnesium, boron and so on [134]. If in the previous case the water had to be treated for an excess of nutrients, in this case the nutrients under consideration are useful for the soil. For this reason, the effluent does not need to be treated again.

The cost of the installation and the maintenance are shown in Tab.18.

Table 18: CapEx and OpEx for reuse of wastewater treatment plant effluent agriculture irrigation.

	Pipe [169] [170]	Pumping stations [171]
CapEx (€)	4,944,572	9,802,536
OpEx (€/year)	45,000	310,812

5.2 STORMWATER REUSE

In both cases, the reuse of stormwater is employed to recharge the aquifers. However, the first strategy employs wetlands to let stormwater infiltrate underground, while the second strategy adopts injection wells.

5.2.1 STRATEGY 1: WETLANDS

Stormwater is an optimal resource for recharging aquifers. For strategy 1, wetlands are employed to collect stormwater to recharge the aquifers.

As explained in paragraph 3.6.5, stormwater is not all discharged directly into the sewer system and then to the treatment plant, but - depending on the area - stormwater might get discharged through a separate sewer system, directly into the canals or water bodies. In this way, stormwater is already collected through the network and just needs to be redirected towards the wetlands. Two different wetlands - one for the rural area and one for the urban one - are suggested in order to accumulate stormwater and through infiltration recharge aquifers. The choice to divide between rural and urban areas is driven by the need to simplify the sewer network, about which there is not much available information. Obviously, the distinction may be insufficient to have a clear and coincident idea of the interaction between rainfall events and urban infrastructure. Nevertheless, this simplification is useful in order to provide a clear picture of the quantity of these flows and where they are located.

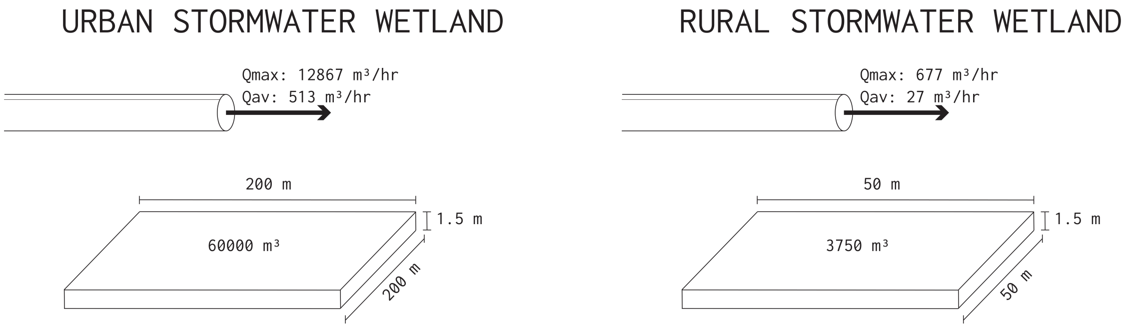
To design a wetland, it is essential to know the infiltration capacity of the sandy soil found in the North Brabant region (paragraph 3.3). The infiltration rate for a sandy loam soil is 25 mm/hr [172].

The first wetland is set close to the extraction point in Dorst, where every year 10.5 Mm^3 of freshwater are extracted (Fig.18). The stormwater accumulated comes from the urbanized part of the municipality. The wetland is designed to have a volume of 33000 m^3, with a length and width of 200 m and a depth of 2 m. The dimensions are designed such that, with the rate of soil infiltration and the inflow rate of average 513 m^3/hr and a maximum of 12'867 m^3/hr, guarantees continuous infiltration without reaching flooding events. Fig.19 (a) shows the draft of the urban wetland.

(a) Urban wetland. (b) Rural wetland.

Figure 18: Wetlands location.

The second wetland collects all the stormwater coming from the rural area. The stormwater flow generated by the rural geographical zone is way less than the one produced in the urban area. The strong concreting process of the downtown prevents water from percolating underground, generating larger volumes of water. Conversely, in less concrete-covered areas, rainwater runs down into the subsoil in greater quantities, directly recharging groundwater. The stormwater enters the wetland with an average flow rate of 27 m^3/hr and a maximum of 677 m^3/hr. For a volume of 625 m^3, the width and length are both 50 m and the depth 1.5 m. Fig.19 (a) shows the draft of the rural wetland. The wetland is located close to Ginneken, where every year 0.4 Mm^3 of freshwater are extracted (Fig.18).



(a) Urban stormwater wetland. (b) Rural stormwater wetland.

Figure 19: Wetland design, recharged with stormwater.

As a matter of fact, stormwater has a level of nitrogen, phosphorus, TDS and coliform that exceeds the parameters for water reuse to recharge groundwater (see Tab.12). However, the values for nitrogen, phosphorus and TDS slightly exceed the required limits, so its treatment can be neglected as the wetland itself succeeds in reducing some of these nutrients. On the other hand, when it comes to coliforms, a very high concentration is detected in the water, around 1900 colony-forming units (cfu) in 100 ml of water. In order to be able to process the stormwater before it is released into the subsurface and do not contaminate freshwater, either the very function of wetland treatment can be employed or a specific treatment unit can be chosen for the in-flowing water. For this intervention was chosen to proceed with a UV treatment unit.

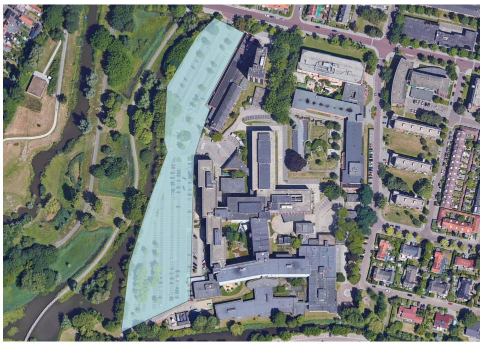
Compared to previous wastewater management costs, wetlands have a lower cost in terms of investment and maintenance. Tab.19 below shows the costs for the two wetlands and the two UV systems for treating the Coliform present in the water.

Table 19: CapEx and OpEx for stormwater reuse intervention with wetlands.

