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Bluebloqs as a circular water solution

A framework to co-design the dimensioning and operations of the decentralised Bluebloqs system

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Field Factors

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A framework to co-design the dimensioning and operations of the decentralised Bluebloqs system

by

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Preface

I would like to start by thanking my thesis supervisors prof. dr. Jan Peter van der Hoek, dr. ir. Edo Abraham and dr. Boris van Breukelen. Without the knowledge within their respective fields of expertise, I would not have successfully connected the dots necessary to execute this thesis. They have let me roam freely within this research through the different sections that water management consists of, and have guided me through the process of writing this thesis.

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A. Feenstra
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Abstract

Urban water management is faced with upcoming challenges due to climate change, the deterioration of existing infrastructures and the depletion of water sources. Climate change brings about more intense rainfall events and longer periods of drought. On top of that, the deterioration of the piped network urges for investments in the existing system, to ensure that the provision of water services can be maintained. Furthermore, the depletion of water sources is raising awareness regarding the value of fresh water which gives rise to the re-use of water flows that have up to now often been considered as nuisance rather than viable resource. Examples of these flows are the wastewater and the stormwater flow.

The existing centralised infrastructure consists of three reliable systems. The first system supplies high-quality water, the second drains out stormwater and the third one discharges wastewater. These three systems operate separately from each other and follow a linear approach to water management. In recent years, circular water management has become more prevalent. Instead of following a linear approach in the three separate systems, the re-use of water flows as viable sources is applied more often. New, often local, solutions can be designed to effectively complement existing systems in maintaining the high provision of water services that societies have consistently been using over the past decade. This circular approach can ensure that current water requirement levels can be met sustainably by the improved urban water systems.

By dealing with the upcoming challenges of high-intensity rainfall and long periods of drought – which both have a high spatial variability – local solutions are able to support the centralised infrastructure. This is done by both mitigating the pluvial flood risk, as well as by providing a high-quality water source. An arguably ideal solution which addresses both the pluvial flood risk and also provides a high-quality water source, is the Bluebloqs system. The Bluebloqs system can help mitigate pluvial flood risk by the attenuation of flow, the result of implementing an attenuation tank in the stormwater drainage system. Also, the Bluebloqs system is able to filter and store this stormwater to provide a high-quality water source during water-scarce seasons.

Whether the Bluebloqs system is a viable solution which addresses both the mitigation of the pluvial flood risk as well as the provision of water challenge, is investigated in this research. The Bluebloqs system is a circular water solution that makes use of an attenuation tank, a bio-filter and an aquifer storage and recovery (ASR) system. The attenuation tank is physically connected to the drainage system and it consequently decreases the risk of surcharged pipes in the drainage network. From the attenuation tank, the water is pumped towards the bio-filter, where pollutants from the water are removed and the water is filtered to such an extent that it can be infiltrated into the aquifer. In the aquifer, the water is stored to overcome seasonal variations in water availability. The Bluebloqs system has the objective to supply water in the dry season, even though its source is stormwater, which enters the system during the wet season. This research has analysed the performance of the Bluebloqs system for different dimensions and operations.

Within this thesis, a framework has been built that presents the performance of the Bluebloqs system. This framework consists of three groups; the interactions with centralised infrastructure, the water quality indicators and the impact of the Bluebloqs system on its environment. These three have their own distinct performance indicators, which characterise the effectiveness of the Bluebloqs system in providing a specific water service. The group of the framework dealing with the interactions with the centralised infrastructure uses performance indicators for the volume of water lost in overflow events, and volume of water supplied through the Bluebloqs system as high-quality water source to the end-user. The indicators for the other groups characterise the Bluebloqs system differently. Each group within the framework projects the performance of the Bluebloqs system for other interest groups. For example, the indicators regarding the impact of the Bluebloqs system on its environment are of interest to municipalities thinking about implementing the system.

The behaviour of the Bluebloqs system has been modelled. This model presents the physical processes taking place within the Bluebloqs system. The output of the model are the performance indicators of the framework. By running the model under different input parameters, the performance of the modelled Bluebloqs system is tested on the three groups of the framework.

The outcome of testing the model on the framework has shown that the Bluebloqs system can be improved. One of the suggested improvements is to work with feed cycles for the bio-filter. These feed cycles consist of the periodic saturation of the bio-filter. Once the bio-filter is saturated, the flow from the attenuation tank towards the bio-filter is interrupted, to let the water gradually filter through the bio-filter.

By applying feed cycles, the bio-filter is better capable of removing pollutants from the water. However, periodically interrupting the water flow from the attenuation tank towards the bio-filter negatively impacts the effective storage capacity of the attenuation tank. When having more feed cycles in a day, these interruptions last for a shorter period of time. Depending on the desired performance of the system, which is based on the performance indicators, these feed cycles should be aligned with the capacity of the attenuation tank and the discharge of the pump for the flow between the attenuation tank and the bio-filter.

Fitting the feed cycles to the seasonality of rainfall patterns can further increase the performance of the system in mitigating flood risks. Applying predictive control when overflow events occur is an additional control option that minimises the environmental impact of the system. Finally, the performance of the Bluebloqs system can be presented based on all the performance indicators included in the framework, and the model can be used to adjust the system dimensioning and operations to present the consequences of adjustments to the desired performance of the Bluebloqs system.

The frameworks' performance indicators can be used to understand the Bluebloqs ideal configuration to deliver a specific desired performance. The desired performance of the system determines the dimensions and operations of the system. Co-designing the Bluebloqs system is thus crucial to its delivered performance.

In conclusion, the framework and model can be used to present the Bluebloqs system for different scenarios. The framework can generate a comprehensive overview of what can be expected of the Bluebloqs system when implementing it in a specific project site, in comparison to other solutions that may be considered, such as green roofs or storage tanks.

Also, its use as circular solution being complementary to existing urban water infrastructure can be presented by the framework and model output. This will help in the transition of urban water systems in dealing with the upcoming challenges related to climate change, the deterioration of the piped infrastructure and the depletion of water sources.

Contents

Acronyms

ASR	Aquifer Storage and Recovery.
RE	Recovery Efficiency.
SUDS	Sustainable Urban Drainage Systems.

1

Introduction

Managing the water cycle in urban areas is a task with many different responsibilities. Good urban water management requires, among others, the delivery of high-quality water, combined with the discharge of low-quality water, while designing an infrastructure that functions over a long period of time, against the lowest cost and the highest service level possible (Sharma et al., 2010). This has been a complex task since the implementation of urban water systems. Nonetheless, the maintenance of – and distribution of water through – centralised systems is under constant development. (Gersonius et al., 2013). This development in relation to the challenges that climate change bring about, having more intense rainfall and longer periods of drought, are part of the reasons to steer the development of urban water systems in a direction of new water solutions.

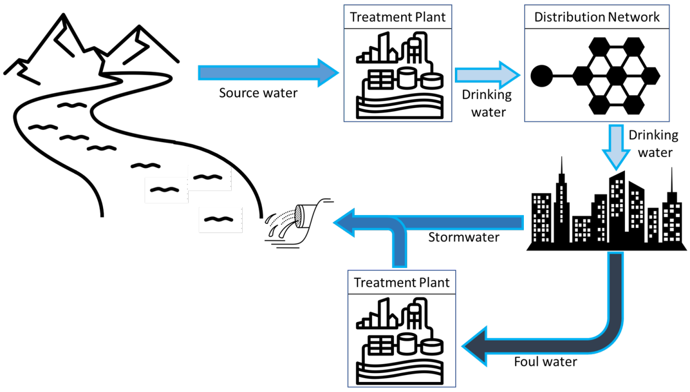

Figure 1.1: Urban Water Systems

The systems used to manage the water cycle in urban areas consist of three main water flows. These are listed here:

- Water supply
- Stormwater drainage
- Wastewater discharge

There is the water supply, which consists of retrieving water from the source to the treatment plant, where it is treated to meet the set drinking water criteria. From here, the water is supplied to the city through the distribution network. Water that enters the urban environment, leaves through either the stormwater drainage system or the sewage system. Groundwater infiltration and evaporation are important processes that affect the need for man-made water systems. The water systems that can be actively used to regulate water flows to their desired locations are the water supply system, the stormwater drainage system and the sewage system. An overview of how these flows interact is given in Figure 1.1.

1.1. The transition of urban water systems

Due to urbanisation, population growth and the effects of climate change, water scarcity and more extreme discharges are expected to challenge the performance of urban water systems (Rygaard et al., 2011; Yazdanfar and Sharma, 2015). Water supply and stormwater drainage systems are specifically prone to being affected by the upcoming challenges. Water managers of urban areas have the task to design systems that can cope with these increasingly challenging circumstances. Innovative solutions are therefore needed to create a water infrastructure that will be able to keep the water services at the highest level possible.

1.1.1. The role of centralised water systems

The way in which human societies have designed urban water infrastructure has brought about the immense clusters of human activity (Weber et al., 2007). The existence of mega-cities arising all over the globe today would not be possible without the underground infrastructure seamlessly providing services that are often taken for granted (Wu and Tan, 2012). These systems are extensive and over the last decades a lot of capital has been invested in the infrastructure to ensure that regions within the urban area are provided with sufficient water services (Leflaive and Dominique, 2018).

Water Supply Systems

Typically, between 50-75 % of the combined operating and capital cost of water service providers is spent on the implementation and maintenance of the pipes in centralised water infrastructure. (Marlow et al., 2013; Speers, 2008; Thomas and McLeod, 1992). In many Western cities, the centralised water systems are at the end of their design lifetime. Also, the assessment of implementable solutions is increasingly less focused on the cost of service and more on dealing with upcoming challenges such as water scarcity and extreme precipitation (Hering et al., 2013). Although the ongoing transition does look for new water solutions, it also notices the value of centralised water infrastructure. As stated in Poustie et al. (2015): *”The traditional, centralised approach to water servicing provides clean drinking water, sanitation and protection from urban flooding with very little apparent risk of failure (Lienert et al., 2006)”*. This extensive infrastructure already being present in many Western cities, results in new water supply solutions to provide complementary services in terms of water deficits in the water provision through centralised infrastructure, rather than a solution that replaces the existing system.

Urban drainage systems

Stormwater drainage systems have traditionally been implemented to control the flow of stormwater when precipitation events occur. Traditional systems tend to drain this stormwater out of the region, by conveying the water to receiving waterways. However, increasingly often, stormwater is considered as a viable resource, rather than a nuisance (Fletcher et al., 2013).

Stormwater systems are designed to deal with a *design discharge*, which is considered to be the acceptable flow rate that the system should be able to accommodate for. This means that the design of a drainage system is based on allowing the system to reach its capacity, for example, once every two years (Schmitt et al., 2004; van der Ent, 2020). When this capacity is exceeded, the system is not able to convey all the water to the receiving water body as fast as water is entering, and therefore the system gets surcharged. The occurrence of floods is the result of the stormwater drainage system being surcharged to such an extent that it exceeds the ground level, causing the water to pond on the streets (Schmitt et al., 2004; van der Ent, 2020).

One of the consequences related to climate change is the change of rainfall patterns. Rainfall will occur with a larger intensity and less often. This means that rainfall events with an intensity

larger than the *design discharge* are expected to occur more often, whereas events that are smaller will occur less frequent.
In recent years, the inclusion of storage tanks in stormwater drainage systems has been acknowledged to significantly improve the performance of these systems in terms of flood mitigation and non-point source pollutant control (Duan et al., 2016; Li et al., 2015; Wang et al., 2017). The implementation of storage tanks can decrease the effect of intense rainfall events while the stormwater can also be re-used as non-potable water source (Mitchell et al., 2008).

1.1.2. Upcoming challenges for water systems

Uncertainty in population growth and climate change

The uncertainty related to when, where and how urban areas will grow as a result of urbanisation, economic growth and population growth is one of the core issues that urban water systems have to deal with (Qi and Chang, 2011; Savic, 2005; Urich and Rauch, 2014). In the design of centralised urban water systems, the addition of new branches – as a result of realising new housing estates or an increase in economic welfare – makes the allocation of the appropriate water infrastructure difficult to determine (Ashley et al., 2005; Nie et al., 2009; Semadeni-Davies et al., 2008). Adaptive governance can be used to decrease the uncertainty related to the expansion of the system, especially when considering the vast amount of investments needed for urban water systems (Speers, 2008). One way of realising adaptive governance which also helps to decrease the uncertainty related to network expansions, is the implementation of local water systems.

Regarding climate change, a number of associated disruptions, such as more intense rainfall events and longer periods of drought, will affect urban water management as a whole (Brown et al., 2009; Muller, 2007; Pingale et al., 2014). The roles and responsibilities of urban water systems have, as a result of making cities more climate resilient, increased (He et al., 2019; Kleerekoper et al., 2012; Richards and Edwards, 2018). An example of this is active groundwater control. The quantitative control of groundwater has become a responsibility of the urban water manager since the implementation of the Water Law in 2009 in the Netherlands. The responsibility of controlling the groundwater table is a tool to deal with the upcoming challenges. The effects of climate change may be uncertain, but their impact is somewhat known and applying additional control to the water cycle for urban environments by inclusion of tools such as activate groundwater control are deemed necessary to minimise this impact.

Groundwater depletion

Groundwater is often used as main or additional resource in regions with frequent water stress. As a result, 39 (± 10) % of water that is abstracted from aquifers annually is depleted (Wada et al., 2010). When not appropriating the pumping of groundwater, the effects of climate change can be exacerbated by the depletion of groundwater sources whereas adequate management can contribute to the mitigation thereof (Konikow and Kendy, 2005). So, another challenge that is likely to result in additional responsibilities for the urban water manager is the sustainable exploitation of groundwater sources.

Sustainable water demand management that counters the depletion of groundwater resources is needed, especially in urban regions with high population densities (Arfanuzzaman and Rahman, 2017). The recharge of groundwater by, for example, stormwater infiltration, needs to be accompanied by transformative changes in the role of aquifer systems that are implemented to operate locally (Aeschbach-Hertig and Gleeson, 2012).

1.1.3. Paradigm shift in urban water systems

In the context of urban water systems, a transition is ongoing which heads towards circularity in management practices, instead of the linear approach that has been applied thus far. Centralised water infrastructure is an example of the linear approach towards urban water management whereas the sustainable exploitation of groundwater sources is an example of the circular approach, where only water is used that has been infiltrated either artificially or naturally.

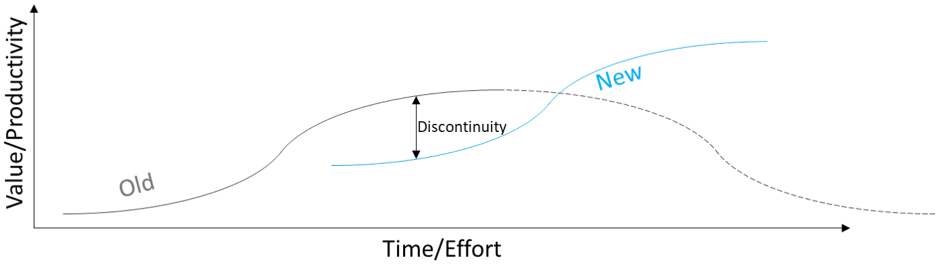

Figure 1.2: Scheme of a paradigm shift

In current developments, the centralised supply of potable water is becoming an increasingly difficult task (Weber et al., 2007). The continuous expansion of urban areas, depending on one supply system that needs to be robust, adaptable and reliable is arguably not what the centralised water infrastructure is best capable of doing on its own. Having additional water sources to the centralised system will increase the adaptability of the system as a whole to changes in demand patterns. This transition towards working with additional water source is ongoing, as can be seen by the vast amount of research relating to storm-, grey- or even blackwater re-use.
Simultaneously, the tendency to stop draining out water and instead make use of so-called Sustainable Urban Drainage Systems (SUDS), is an example of the transition towards a more circular approach (Jochen et al., 2015). Although the retention of water is not directly contributing to circularity in urban water management practices, it is a first step towards providing a new water source to the urban environment.