	Wetland urban [173]	Wetland rural [173]	UV treat urban [174][175]	UV treat rural [174][175]
CapEx (€)	20,850	9,496	68,712	34,356
OpEx (€/year)	1,474	630	3,637	2,425

5.2.2 STRATEGY 2: INJECTION WELLS

Instead of discharging stormwater into the canals, it is redirected to recharge a groundwater aquifer in the rural part (south of Breda) where agriculture necessitates water. Three ASR (Artificial Storage Recovery) are projected. Each ASR is designed to have a storage volume of 230,000 m^3 [142]. Stormwater is collected during the first fourth months of the year. As shown in paragraph 3, the winter months present a condition of better water balance, while during summer and late spring, as rainfall events decrease and temperatures increase, there is less water available. However, stormwater is not always available, as rain events do not occur constantly and with the same intensity. Hence, in order to be able to carry enough volume of water during the winter months to fill the aquifers a possible solution may be a tank. There are two possible solutions on where to deploy the tank. The first would be to install one (or more) in the area where the stormwater is produced - so in the residential center - and then pump it constantly towards the place of interest, where then through the injection wells stormwater is pumped into the aquifers. The other option would be to install the tanks in the ASR project work area, and pump all water to the tank location. Both options have disadvantages and advantages. The problem with the first proposal would be installing massive tank(s) in the downtown area, and whether it is underground or not, it would take up a lot of space and be an aggressive intervention for the city's urban planning. On the other hand, if stormwater would be transported to the area of interest, and then accumulated for the dry days, it would imply building a pipe in order to transport water volumes in the order of magnitude of 10000 m^3/h, thus conveying all the stormwater accumulated during peak rainfall hours.



(a) Urban tank of 60,000 m^3.

(b) Urban tank of 10,000 m^3.

Figure 20: Tanks location.

Considering the two possible scenarios, it has been considered to install two volume tanks, one for each area - rural and urban - of respective sizes of 60,000 and 10,000 m^3 (Fig.20). In this way, it would be possible to channel enough stormwater in the first months of the year to then transport it, with a flow rate of 350 m^3/h from the tank located in the urban area and 50 m^3/h in the rural one. During rainy periods, stormwater is first collected by the sewer system and then pumped into the tank of interest. Then, the stormwater accumulated in the tank is pumped to the ASR area. If the tank is drained, the process of injecting water is stopped, while waiting for the next rain event to recharge the tank. There should be no problems with water stagnation, as there would be a constant volume of water flowing in and out. However, the tank would be subject to maintenance and overhaul whenever it becomes empty.
Based on 2020 data, this approach recharged three 230,000 m^3 artificial storage tanks. Obviously, the data of the year under consideration cannot be taken as reference for the next

future. However, the two tanks are useful to solve the problem of occurrence of the raining phenomenon. Obviously, since it is not known how the water is accumulated in the city and where it flows to, the tanks may not be optimal as a tool to capture and store stormwater. Nevertheless, the simplification made, allows one to have an idea of a potential measure to perform.

To transport the water accumulated in the city to the ASR area, an average line-of-sight distance of 8 km was established based on the maps (Fig.21). As mentioned before, two different pipes from the respective tank are designed in order to transport stormwater. Each pipe has a length of 8 km, of 315 mm and 125 mm are transporting stormwater.

(a) Tanks location.

(b) Pipelines from tanks to ASR area.

Figure 21: Reuse stormwater project.

Two pumping stations are needed to deliver stormwater from the tanks to the injection wells area. Since the flow rates are low, one small size pumping station, with a capacity of 50 L/s is employed for the tank located in the rural area, while a bigger one with a capacity range from 50 to 200 L/s is used for the urban one. No pump station is needed to transport stormwater to the tanks, as those are placed underground, and ideally the wastewater collection system could convey the water directly to the underground storage.

Based on the threshold values allowed for injecting water into soil (Tab.12), without affecting fresh water, the coming stormwater needs to be treated due to high concentration of coliform present. As a result, the stormwater is first collected in the municipality of Breda and after being transported, it is treated by an UV treatment plant.

For the following strategy, the CapEx and OpEx are shown in the following Tab.20.

Table 20: CapEx and OpEx for reuse of stormwater intervention with injection wells.

	UV Treat [174][175]	Pipeline (315mm) [176][170]	Pipeline (125mm) [176][170]	Pump stat rural [171]	Pump stat urban [171]	Tank (60,000 m^3) [177]	Tank (10,000 m^3) [177]	3 ASR proj [101]
CapEx (€)	659,428	266,197	45,353	325,704	462,667	1,848,000	308,000	5,265,000
OpEx (€/year)	15,826	5,000	5,000	10,021	13,362	36,960	6,160	419,760

5.3 SEWER MINING: STRATEGIES 1 AND 2

While for the other two interventions, there was a different type of use for stormwater and wastewater, for sewer mining it was decided to apply the intervention in the same way for both strategy 1 and 2.

As mentioned in paragraph 4.1.3, the water reclaimed through sewer mining can be used only for a limited range of possibilities. The main applications are for irrigation (which can be either agriculture but also sport facilities, green areas, etc.) and household applications. It could also find other usage as stream flow augmentation or aquifer recharge.

For both strategies, two sewer mining units with treatment capacity of 100 m^3/d, featuring dual membrane and UV disinfection, are installed in the rural area to satisfy the agricultural water demand in the area. The rural area was chosen as the preferred area for the installation of the two units, as the land use for agricultural activities is more likely to happen in the suburban area than in the city center, where asphalt and urbanization are predominant. Based on the data given and already explained previously in chapter 3.6.1 regarding water demand, the water consumed by the primary sector of the economy counts only for 5.6% of the total. Based on that information, it has calculated that the yearly average demand for agriculture in 2020 was 209.29 m^3/d, with a minimum average during the dry months of 142.47 m^3/d and a maximum during summer of 260 m^3/d. Several options can be considered for periods of reduced water demand in the area, including storing the water in a tank, transporting excess water to nearby areas of need, or shutting down one treatment unit and leaving only one operational.

The adoption of two sewer mining units allows to decentralize, even if partially, the wastewater treatment process, and make the system less dependent on a central facility. Tab.21 shows the initial investment costs and the maintenance and operational cost over a year.

Table 21: CapEx and OpEx for sewer mining installation.

	Sewer mining 1 [126]	Sewer mining 2 [126]
CapEx (€)	35,370	35,370
OpEx (€/year)	20,734	20,734

5.4 ASSESSMENT OF STRATEGY 1 AND 2

This paragraph presents how the proposed interventions change the framework of circularity and adaptability. Then, the two strategies are compared. The changes, in the water system, after the implementation of each strategy are shown in Tab.22 and 23.

Table 22: Circularity after implementation of strategy 1 and 2.