1.2. The Bluebloqs System

The company FieldFactors has conceivably started to provide a solution that is able to support existing urban water infrastructure, to cope with the upcoming challenges. A circular water system that complements the urban drainage system, named Bluebloqs. A general overview of the system configuration is presented in Figure 1.3. This system retains, naturally filters and exploits aquifer storage to turn stormwater into a high-quality water source that can be used for non-potable purposes. By doing so, this solution has the potential to not only complement the stormwater drainage system, it could also function alongside the water supply system. In essence, it provides a circular system that complement centralised water infrastructure in urban areas, making the combined system transform into a hybrid system.

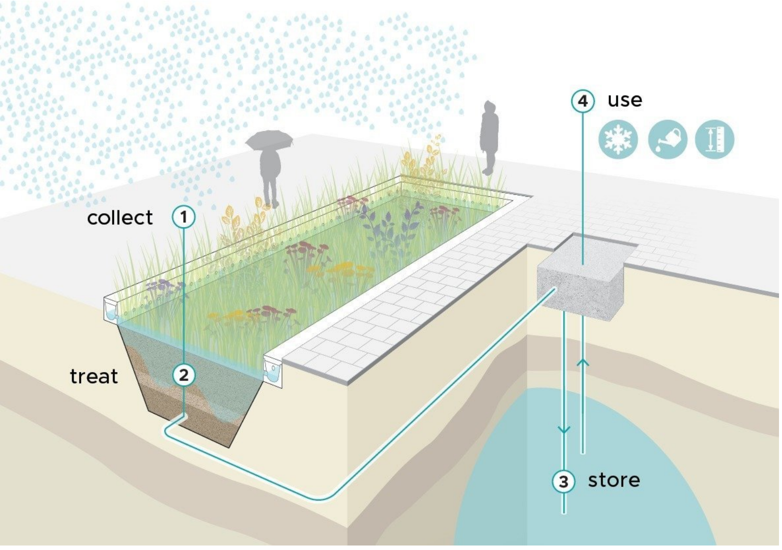

Figure 1.3: Bluebloqs system configuration

1.2.1. Hybrid water systems

The transition towards a circular approach in urban water management presents opportunities for so-called hybrid systems. These kinds of systems combine centralised infrastructure with local solutions to meet the required design standards that the integrated system should adhere to. By applying this combination of systems, the hybrid solution can deliver water services that are characterised by the good traits of both the centralised system in terms of robustness and high reliability, while creasing a more adaptable system with the inclusion of decentralised systems (Sapkota et al., 2014, 2015, 2018; Sitzenfrei et al., 2017; van Zyl et al., 2004).

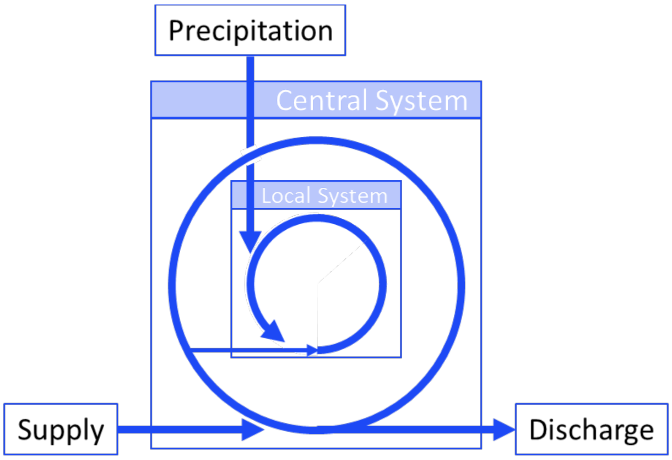

Figure 1.4: Schematic presentation of hybrid system

The term ”hybrid system” is used in this research, although the use of it among academia is ambiguous. Here, the meaning as used in this research will be elaborated upon for the specific interactions taking place between centralised infrastructure and the proposed circular water solution: the Bluebloqs system. The Bluebloqs system has been briefly introduced in Section 1.2 and will be further elaborated upon in Section 2.2.

The interaction between the systems consist of a physical integration of the local solution into the existing drainage system whereas for the supply of water, a separation of flows is necessary to maintain. The main reason for this separation of flows in the supply of water is related to the quality of the water that is supplied. Centralised infrastructure typically supplies potable water in bulk. Adding a water flow to this which supplies water for non-potable uses is not wished for. The interaction between the drainage system and the local solution can be physically realised because the local system and the stormwater drainage system both receive stormwater and thus no quality separation exists.

1.3. Knowledge Gaps

Current research as well as practice are showing a great interest in the use of Sustainable Urban Drainage Systems (Fletcher et al., 2015). Also an increasing amount of researches have been conducted that regard the decentralisation of water supply systems (Sapkota et al., 2014, 2015, 2018; Sharma et al., 2010; Sitzenfrei et al., 2013, 2017; van Duuren et al., 2019; van Zyl et al., 2004). Both these research areas as well as the implementation of local water systems in urban areas in practice, show the potential for decentralised solutions in the urban environment. This section will discuss which knowledge gaps are targeted in this research.

1.3.1. Interaction between local and central systems

It is important to gain more knowledge on the interactions that take place between the Bluebloqs system and the centralised infrastructure. If these interactions are better understood, then the implementation of the Bluebloqs system – as being a complementary solution to existing water systems – becomes more appealing.

The implementation of local solutions can have positive effects as well as negative effects on the centralised infrastructure (Sapkota et al., 2018; Sitzenfrei et al., 2013, 2017; van Duuren et al., 2019). This research intends to present the impact of the Bluebloqs system on the objectives of the water supply systems as well as the drainage system. By finding out what the added value can be of the system in terms of providing a freshwater source whilst mitigating the risk of flooding, better supported decisions can be made on the application of the Bluebloqs system as a complementary urban water system.

From an urban drainage system point of view, the recent tendency to retain water rather than drain it away, has resulted in research focusing on the dimensioning and applicability of green roofs, storage tanks, wadi's, and many other retention solutions (Joshi et al., 2021). For the Bluebloqs system, there is not yet a framework created to which the solution can be tested. This research intends to built such a framework, and present the performance of the Bluebloqs system in such a way that the impact of its implementation can be understood.

1.3.2. Co-designing the dimensions and operations to trade-off multiple objectives

The Bluebloqs system, being a circular solution that is applied in the urban context, preferably uses limited space, while maximising the flow that can be supplied and minimising the flood risk. These trade-offs all relate to the dimensioning of the different system components and how the flow between these components is operated. The design of the system should at all times be related to the way in which it will be operated, since it will otherwise not reach its designed for performance criteria. Within this research, co-designing the dimensions and operations is important both to the internal performance of the Bluebloqs system as well as its function in the urban context. This co-designing entails making the trade-offs between the design choices, such as the available storage capacity, and the operations of the flows, such as the pump discharge that removes the water from storage. The interactions between these dimensions and operations of the system are addressed in the co-designing process.

Sustainable Urban Water Systems

Since the Bluebloqs system is a circular system, the use of the attenuation tank is multi-faceted. On the one hand this tank should support the drainage system by creating enough available storage. On the other hand, it should facilitate a controlled flow towards the bio-filter. Different dimensioning of the system as well as the operations impact the performance of the Bluebloqs system. However, the trade-offs that underlie the performance of the solution are not yet fully understood. Presenting these trade-offs and advising on preferred decisions in terms of dimensioning and operations of the system is what this research intends to do.

Storage or attenuation tanks that relieve the pressure on centralised drainage system when extreme flows occur are nowadays widely applied (Lin et al., 2019). The optimal placement of storage tanks in the system is already studied extensively for flood mitigation and point-pollutant control (Wang et al., 2017). However, if a storage tank is not only considered as storage facility in the case of extreme precipitation or to control pollution, but would also be considered as component for the re-use of stormwater, this multi-functionality will add value to the storage tanks.

This research will look at the use of an attenuation tank in the configuration where it maximises the amount of water fed to the Bluebloqs system without hindering the performance of the storage tank in minimising flood occurrences. To do so, predictive control of the incoming flow is looked at as a possible solution to reduce the impact of overflow events. Predictive control of storage tanks is presumed to be a useful tool that will spread out an overflow event over a longer period of time, as to ensure the supply objective can be maintained whilst the impact with which an overflow event occurs decreases.

1.4. Research Setup

This thesis aims to present the Bluebloqs system as solution in the transition of urban water management to make cities more climate-resilient. This research will therefore try to find out *how the co-design of the Bluebloqs system and its operations can improve the functionality in providing water services to urban areas*.

1.4.1. Research Scope

This research will build a framework and a model for the Bluebloqs system. By doing so, it intends to gather new knowledge on the improved dimensions and related operations of the Bluebloqs system. By running the model under different input parameters, the changes to the output are analysed. These relate to the performance indicators, which the framework consists of. By presenting the framework for different performance indicators, the trade-offs between drainage objectives and supply objectives will become prevalent. Optimising for these trade-offs is what the co-designing process entails to do. In this research, the project site in Spangen, Rotterdam is used to present this co-designing process.

1.4.2. Goal of this research

Here, the main research question and sub-questions are mentioned. This research intends to answer the following main question:

How can co-designing the Bluebloqs dimensions and operations improve its function as a circular urban water system?

To answer this question, the following sub-questions should be answered.

1. What performance indicators should be included in the framework?
2. Which additions to the current control of the Bluebloqs system should be considered?
3. Which physical aspects of the Bluebloqs system should be modelled?
4. What adjustments can most significantly improve the supply of water through the Bluebloqs system?
5. What is the impact of the Bluebloqs system on its environment and how can it be reduced?
6. What limitations do the modelling assumptions impose on the application of the model?

1.4.3. Outline of thesis

The research will first discuss the methodology applied to find the answers to the above-mentioned research questions. Then, the framework used to analyse the Bluebloqs system will be presented. Improvements to the system in terms of applying new control options will be discussed next. Once this framework and the possibility for additional features to the system are known, a model will be built of the Bluebloqs system that presents the performance indicators included in the framework as model output. Then, different input will be fed to the model to test the performance of the system. This testing will be done on a case study, for which parameters are used to present the applicability of the model. The outcome of different dimensioning and operations will then provide information on the performance that can be expected from the Bluebloqs system.

2

Methodology

This chapter will discuss the methodology that has been applied in this research, to find the answers to the research questions. First, the road to answering each of the sub-questions will be discussed briefly. To answer the sub-questions, this chapter will describe the framework applied, a specific case study and the additional control options that are identified.

The Bluebloqs system as it will be considered in this research will firstly be clarified. The framework is then presented and the specific case study that is used to test the performance of the Bluebloqs system is elaborated upon. Additional control options are furthermore included.

2.1. Methodological Approach

This section will briefly discuss the approach that has been applied to find the answers to each research question. Also, the links between the questions, and how they relate to the further steps in the research are mentioned.

Analysing the Bluebloqs system

This research will regard the Bluebloqs system as proposed solution to improve urban water systems. It is therefore important to start off by explaining the configuration of the Bluebloqs system. It is this solution that is presented and therefore the components, internal interactions and interactions with the external water infrastructure – the centralised supply and drainage system respectively – should first be described. Describing the Bluebloqs system is not explicitly part of the methodological approach, yet it is key to first understand the system at hand, before it can be decided what indicators its performance can be based on.

Finding the performance indicators

Once the system is described, a framework is necessary to test the performance of the Bluebloqs system. To create this framework, it is essential to analyse what indicators present the performance of the Bluebloqs system as circular water solution. The outcome of this analysis will yield viable information regarding the challenges that urban water management has to deal with and how the Bluebloqs system is able to cope with these challenges. By acknowledging the circular role that the Bluebloqs system can fulfil, the performance indicators are presented within the framework to test the performance of the solution on specific objectives that urban water systems should reach, such as the number of allowed overflows.

Including new control options

Improvements to the Bluebloqs system can be applied in two-fold. Either the current system and dimensioning can be altered, or additional control options can be considered to find out how these could further improve the Bluebloqs system. In this research, new control options are explored and the performance of the Bluebloqs system is tested to see the impact of adding these new control options to the system.

Modelling the physical behaviour

To test the existing Bluebloqs system – and the suggested improvements – on its performance indicators, a model of the system is needed. This model should present the Bluebloqs system in a way that the physical behaviour is in accordance with reality. However, the principle of modelling is that reality is simplified. Therefore, the focus of the modelling approach is to simplify the Bluebloqs system where appropriate, but to keep in mind the objective of the model; to test the performance of the Bluebloqs system on the framework.

The objective of the framework is not solely testing the performance of the Bluebloqs system for different dimensions and operations, but also to gain insights in the impact of the system on its environment. The effect that behavioural aspects have, should thus also be presented as model output.

Since the Bluebloqs system will be modelled and tested on the framework to find out how the performance can be improved, there should also be a base design and base operations to the system, which presents the current situation. It is decided to make use of the Bluebloqs system which is realised in Spangen, Rotterdam. Although the framework and model presented in this research can be used to test the applicability of the Bluebloqs system in different contexts, this case study has been used to present the impact of co-designing the system dimensions and operations.

Presenting improvements to the supply of water

One of the outcomes of testing the Bluebloqs model on the framework, is to find out how the performance of the system can be improved in terms of the supply of water. The adjustments of parameters and the inclusion of new control options will be laid out in a sensitivity analysis, where the most significant improvements to the system are taken into consideration.

Evaluating the impact of system on the urban environment

Being a circular solution means there is an impact of the system in minimising the flood risk and providing a source to supply water. These can be considered the interaction points of the Bluebloqs system with its environment, where the positive and negative traits of the system are necessary to be included in presenting its overall effect on the environment. An important notion to make is the terminology related to *environment*. By looking at the impact of the system on its environment, the direct impact of overflow events or the storage of water in the aquifer are considered. Environmental concerns such as materials used are not considered.

Discussing the effect of model assumptions on applicability

Once the Bluebloqs system is modelled and different simulations have been run, the legitimacy of the model approach must be taken into consideration. The performance of the Bluebloqs system as presented by the model outcome should be put into perspective with regard to what the simplifications mean for the presented results. This will also implicitly determine the application of the model in terms of being a calibration and monitoring tool or that it can better be used to test the applicability of the Bluebloqs system in a given setting.

2.2. The Bluebloqs System

In this section, an overview of the Bluebloqs system is given. The system configuration is elaborated upon. The interactions between the internal components of the system are mentioned and also the relation with the components that are not part of the Bluebloqs system are also discussed.