Principle	Indicator	Strategy 1	Strategy 2	Unit
Reduce consumption of natural resource	Volume of freshwater (groundwater and surface water) used for consumptive and non-consumptive purpose	99.3	*99.3	%
Keep resource in use	Reclaimed wastewater treatment plant effluent	97.83	97.83	%
	Reclaimed stormwater	45.00	5.17	%
Regeneration of natural capital	Water restored as groundwater	57.20	6.57	%
	Water restored as surface water	24.59	0	Mm^3

* The metric does not consider the water consumed in the south of Breda.

Table 23: Adaptability after implementation of strategy 1 and 2.

Indicators	Metrics	Strategy 1	Strategy 2	Unit
Water resources availability	gained renewable surface water + gained renewable groundwater + additional imported water desalinated water, reclaimed water (as applicable) per year	28.49	23.17	$M(m^3/yr)$
Additional water storage capacity	Total volume of additional water stored in water reservoirs (m^3) expressed as a multiple of average daily demand	209.36	24.05	(No. days)
Diversity of water source	Contribution of alternative sources (all sources excluding the largest source) by volume to total available water resources	0.70	0.70	%
Water treatment capacity	Total treatment capacity not relying on a central structure	0.40	0.40	%

* The metric does not consider the water reclaimed in the south of Breda.

In both cases, the proposed strategies improve the overall situation in terms of circularity and adaptability. Although there are similar values, there are noticeable differences between the two strategies. Despite the fact that the volume of freshwater consumed is always the same in both cases (by 99.3%), in the second case the decrease of freshwater by agriculture after the use of wastewater as irrigation water is not taken into account. If the boundaries of the area under consideration would also contain South Brabant, there would be a lower value of fresh water consumed. One significant difference is stormwater reused. In strategy 2, through the use of injection wells, you can only store 5.17% of the stormwater produced. Applying wetlands instead can completely redirect the stormwater produced, especially in the urban area.
By being able to re-integrate more water into the ground, it results in a greater ability to meet the city's water demands. In fact, in the adaptability framework, the storage capacity in strategy 1 is almost 9 times strategy 2. This is also reflected in the water reclaimed by the two strategies, since strategy 1 manages to claim almost 5 Mm^3 more than strategy 2.

Adaptability is strongly influenced by sewer mining technology, and since it has been applied in the same way in both of the strategies, the values for diverse treatment and sources are the same. However, the diversity in strategy 2 does not count for the diversity of source created by the reuse of wastewater from the treatment plant. If the boundaries would have also included the South Brabant, the index for diversity for strategy 2 would have been higher.

The comparative indicators framework for strategy 1 and 2 is shown in Tab.24. For a deeper look of each cost estimation, it is possible to consult from Tab.7 to 14 and from Tab.16 to 22 in Appendix A.

Table 24: Comparative indicators for strategy 1 and 2.

Indicators	Metrics	Strategy 1	Strategy 2	Unit
CAPEX	Capital expenditure or is the money an organization/ a corporate entity/ public administration spends to buy, maintain, or improve its fixed assets, such as buildings, vehicles, infrastructure, etc.	31.78	27.71	M€
OPEX	Operational expenditure is an ongoing cost for running a product, business, or system	1.37	0.61	M€
Cost recovery of water	Cost water recovered by wastewater reuse for agriculture over a period of 10 years	-	0.04	€/m^3
Cost water recovered by injection wells over a period of 10 years	-	1.16	€/m^3	
Cost water recovered by wetlands over a period of 10 years	*0.00295	-	€/m^3	
Cost water recovered by sewer mining over a period of 10 years	0.5	0.5	€/m^3	
Investment	Ease of finding investors/investments for such a project	5	5	
Regulation	Ease of apply the strategies from a regulative point of view	5	7	
Social Acceptance	How the adoption of this new strategy is perceived	6	6	
Water Balance	Amount of water entered into the area boundaries and that outflow from the area in a year	100.73	47.38 mm/yr	mm/year

*the calculation for the following value has been performed without considering the extraction cost of groundwater.

The total of initial investment for strategy 1 is calculated to be around 30.87 M €, with a yearly cost of maintenance and operation of 1.37 M €. Compared to strategy 2, a decrease in investment and maintenance costs can be noted. The cost of water produced by the single interventions are reported in Tab.24. It can be noted that the highest cost for water recovery is injection wells, with a higher price than the actual one for both drinkable and irrigation, while the cheapest one is the adoption of wetlands.

The indicators that refer to governance and social acceptance are slightly different. The metric for the ease in finding investors is the same, since for both strategies *"is rather easy* *to find investors because of the innovative appearance of the strategy. On the other hand, the effectiveness of the solution is difficult to assess for investors"* [65]. Same goes for social acceptance, since *"the public do not get much attention on water quality, wastewater treatment and drought"*. The only difference found regards the regulation indicator. In their opinion (the water board), for strategy 1 it would not be difficult to apply the three interventions. For strategy 2, the application of injection wells raise concern of water quality, then "water quality will have to meet very stricter requirements" [65].

Lastly, the water balance generated by the two strategies is very different. The first one generates a surplus of water in the municipality of Breda of 100 mm/year, while the second one only generates 21 mm/year. For both cases, as mentioned earlier, the water balance does not take into account the wastewater effluent reclaimed, since for both strategies, it is redirected outside of the boundaries.

5.5 WORKSHOP AND INTERVIEW: CONSIDERATION AND DISCUSSION

Given the complexity of the movement and the interaction of the various flows in space, a workshop was held with people working in the water management sector in the municipality in order to fill in the gaps mainly on spatiality, but also on other issues. The idea was to present to the participants the two initial strategies and receive feedback and comments on the work done. This allowed to re-evaluate and finalize a final strategy. In addition, the other key aspect of the workshop was to understand what circularity and adaptability meant to the people who work daily in the water management field, and if for them these two features might be a possible solution to the problems of drought and uncertainty, or not.

In order to organize the workshop, the water board of Breda (Waterschap Brabantse Delta) was contacted. The people who work there were asked if they would like to participate in the workshop, in order to help to understand the complex system of water management in a broader way. To achieve a wider variety of components, the drinking water company in Brabant (Brabant Water N.V.) was asked if they would like to take part in the workshop. One employee from the Waterschap Brabantse Delta and one attendee from Brabant Water N.V. participated in the workshop. One more interview was carried out with a Professor within the faculty of Civil Engineering and Geo-sciences at TU Delft. Although not working in the water management of Breda (or other cities), the third participant was an important contributor. As a geo-environmental engineer and academic, they[1] were able to bring a different perspective to the topic and more insight into circularity and adaptability through their[2] lens.

The entire transcript of the workshop and interview can be found in Appendix C. This section discusses and analyses the outcomes of both meetings. The suggestions and analysis brought by participants were useful to re-evaluate the two strategies, but also the concepts of adaptability and circularity as applied to the system.

Starting with the latter, it can be seen that the participant's notion of circularity resembles the one given in paragraph 2.1. According to the participants, a system can only be circular if it is completely natural, while an anthropocentric system cannot be (fully) circular. In the explanation given by this study, circularity is a system that promotes the ecosystem, through the

[1] They is used as singular they. In this case, they is a gender-neutral third person pronoun.

[2] Their is used as a derivative form of the singular they. In this case, their is a gender-neutral third person pronoun.

regeneration of natural capital and ensuring the functioning of its flows. However, a distinction between those two perspectives can be underlined. For the attendees there is a dichotomous division between what is natural and technical (anthropogenic). Hence, nature corresponds to circular and anthropogenic does not. In accordance with this point of view, an anthropogenic system will never be able to achieve circularity, so the goal becomes to "revert" to a completely natural system. This precludes the possibility of imagining a real goal, in a system neither anthropocentric nor natural. Only by overcoming the idea of nature as a stationary object, and realizing that nature is a product of our interactions with the external environment, which changes over time, one is able to encompass a hybrid reality, where one does not preclude (or include) the idea of circularity.

When it comes to adaptability, often two terms were mentioned as similar: flexibility and robustness. Especially the latter was traced as a consequence or cause of an adaptable system. As discussed in paragraph 2.2, these three terms, since they have only recently arisen, are often confused, partly because there are no unambiguous definitions accepted by all. Nevertheless, as far as all these terms indicate a specific feature of the system to be able to respond to changes without compromising the operability, the modus operandi is inherently different. Robustness might be defined as "a system's capacity to endure change without altering its basic configuration" [178]. Instead, adaptability is the ability to mutate to new conditions while remaining performative.

Regarding drought and how this can be tackled, everyone agreed that water consumed, being discharged out of the territory, is a problem and that a way should be found to hold it and reuse it. In addition, interesting perspectives about the topic have been covered by the participants. There were discussions around the responsibility of consumers to have to change their attitude towards water use. The less water is demanded, the less water must then be extracted. Furthermore, concern has been raised over how farmers employ water and the fact that much of it may be wasted. This perspective is interesting as it focuses additional causes of drought and not on the consequences. Also, it was emphasized how there is a lack of active collaboration between the different stakeholders. This then leads to a lack of effectiveness in being able to combat the problem. The different points discussed were of great interest as they presented the problem not only from a purely technical point of view, but rather it was shown that drought is a result of multiple influences and actions, such as administrative, sociological, economical and environmental.

As for the proposed strategies, there were several comments and feedbacks. One of the most significant criticisms was on the spatial use of reclaimed water. It was questioned why stormwater and wastewater treatment plant effluent are transported to the south, when the water balance in the urban area shows a water deficit. In addition, this type of solution is very costly. It would be more efficient to find reuse solutions locally. The reasons why the two water streams in the urban area cannot be replenished relate to quality. The quality of the water itself indicates its possible applications. Both stormwater and wastewater effluent are not suitable for potable use, as the main water demand in the municipality is related to consumption by citizens. In addition, since the urban area is densely populated, it is difficult to reclaim space for wetlands-type solutions. For this reason, water is channelled towards the south of the municipality, where agriculture is one of the main activities present in the area.

One might argue that even in the urban setting, non-potable water is serviceable, for example as flushing water or for other uses that do not require drinkable water. However, this would require additional effort to put into practice. It would require dealing with each individual house-owner to find out whether or not they would want to implement such reuse solutions and change the plumbing and water system of each residence. As much as it is desirable, these kinds of solutions would require more work by more people to make it happen. Nonetheless, it would be worthwhile and necessary to identify other wastewater discharge points (e.g., industries), to be able to reuse the effluent in the surrounding area instead of dumping it into the sewage system. In this thesis, this was not possible as information about the area and its activities were limited.

An additional criticism was made of the lack of certain parameters for reuse water quality, specifically on antibiotics and other types of drugs. They were not presented in any guidelines used for the thesis, yet possible future issues need to be anticipated on. As antibiotics consumption continues to increase [179][180], it is more important to start controlling water quality in this aspect as well.

6 FEASIBILITY OF THE FRAMEWORK

This section presents the final design of the strategy. After the workshop and meeting, it was possible to finalise each intervention in order to be implemented on the territory. The proposed final design and its circularity and adaptability are discussed. Therefore, final considerations regarding the application of circularity and adaptability are made.

6.1 FINAL STRATEGY

The final strategy aims at shifting the linear paradigm to a circular one and changing the current approach (command-and-control) to an adaptable one.

After considering wastewater as a source both for agriculture and for enhancing the river(s) stream flow, it was thought, to use this effluent only for agriculture. The initial goal was that the interventions fit within the system boundaries. However, based on the water application options for the wastewater effluent, the interventions are located outside of the boundaries. Then, in terms of circularity and adaptability, both interventions are not being represented by the framework. Therefore, the considerations made to choose the best intervention regarding wastewater effluent were based on the suggestions of the two meetings and the comparative indicators framework.

As pointed out by one of the workshop participants, it is important to find *"the best possible reuse for each droplet of water"*. Therefore, the wastewater produced does not need further treatment to be reused, as its phosphorus and nitrogen levels are optimal for irrigation. However, it should be underlined that it is more necessary than ever to improve and integrate water controls and treatments for hospital drugs and by-products.
During summer the need for water is higher, due to high temperatures and the harvesting and cultivation cycles (crops require more water since its their active growing season and since they are losing more water due to the raised temperatures and persistent daylight [181]). However, it is also true that in the Netherlands there is a significant amount of intensive greenhouse cultivation. Although the number of greenhouse vegetable growers decreased from over 8,000 in 1980 to 1.26 thousand in 2017, greenhouse vegetable acreage increased by 7% to approximately 5,000 hectares (ha) [182]. Therefore, even during winter, water is needed in the agricultural industry. From the wastewater treatment plant a pipe is designed to transport all the effluent to the centre of the south of the municipality, where the water will then be distributed to farmers.