2.2.1. Contributing flows and their interactions

The Bluebloqs system consists of three components which altogether create a circular system. This system is able to retain stormwater, but also filter it to such an extent that it can be stored for extended periods of time, after which it can be re-used as high-quality water source. A schematic overview of the system is given in figure 2.1. Now, each component that is displayed and that will be included in this research, will be discussed.

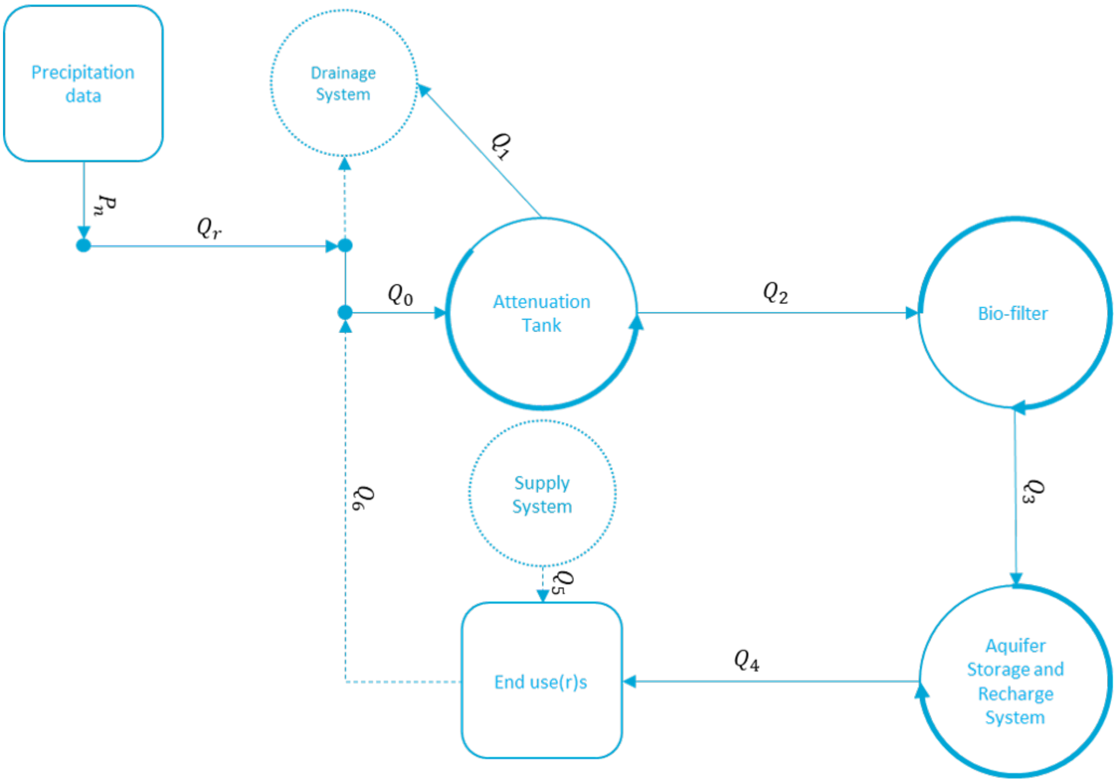

Figure 2.1: Schematic overview of the system components

The flow entering the system is directed towards the attenuation tank through the stormwater drainage system. The flow that enters the centralised drainage network is presented as Q $_r$. This incoming flow is based on precipitation data, which is translated to runoff. The runoff entering the network can be diverted either towards the attenuation tank or towards the downstream drainage system. This direct flow further through the drainage system is what nowadays is often applied. This line is dashed in Figure 2.1 because it is excluded from this research, and it is assumed that all of flow Q_r will contribute to flow Q_0. The incoming flow Q_0 fills up the attenuation tank. From the attenuation tank, the water is fed to the bio-filter, depicted as flow Q_2 in Figure

2.1. The water is fed to the bio-filter from the top and drains vertically under gravitational force. The outflow Q_3 leaves through a filtration pipe at the bottom of the bio-filter. This is the flow that is infiltrated into the aquifer where the water is stored for extended periods of time. The flow Q_4, the flow out of the aquifer, follows the demand pattern specified for or by the end-user.

Additional flows that should be considered are the flow Q_1 and flow Q_6. Flow Q_1 presents the water that is lost in overflow events when the attenuation tank does not have the capacity to retain the incoming volume of water. Also, flow Q_6 is presented in Figure 2.1 which is the re-use of water from the end-user. This flow could take on many forms but is in this research excluded, to simplify the Bluebloqs system to a circular solution that only makes use of stormwater harvesting as source.

2.2.2. Approach to system behaviour

This section will discuss the behaviour of each component in more detail. The configuration and interactions remain as presented in Figure 2.1.

Flow entering the system

From precipitation data, initial losses are subtracted to get the net precipitation, P_n. This net precipitation is then multiplied by an average runoff coefficient and the catchment size to get the runoff flow Q_r. This flow is also known as runoff that enters the stormwater drainage system.

The incoming flow sums up to the incoming flow Q_0 which enters the Bluebloqs system in the attenuation tank. Important to note about the method that is applied is that no delays are taken into account. The focus of this research is on the Bluebloqs system, of which the impact limits itself to a maximum area that has contributing flow towards the attenuation tank. Due to the limited area size, the piped network from the outer corner of the area heading towards the attenuation tank is of limited length. If the assumption of a maximum flow path of one kilometre is used, and a flow velocity ranging between 0.3 meters per second for little precipitation events and 1 metre per second for large events, it can be concluded that the travel time for water from the point furthest from the attenuation tank to the inlet, ranges between 0.28 and 0.93 hours. The model makes use of hourly time steps for the calculations of volume flow. The travel time under the given conditions does not exceed the one-hour time scale and it can therefore be concluded that, for this type of system, the Rational Method suffices.

Water balance for the attenuation tank

The attenuation tank is considered as the system component where the Bluebloqs system and drainage objectives integrate. The flow Q_1 presents the overflow of the attenuation tank back into the drainage system.

The main function of the attenuation tank is to attenuate the incoming flow. This tank fills up during precipitation events and will let the water flow periodically towards the bio-filter, this flow is depicted as Q_2 in Figure 2.1. The operations of the flow towards the bio-filter should regard both the water level in the attenuation tank, minimising the number of overflows, while ensuring the bio-filter can be operated to yield the best removal performance. Research by FieldFactors regarding the optimal retention in the bio-filter and the related flow pattern, which regulate the removal efficiency, is ongoing. This model therefore creates a design choice for the user that makes it possible to adjust the periods of turning the flow from attenuation tank to bio-filter on and off.

Behavioural considerations for the bio-filter

Once the water leaves the attenuation tank, it reaches the components of the system that deal with the removal of pollutants from the water. The replenishment of the bio-filter with polluted water causes the head level in the bio-filter to increase. This increase imposes a pressure gradient that results in an outflow out of the bio-filter towards the Aquifer Storage and Recovery (ASR) system, flow Q_3. The assumption is made that a linear laminar flow regime can be considered in the bio-filter, which means that the head level increase can be calculated based on a volumetric balance and the geometry of the bio-filter shape. From this, the pressure gradient found from the head level increase results in an outflow, which can be calculated by applying Darcy's Law.

The application of aquifer storage and recovery

The last component of this system is the ASR system. The use of the aquifer for the managed storage of fresh water makes it possible to overcome seasonal water deficits. A balance between the water put in the ground and taken out of the ground should be a strict requirement for an ASR system to be operated in a sustainable manner. By adding water to a saturated soil layer, additional pressure on the covering aquitard [1] may lead to seepage. Since the Bluebloqs system has its infiltration well located in the most shallow aquifer layer, seepage leads to changes to the groundwater table.

End-user water demand and aquifer recovery efficiency

From the aquifer, water is also extracted for re-use. Based on the objectives of the Bluebloqs system, this re-use can vary in seasonality and in total amount of water demanded. One of the objectives of the Bluebloqs system is to complement water supply systems. The water that can be delivered to the end-user, flow Q_4 in Figure 2.1, presents this flow. The amount of water that can be extracted from the aquifer is limited by the amount of recoverable water. Since most of the water that is infiltrated is extracted in summer, the effects of water mixing with antecedent groundwater and background flow decrease the ability to extract water. These processes are simplified by assuming a recovery efficiency (RE), which constraints the extraction of water to a percentage of the infiltrated water.

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[1] A layer (often clay) with low hydraulic conductivity limiting vertical flow

2.3. Building a framework for the Bluebloqs system

The framework that is being created will test the solution based on three main principles. Firstly, the interactions between the Bluebloqs system and the centralised infrastructure will be considered. Based on these interactions, objectives for the local system can be found that can be translated into performance indicators. Secondly, the internal operations and dimensions of the system have an effect on the provision of water services. How the water quality of the supplied water is affected by adjustments to the system should become more clear from the performance indicators. Lastly, the impact of implementing the Bluebloqs system on its environment should be considered. Here, the actual environment in which the Bluebloqs system operates is considered. In Figure 2.2, the performance indicators for the three applications of the framework are presented. In the next sections, these will be explained.

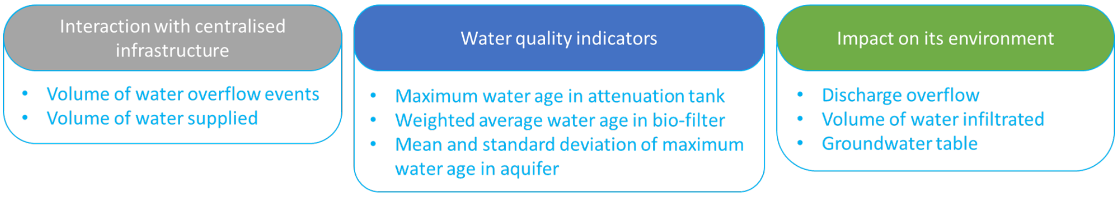


Figure 2.2: Framework for testing the performance of the Bluebloqs system

2.3.1. Interactions with centralised infrastructure

With the envisioned urban water system – consisting of centralised infrastructure and local solutions that complement each other – the function of the Bluebloqs system in providing water services can be translated to objectives. Whether or not the system meets the set objectives can be answered by comparing the actual performance of the system to the performance indicators.

Supply Objective

Based on the configuration of the Bluebloqs system that has been presented in Section 2.2, the role of the Bluebloqs system in terms of supplying water to the end-user can be determined. This role is based on the circular nature of the system, hence the supply of water is limited by the volume of the stormwater that is captured by the system. The performance of the system in terms of supplying water to the end-user for non-potable use is also determined based on the water demanded by this end-user.

The end-user water demand determines when and how much water is to be extracted from the aquifer. The performance of the system in terms of supplying water is based on whether or not this water demand is met. Within the model, the constraints that the system should adhere to – for example in terms of having sufficient water infiltrated before extraction of water can occur – are included, which makes the outcome of the model, the volume of water extracted, an indicator that can be compared to the annual water demand, and thus presents how much percent of the water demand can be supplied by the system.

Drainage Objective

The configuration of the Bluebloqs system consists of a physical interaction with the centralised stormwater drainage infrastructure. This implies that overflow events taking place in the attenuation tank will be conveyed towards the downstream piped network, through which it is discharged to the receiving water body. For the design of the downstream piped network, it is necessary to asses the volume of water that will flow through the system. Therefore, the performance indicator obtained for the integration of the Bluebloqs system into the centralised stormwater drainage system is the annual volume of water lost in overflow events from the attenuation tank.

Figure 2.3 presents the two performance indicators for the Bluebloqs system in relation to the interactions taking place with centralised infrastructure.

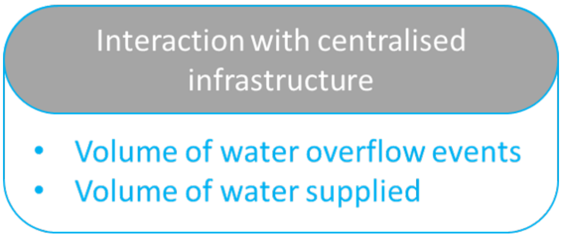


Figure 2.3: Performance indicators based on interactions with centralised infrastructure

2.3.2. The impact of the Bluebloqs system on its environment

Being a circular system means that the interaction with the surroundings occurs in two-fold; on the one side there are the overflow events which interact with the downstream water system. On the other side there is the seasonal storage of water in the ground which affects the antecedent groundwater quality and the storage capacity of the aquifer. These two ways in which the Bluebloqs system affects its environment are presented here.

Impact of overflow events

To determine the dimensions of centralised piped networks, the peak-over-threshold method is often applied. This method uses time series of incoming flow and translates this to a maximum acceptable flow discharge that the pipes should be able to deal with. By implementing the Bluebloqs, the volume of water that is lost was already presented as important performance indicator for the integration with the centralised infrastructure. Here, it is decided to also include the discharge with which these flows through the downstream piped network will take place. This can be insightful for the dimensioning of future piped systems that are necessary to convey the water to the receiving water body, but also to determine the impact of overflow events from the Bluebloqs on the receiving water body. Overflow events with a large discharge result in larger volumes of water entering the stream. At this interaction point, more erosion will take place but also a higher flood risk downstream can be the result of large discharges leaving the Bluebloqs system.

The infiltration of water into the aquifer

Having water stored in the aquifer to later extract is the overall objective of the Bluebloqs system. To make this possible, infiltrating water into the aquifer is necessary. The volume of water that can be extracted is related to the volume of water that enters the system in the form of stormwater through the infiltration of water. Infiltrating more water would presumably result in the extracted volume of water being closer to the water demand. This relation is expected to occur up to certain extent. At some point, the infiltration of additional water will not result in more extraction. However, to find when this happens is an important indicator for the systems' performance, and is therefore included in the framework.

Consequences to the groundwater table

Since the Bluebloqs system infiltrates filtered stormwater into the most shallow aquifer, the effect of filtrating water into – and extracting water from – this layer on the sub-soil should be taken into consideration. To do so, the aquifer is analysed and the infiltration of water is analysed by applying the solution of Jacob and Hantush (Bakker, 2020). This solution presents the groundwater level variations in the layer above the aquifer where infiltration and extraction occurs. For the Bluebloqs system, this solution thus presents the effect on the groundwater table. If seasonal storage of water in the aquifer has a large impact on the groundwater table, this would interfere with the active control that water boards are pursuing. The groundwater table is constantly monitored to reduce the risk of pluvial flooding. It is therefore important to analyse the impact of the Bluebloqs system on the groundwater table.

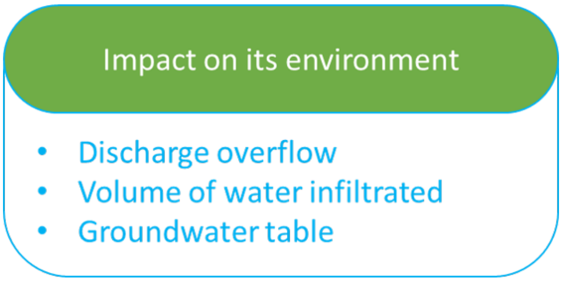


Figure 2.4: Performance indicators based on the impact on the environment

2.3.3. Water quality indicators

In this research, a deterministic model will mimic the behaviour of the Bluebloqs system. By doing so, this research tries to find relations between the dimension and operations that underline the functionality of the Bluebloqs system in terms of draining out stormwater and providing a water source for high-quality use.