In order to transport wastewater from the treatment plant to the south of the municipality, a pipe is designed. The characteristics of the pipe are the same as explained previously in paragraphs 5.1.1 and 5.1.2. The pipeline is projected for minimum flow rates of 929 m^3/hr up to a maximum of 6700 m^3/h. The distance from the wastewater treatment plant to the "ideal" center of the basin as the crow flies is 10 km, where it is thought that water can then be conveyed and supplied to the various farmers who require it. The cost for its installation are the following:

Table 25: CapEx and OpEx for reuse of wastewater treatment plant effluent agriculture irrigation.

	Pipe [169] [170]	Pumping station [171]
CapEx (€)	4,317,536	684,814
OpEx (€/year)	45,000	21,713

With regard to stormwater, it was decided to discard the option for injection wells. This was done for several reasons. The first one, is that it surpasses the ecosystem and its function. As already stated by some of the stakeholders, the direction to be taken in the future is to aim to develop a system that incorporates natural features as much as possible, such as water infiltration. The use of injection wells would mean, among other things: the construction of an area for ASR that would not be accessible to the public and would be restricted to professionals, without any aesthetic or recreational added value; the use of numerous components such as a xmas tree (trim), a wellhead, a valve packing and seals and tubing [183]; a high environmental impact due to the use of component materials; a limited amount of water to store; and finally a high investment cost already showed previously in paragraph 5.2.2.
In terms of circularity and adaptability, the ASR intervention was not enhancing the system as much as the wetlands. The reclaimed stormwater and the water stored as groundwater was less compered to the wetlands (Tab.22).

For the reasons just listed, it was then decided to use stormwater as a resource to recharge aquifers through wetlands. The design of the wetlands stays as shown above in paragraph 5.2.1. Therefore, two wetlands, one for the urban area and one for the rural area are designed, with respective volumes of 33000 m^3 and 625 m^3.

Following the cost for the intervention is shows in the table:

Table 26: CapEx and OpEx for stormwater reuse intervention with wetlands.

	Wetland urban [173]	Wetland rural [173]	UV treat urban [174][175]	UV treat rural [174][175]
CapEx (€)	20,850	9,496	68,712	34,356
OpEx (€/year)	1,474	630	3,637	2,425

Regards sewer mining units, as explained above, their use is ideal for the rural area of the municipality. For this reason, it was decided to install three different ones in the territory, each with a treatment capacity of 100 m^3/hr. Therefore, the cost are shown in the following table:

Table 27: CapEx and OpEx for sewer mining units installation.

	Sewer mining 1 [126]	Sewer mining 2 [126]	Sewer mining 3 [126]
CapEx (€)	35,370	35,370	35,370
OpEx (€/year)	20,734	20,734	20,734

After having introduced the three final interventions to make the system more circular and adaptable, through the framework the strategy is evaluated as a whole. Tab.28 and 29 show the change in the new system.

Table 28: Circularity after implementation of the final strategy.

Principle	Indicator	Metric	Calculation
Reduce consumption of natural resource	Volume of freshwater (groundwater and surface water) used for consumptive and non-consumptive purpose	98.95%	(reclaimed sewer mining water / water demand)
Keep resource in use	Reclaimed wastewater treatment plant effluent	96.14%	(reclaimed wastewater / wastewater produced)
	Reclaimed stormwater	45.00%	(reclaimed stormwater / stormwater produced)
Regeneration of natural capital	Water restored as groundwater	57.20%	(stored groundwater / groundwater consumed)
	Water restored as surface water	0 Mm^3	(Mm3 water restored)

Table 29: Adaptability after implementation of the final strategy.

Indicators	Metrics	Unit	Calculation
Water resources availability	gained renewable surface water + gained renewable groundwater + additional imported water desalinated water, reclaimed water (as applicable) per year	28.49 Mm^3/yr	(reclaimed sewer mining water + wetland + wastewater)
Additional water storage capacity	Total volume of additional water stored in water reservoirs (m^3) expressed as a multiple of average daily demand	209.36 (No. days)	(water stored / average daily consumption)
Diversity of water source	Contribution of alternative sources (all sources excluding the largest source) by volume to total available water resources	1.05%	(reclaimed sewer mining water / water demand)
Water treatment capacity	Total treatment capacity not relying on a central structure	0.43%	(reclaimed sewer mining water / wastewater production)

In contrast to the starting situation and the two preceding strategies, it is seen a reduction in freshwater consumption from a total dependence to 98.95%. The wastewater reclaimed is the same as the two previous strategies, so 96.14%, while for stormwater it is 45%. This last strategy can see a (small) boost for adaptability, along with the increased adoption of sewer mining units, of the last two parameters. In fact, the dependence for central treatment decreases with the increase of independent treatment units like sewer mining. Also, a "larger" portfolio of alternative sources can be noticed in this scenario.
Tab.30 represents the comparative indicators framework for the new network.

Table 30: Comparative indicators for the final strategy.

Indicators	Metrics	Unit
CAPEX	Capital expenditure or is the money an organization/ a corporate entity/ public administration spends to buy, maintain, or improve its fixed assets, such as buildings, vehicles, infrastructure, etc.	16.81 M €
OPEX	Operational expenditure is an ongoing cost for running a product, business, or system	0.38 M €
Cost recovery of water	cost water recovered by wetland over a period of 10 years	*0.00295 €/m^3
	cost water recovered by sewer mining over a period of 10 years	0.5 €/m^3
Investment	Ease of finding investors/investments for such a project	5
Regulation	Ease of apply the strategies from a regulative point of view	7
Social Acceptance	How the adoption of this new strategy is perceived	6
Water Balance	Amount of water entered into the area boundaries and that outflow from the area in a year	100.73 mm/year

*the calculation for the following value has been performed without considering the extraction cost of groundwater.

Compared to the two initial strategies, it can be noticed an important decrease of CapEx and OpEx. This can be explained, as the two most expensive interventions are not taken into account: stream enhancement and injection wells. For river stream enhancement, a considerable amount of investment would have gone for the different treatments in order to match the water quality parameters required. The score of 7 given to regulation, as the first strategy, was lower in the second strategy, due to ASR projects, since to recharge aquifers through that method, a more strict control on water quality is placed.