Although the main goal of this research is to determine relations between the design and operations of the Bluebloqs system in dealing with water quantities, the inclusion of water quality aspects needs consideration. The water quality is tracked by using the water age in the different system components. The modelling of water quality aspects relates to many processes, parameters and initial conditions which at this time are not yet readily available for the Bluebloqs system. Consequently, the water age in the system is considered as best alternative to relate design and operational adjustments to water quality aspects.

The deterioration of water quality in the attenuation tank

For the attenuation tank, the maximum water age is kept track of. The maximum water age is presumed indicative for the water quality. The deterioration of water is related to the duration of water being contained in the attenuation tank. Hence, the inflow that did contribute to the volume of water present at a given time step, furthest away from the current time step, should be considered. This volume of water has been contained from the moment it entered up until the time step considered. Having a reduced maximum water age means the deterioration of the water quality is less.

Using the minimum water age in the attenuation tank could also be worth considering, since this provides information on the ability for particles entering the attenuation tank with the stormwater to settle. However, this minimum water age in the attenuation tank is not included as performance indicator in this research.

Water quality indicators

- Maximum water age in attenuation tank
- Weighted average water age in bio-filter
- Mean and standard deviation of maximum water age in aquifer

Figure 2.5: Performance indicators based on the supply of high-quality water

The weighted average water age in the bio-filter as indicator of retention time

For the removal of pollutants from the stormwater, the bio-filter gradually lets the water flow through the porous media. To find out how well the water is being filtered, it can be considered useful to find a value that presents how long water has been retained in the bio-filter. This is done by calculating the average water age that is present for a given time step. For each time step, the preceding incoming flows that have contributed to the current volume of water available have been accumulated. For each of these, the volume of water that has entered the bio-filter is related to the duration between this flow entering the bio-filter and the time step under consideration. By multiplying this weighted water age with the outgoing flow, an indicative value is obtained that presents how long, on average, the volume of water that leaves the system for a given time step has been retained in the bio-filter. This is explained in more detail in Section 3.3.1.

Also, regarding the weighted water age in the bio-filter, it is insightful to present the standard deviation of the weighted average water ages. If this value is relatively high, this indicates that the system relatively often is not operated in accordance with the activation frequency that is being considered.

Water age in aquifer to determine the positioning of the extraction well

As described, the processes affecting the availability of water for extraction from the aquifer are complex. An example of this is the background flow, which moves the water stored in the aquifer horizontally (and vertically). To be able to extract the water, it is useful to have an indication of how long this water is stored in the aquifer. This can be determined by using the maximum water age in the aquifer, in combination with the standard deviation. Once it is known how long most of the water is retained in the aquifer, based on this mean and standard deviation, this information can be used in the design of the Bluebloqs system. The placement of the extraction can be optimised based on this information.

2.4. Case Description

The framework will be tested on the Bluebloqs system that is in operations in Spangen, Rotterdam. The decision to make use of this location is based on the fact that more research has been performed already on this system. These researches have already presented improvements to the system as well as results regarding the performance of the system. The configuration of the Bluebloqs system as realised in the Sparta stadium in Spangen, Rotterdam, is presented in Figure 2.6.

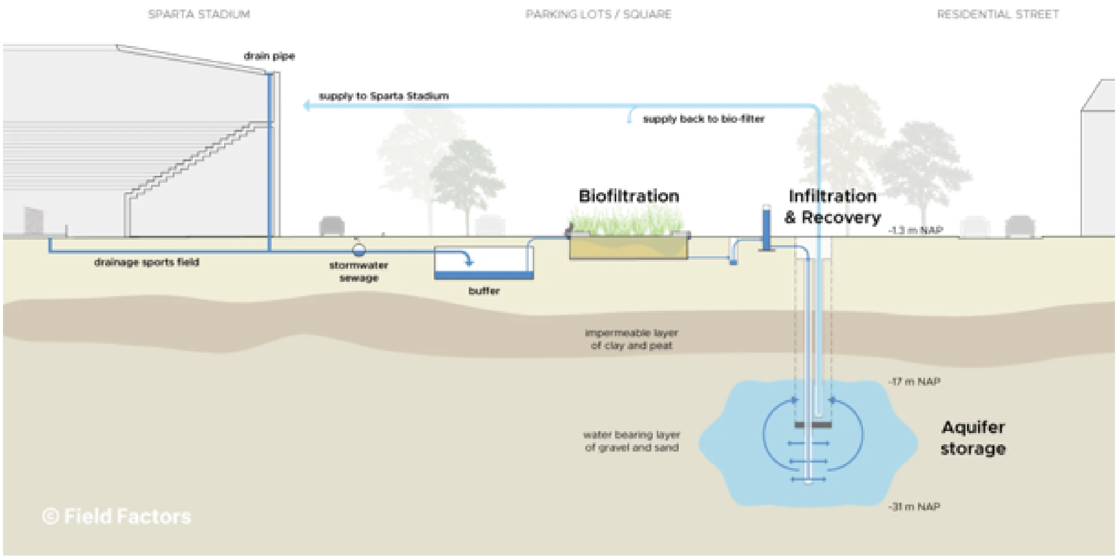


Figure 2.6: Bluebloqs configuration in Spangen, Rotterdam

Validation of the system

Validation of the modelling approach based on reality is not considered a feasible option since the existing system is pilot project. This means lessons have been drawn from the flaws in design choices and operations of this system, which should not be included in the modelling approach. Since the goal of this research is to find out the potential of the Bluebloqs system for future implementation, it is decided to not validate or calibrate on the system in Spangen, Rotterdam.

By choosing to build a model that is not validated or calibrated on existing systems, the model must adhere to theoretical frameworks for it to present reliable outcomes. Although validation based on the project site in Spangen is not deemed feasible, the model should still somewhat align with the results that are presented in previous research. If, for example. the volume of water that can be extracted in reality, is one order of magnitude larger, or smaller, than the model presents, it can be concluded that the model does not yield feasible outcomes that can create insights for new projects.

The next section will present the main assumptions and parameter values that are used in relation to the project site.

Data collection

Data that has been used in this research for the modelling of the system are location-specific and have been taken from previous research done by FieldFactors, TU Delft, and KWR. (Jonker, 2020; Wesselink, 2019; Zuurbier and van Dooren, 2019). The data collection from the researches will be discussed now, where the research of Zuurbier and van Dooren (2019) presents information regarding the overall performance of the system, the research of Wesselink (2019) focuses on the aquifer characteristics and from the research performed by Jonker (2020), the bio-filter is thoroughly discussed. Information that is uncertain from these researches is compared to literature (De Wiest et al., 1969).

Rainfall data is gathered from the Royal Dutch Meteorological Institute (KNMI). Here, hourly data is used of precipitation events occurring between January 2015 and January 2020 in the city of Rotterdam. This data is used because of its high density of data points and because it adequately represents the climatology of a Dutch urban setting. Also, since the data is taken from a trusted source which handles precipitation data for all weather stations in the Netherlands in the same way, choosing to use other data is easily implementable in the model. The translation of columns and rows is automated and therefore loading a time series of more data, for a different location or for a different period would all immediately result in the model presenting the chosen for configuration and operational performance of the Bluebloqs system for this different precipitation data. It therefore creates simplicity in analysis of the systems performance under different conditions.

The catchment area is equal to 3.7 hectares, which consists of 0.6 hectares of roof, 1.8 hectares of parking and 0.6 hectares of football pitch (grass). From research, a weighted runoff coefficient of 0.55 is found. However, there are some uncertainties related to the catchment scale as well as this runoff coefficient. In this research, runoff coefficients for the land use types are applied, rather than making use of the runoff coefficient of 0.55. By making use of the values found in Dickinson (2017), a weighted runoff coefficient of 0.75 is found and used in this research.