The yearly water balance of the area also increased substantially. These interventions have the effect of improving the water balance for the entire area, with a positive value of

100.73 mm/yr. This is due to a better water balance in the rural area of 52.19 mm/yr and in the urban area of 131.55 mm/yr. It can be seen, also through the comparison from Fig.22 and Fig.23, that the urban area has benefited the most, as it is the one that produces the majority of the stormwater, which is then returned. For a complete view of the maps produced on QGIS 3.10 and the conceptual maps for each month, for the new water balance, proceed to Appendix B from Fig. 27 to 52.

Table 31: New monthly water balance after the application of the intervention.

Month	Monthly water balance (mm/month)	Monthly new water balance (mm/month)	Monthly water balance (Mm^3/month)	Monthly new water balance (Mm^3/month)
January	15.69	18.60	1.43	1.69
February	84.08	93.49	7.66	8.51
March	1.13	5.65	0.13	0.54
April	-64.32	-63.771	-5.86	-5.80
May	-75.28	-74.23	-6.85	6.76
June	42.13	51.94	3.84	4.72
July	-19.53	-15.273	-1.78	- 1.39
August	-43.61	-41.14	-3.94	-3.75
September	5.67	10.39	0.52	0.94
October	42.16	48.03	3.84	4.37
November	11.95	14.55	1.09	1.34
December	47.29	52.60	4.31	4.79

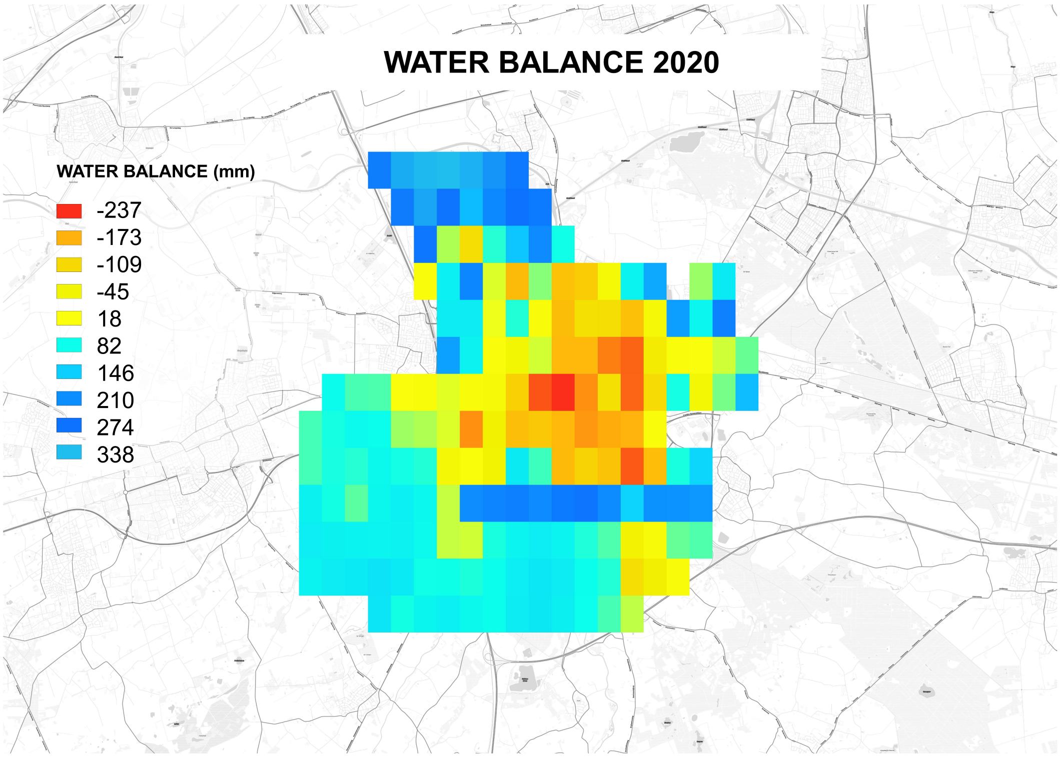


Figure 22: Representation of the annual water balance for the municipality of Breda, through QGIS 3.10., before thje application of the final strategy.

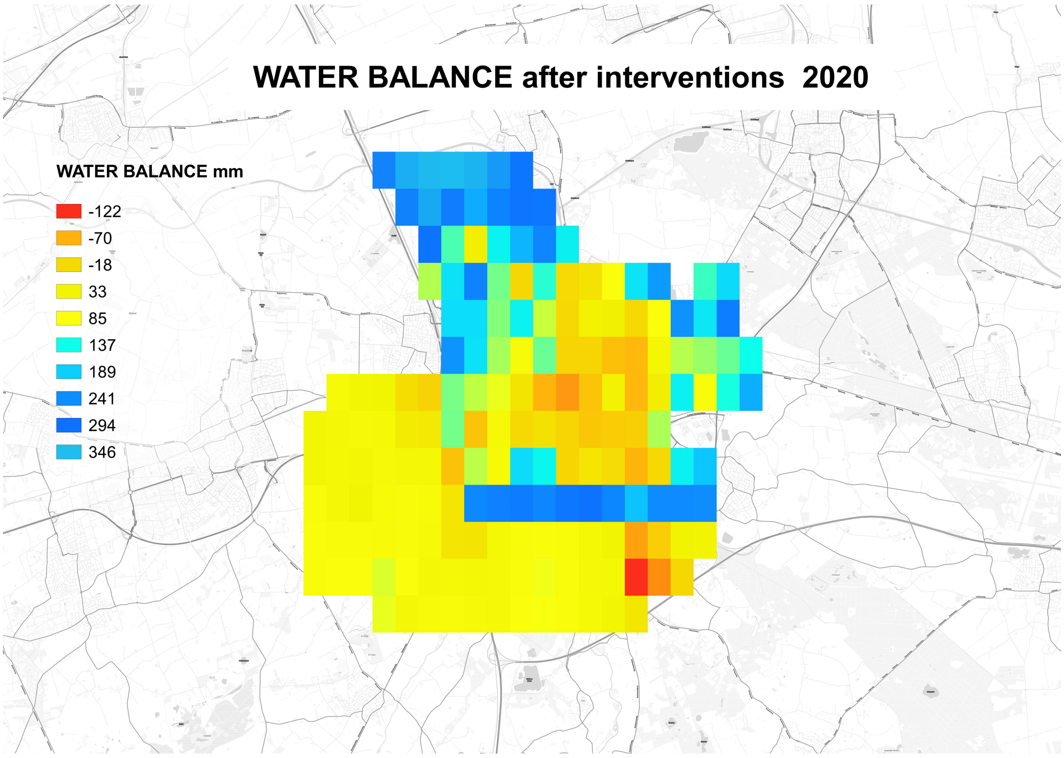


Figure 23: Representation of the annual water balance for the municipality of Breda, through QGIS 3.10, after the application of the final strategy.

The way the water balance has been set up, of the following interventions only two have affected the final result: sewer mining and wetlands. This is because the wastewater treatment plant effluent employed for agriculture falls outside the established boundaries, so it counts as a negative value for the water balance, even if the wastewater has been reclaimed. This can be noticed clearly in the monthly water balance shown by Tab.31. There is an improvement in the water balance for every month. However, the months with a smaller enhancement are the ones with already a negative water balance. Since it rained infrequently during these months, stormwater was not generated and could not be reclaimed. At the same time, wastewater treatment plant effluent is not considered for the calculation of the water balance since it is reused outside of the boundaries. Therefore, during the driest months, the interventions applied did not significantly change the water balance.

As a result of the wetlands, the stormwater channeled by the separate sewer system, instead of being discharged north of the municipality and leaving the boundaries, is replenished through the wetland. This, referring to Eq.1, means that the SW term is considered null. Whereas, sewer mining subtracts 300 m^3/d from the wastewater effluent, for a total of 109'800 m^3/yr less effluent. Therefore, from the wastewater produced in the rural area, the water claimed by the sewer mining units is subtracted. Looking at Fig.24 can be seen that evaporation levels are quite high for both urban and rural area [65]. During 2020 circa 40 Mm^3 of water have evaporated based on the methodology of the study. For the calculation of evaporation, it was considered potential evaporation and not actual evaporation. Therefore, the evaporation values calculated are higher. As a consequence, the water balance shows a lower value of water stored within the system. In fact, during these dry years, it is expected a lower evaporation rate due to lack of water to evaporate.

The runoff coefficient of 0.56 was the same for the entire area. No distinction has been made between rural and urban one. The data available did not allow to establish precisely the runoff coefficient for each area. However, it is presumable that the runoff coefficient for the urban area is higher than 0.56, and the one for the rural area is lower than 0.56. In term of km^2 the urban area is the biggest one of the two , and the one with a larger portion of impervious area. If the urban area had a higher coefficient, therefore the stormwater produced would have been higher too. This mean that the total water balance would have been lower in term of water stored within the boundaries.

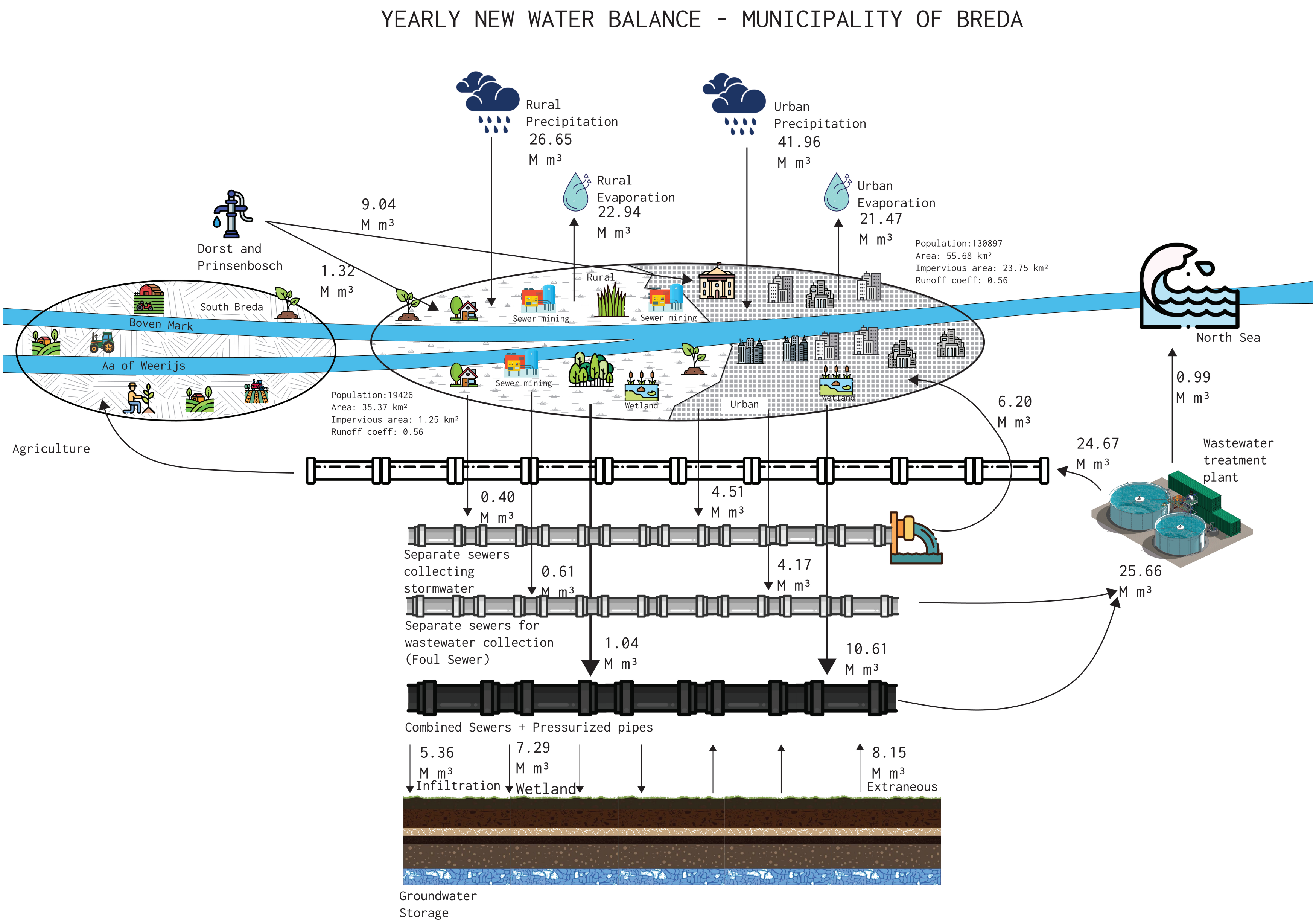


Figure 24: Conceptual map of water balance for the municipality of Breda, after the application of the final strategy.

6.2 CIRCULARITY AND ADAPTABILITY: WHAT BREDA IS TELLING ABOUT THE FRAMEWORK

Starting from the case of Breda and its challenges in the management of water, this thesis aims to examine and study how the concepts of circularity and adaptability can be applied. It was tried to shift, through the application of three different interventions, from a linear and rigid system to a circular and adaptable one.

The study tried to implement circularity in Breda by following three basic principles, namely reducing, keeping and regenerating a natural resource. However, none of these emphasize the value of reusing. The three proposed interventions increase circularity based on the devised framework, however, there is no metric that investigates what is actually the best added value of the reclaimed water. The reuse of discharged water (as wastewater and stormwater) does not have a positive value in and of itself. In the case study of Breda, the decision to use water from the north in the south of the region was made. Yet, it is unknown what the best use value is for this water. To get the full picture, it would be necessary to investigate what the impact of water discharged to the north is, and how it is used.
This brings up a fundamental problem, namely understanding which is the optimal use of water and what the circularity consequences are. The structural problem is that when implementing the concept of circularity, there is the need to set territorial boundaries to the location, consequently excluding what occurs in adjacent boundaries. One possible approach to this would be adopting only local solutions. However, this would bring different limitations, like restricting possibilities of reuse and forcing local solutions even if they are not the most suitable.

If for circularity it was more immediate and intuitive to be able to translate the concept in the form of indicators, for adaptability it was more complicated. As explained in paragraph 2.2, the concept of water security was applied to help. This is partly because these two concepts are intrinsically linked [58], but also due to the fact that in Breda's case, drought was one of the two key problems. This is the reason why it was decided to enhance water reserves as sources to endure the uncertain future changes and droughts in the area.

From the framework, it can be seen that the concept of adaptability is closely related to the infrastructure of the system. In fact, the water treatment capacity indicator was changing only with the introduction of sewer mining units. This is because a decentralised urban water system has a higher capacity to cope and adapt: it can rely on a diversified portfolio of water sources, enhance the buffering capacity of the system by lowering drinking water demands, and use multi-scale networks and pathways [184][185][186].

For both circularity and adaptability, it was not feasible to propose a set of reuse options as it would be very difficult to apply them. For the reuse of stormwater and wastewater, the interventions proposed were located outside of the urban environment. However, interventions such as the reuse of stormwater and/or wastewater as non-potable water for use in homes would have been desirable. They were not proposed since these types of interventions require more effort and an increase in participating stakeholders. The introduction of certain interventions to make a system more circular and adaptable are still very complex to put into practice, thus reducing the margin for actions.

With the improvement of parameters and indicators of both circularity and adaptability, with respect to the initial situation, the system would become more effective at being able to cope with drought and uncertainty. However, a technical solution does not solve (completely) the problem of how to anticipate drought and effects of global warming. Through direct and/or indirect causal mechanisms, increasing efficiency may lead to increased resource utilization. This is explained through the Jevon paradox. The paradox states that when technology innovation or government policy improves the efficiency with which a resource is employed (cutting the quantity required for each usage), the consumption rate of that resource rises due to increased demand [187][188][189][190]. Therefore, the problem is a system for which a constant economic growth is necessary, and consequently of production and consumption [37]. Then, making the system more technically efficient could even cause more damage than it already does. It is critical to note that the Jevons/rebound effect is not guaranteed. In theory, policies may be structured to guarantee that efficiency increases result in decreased resource use rather than increased output [187].

7 CONCLUSION

The overarching objective of this study was, for the case of Breda, to explore current water management practices, and to study whether a shift in the management paradigm, through the implementation of circularity and adaptability, might succeed in mitigating the problems of drought. This chapter presents the findings of the study and suggests several recommendations for further investigation.

The water balance for the city of Breda shows that for the year 2020 there has been a decrease of water entering the system compared to average conditions, resulting in a positive water balance only of 50 mm/year. Consistent with KNMI's reporting that there was a water deficit of -170 mm in the spring months and -280 mm in the summer period [7], the months that reported a negative water balance were March, April, July, and August.

QGIS 3.10 and Excel 2103 were found to be useful tools to model the municipality water management. Excel 2103 was helpful to represent numerically the inflows and outflows in Breda, while QGIS 3.10 depicted the spatiality of water balance in the area.

Applying the framework shows that the current system scores extremely low on adaptability and circularity. Concerning measures to change this, the reuse of wastewater effluent and stormwater has the ability to decrease freshwater consumption and store excess water during rainy periods. The implementation of sewer mining allows an increased independence from the central system, and consequently enhances both the water treatment capacity of the system and a wider diversity in the water resource portfolio. However, developing new strategies for wastewater and stormwater had a greater impact on the system, whereas the application of sewer mining units had a lower impact in terms of adaptability and circularity. This is due to the limited capacity of the technology to treat water.

The strategy which results in a better overall performance for the municipality is reuse of wastewater as irrigation water for agriculture, redirect to stormwater in the wetlands and apply sewer mining units in the rural part of the municipality. These interventions improve both circularity and adaptability parameters. The portfolio of resources has been enlarged, and a considerable amount of water has been reclaimed to recharge the aquifers and to use for agriculture irrigation. The water balance for the entire area showed an increase in resulting access water from 50 mm/year to 100 mm/year, with an improvement especially in the urban area, as more stormwater is reused.

Using this information from the case of Breda, the study evaluated the concepts of circularity and adaptability. The circularity framework values water reuse, but does not value the end goal of reuse. Creating a circular system has no positive value in and of itself. However, to understand what is the best added value for recycled water, all possibilities for reuse should be considered. This is not possible, since to apply circularity to a location, one needs to set boundaries. Therefore, excluding possibilities of reuse outside of the boundaries.
The concept of adaptability was complicated to translate from theory to practice. The concept of water security prompted the conception of a framework for adaptability. This is because the two concepts are intrinsically linked to each other [58]. Also, water security was introduced in Breda as a consequence of severe drought . Thus, shifting to a more adaptable water system implies a system with ample water reserves which will be better prepared to face drought [184][185][186].

This work can be taken as a starting point for developing more detailed strategies to be implemented in the city of Breda in the future. Moreover, it is necessary to continue to investigate circularity and adaptability, and how their applications translate into reality. For circularity, it is important to continue to research its implementation referring not only to the waterways but to integrate reflections on its added value. For adaptability, future work should focus on what it might mean within a wider spectrum of processes. Moreover, it is crucial for future research to have a comprehensive approach to problems, and, especially in complex societies, to be able to have a critical understanding of all the factors and players involved.

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