From the KWR research, the demand pattern for the end-user was found. The demand in summer months, starting in June and ending in September, is equal to 120 m^3 per day. For the winter months, the demand decreases to 10 m^3 per day. This results in an annual water demand of 17.000 m^3.

There is also a requirement regarding the hourly discharge. The desired supply of water in half an hour is equal to 4 m^3, which means the supply of water should at least be able to have a discharge of 8 m^3 per hour.

Moreover, the KWR research has stated the pump discharge from the attenuation tank to the bio-filter, which is set to 30 m^3 per hour. The attenuation tank itself has a total capacity of 1400 m^3. Also, the bio-filter top area is equal to 120 m^2, where the filter bed is divided in three layers of filter media with different porosities. An average porosity of 40 % is abstracted from this.

From the research of Wesselink (2019), many important behavioural aspects of the water in the aquifer are presented. However, the Bluebloqs system is operated with a one infiltration well, and one injection well which are at the same location. The extraction well is more shallow, which ensures the water is retained in the aquifer for sufficient time. The behaviour of the water in the

Table 2.1: System dimensions

Dimensions		
Attenuation Tank	Length	40 m
	Width	25 m
	Height	1.4 m
Bio-filter	Length	13 m
	Width	4 m
	Porosity	40 %
	Slope	45°

aquifer is simplified by assuming a recovery efficiency (RE). This value varies over time, yet from the mentioned research it is concluded that a value of 70 % can be deemed representable for the situation in Spangen. This research also presents the constraints that the aquifer imposes on the system, presented in Table 2.3.

Table 2.2: System operations

Operations			
Attenuation Tank	Summer	Self-preservation Volume	100 m^3
Pump	Summer	Activation Frequency	Continuous
		Discharge	10 m^3/hour
		Break Duration	-
	Winter	Activation Frequency	Continuous
		Discharge	10 m^3/hour
		Break Duration	-
Demand Pattern	Summer	Activation Frequency	1 / 12 hours
		Hourly Demand	10 m^3/hour
		Break Duration	12 hours
	Winter	Activation Frequency	1 / 24 hours
		Hourly Demand	10 m^3/hour
		Break Duration	23 hours
Aquifer	All year	Recovery Efficiency	70 %

Information regarding the bio-filter is taken from Zuurbier and van Dooren (2019) and Jonker (2020). The research performed by Jonker (2020) goes into great detail on the removal of pollutants from the water, and to do so gives a thorough explanation regarding the behavioural aspects of this system component. Since the research that is being executed focuses on the water quantity perspective, much of the findings are simplified, such as the bio-filter medium composition. The values found in this research are presented in Table 2.3. The permeability has been simplified in relation to the porosity of the bio-filter based on De Wiest et al. (1969). The reason for this is the heterogeneity of the bio-filter medium found in Jonker (2020), which is undesirable for future systems and therefore a homogeneous value is used that is proposed by research for flow through porous media.

2.5. Additional control options

A number of additional control options are considered to improve ethe performance of the Bluebloqs system. These control options will be presented here, with explanations regarding their

Table 2.3: System Constriants

System Constraints			
Land cover & use	Average Runoff Coefficient	C	0.75 [-]
	Connected Surface	A	3.7 ha
Bio-filter	Permeability	k	34.6*10^{-6} m/s
	Kinematic Viscosity of water	η	$1 \cdot 10^{-6}$ m^2/s
	Pore volume of bio-filter	μ	1 30 m^3
	Water Density	ρ	1000 kg/m^3
Aquifer	Hydraulic Conductivity	k	40 m/d
	Aquifer depth	H	10.75 m
	Transmissivity	T	430 m^2/d
	Clay layer resistance	c	2000 days
	Leakage factor	λ	95 m
	Specific Storage	S_s	1 * 10 $^{-5}$ m^3

expected impact. Both improvements and possible negative side-effects to the performance of the Bluebloqs system as a whole will be mentioned.

2.5.1. Activation frequency

The Bluebloqs system is a circular solution. This means that the system should be tested on both the reduction in flood risk it can provide, as well as the water it supplies. Although this research focuses on the water quantity perspective, it should also yield outcomes that relate the design and operations of the system to its performance in terms of providing a high-quality water source. It is assumed that more control of water being fed to the bio-filter will result in insights regarding the removal efficiency of the bio-filter and thus the water quality delivered to the end-user. To gain more control of the flow going in and out of the bio-filter, the activation of the pump that discharges water from the attenuation tank onto the bio-filter should be controlled. This research adds the following control to this pump, to find out what its consequences are on the performance of the Bluebloqs system.

The pump that discharges the water from the attenuation tank to the bio-filter is, in the current configuration of the Bluebloqs system, activated whenever the water level in the attenuation tank exceeds a certain threshold. As long as the water level in the attenuation tank does not go down to a minimum level, the pump will remain activated. This can result in prolonged pumping of water over the bio-filter resulting in a minimum removal of pollutants for the processed water. It is therefore decided to look into the possibility of having an activation frequency set for this pump. This means a maximum duration for which the pump is activated, given the existing constraints of having sufficient water available in the attenuation tank. The control of this activation frequency proposed in this research is the following.

One activation of the pump will have the duration that is equal to filling the pore volume of the bio-filter. This means that, for the given study location, where the bio-filter pore volume is 30 m^3 and the pump discharge is set to 30 m^3 per hour, the pump should be activated for one hour. If an activation frequency of, for example, six times per day is chosen, then the 24 hours of a day are divided by six, to find the process duration for one feed cycle. This is $\frac{24}{6}$ =4 hours. So, one feed cycle takes 4 hours. Given the pump discharge and pore volume, the activation of the pump takes one hour, and therefore the resulting break duration, or time for the water to be filtered in the bio-filter, is extracted to be equal to 3 hours.

2.5.2. Summer and winter regime

A trade-off between having enough storage capacity available and increasing the removal efficiency in the bio-filter can be established by applying a summer and winter regime. By having an increased number of flows with a pre-defined volume of water heading towards the bio-filter in periods where large volumes of water are expected to enter the system, can ensure the system does not lose water in overflow events. Also, having a controlled flow towards the bio-filter that is not activated too often can increase the removal efficiency of the bio-filter.

2.5.3. Predictive control

The Bluebloqs system is expected to have overflow events taking place. To minimise the impact of these flows, predictive control is proposed. Based on a prediction horizon, the accumulated volume of water entering the attenuation tank can be estimated. If there is insufficient storage capacity in the attenuation tank, the water would, without a prediction horizon, overflow in the time period at which the incoming flow exceeds the available storage. This may lead to unfavourable timing, because the overflow may be aligned with large volumes of water flowing through the downstream centralised water infrastructure, where the overflow event is conveyed towards. By making use of predictive control, this can be averted.

3

Mathematical Modelling

In this chapter, the model of the Bluebloqs system will be elaborated upon. The theoretical frameworks are associated to the following components:

- Incoming flow
- Attenuation tank
- Bio-filter
- Aquifer Storage and Recovery (ASR)

The incoming flow and three components of the system – including the interactions between them and the exterior urban water infrastructure, will be modelled. Their respective performance indicators will be translated to behavioural model assumptions and operations. Now, the model assumptions per system component are presented. For each component, the translation of the characteristic behaviour into the model is first described. Then, the operations of are presented, if the system component has control options.

3.1. Incoming flow

The incoming flow is based on precipitation data, which is translated into runoff. This runoff enters the attenuation tank and is modelled as presented in the next section.

3.1.1. System behaviour

The incoming flow Q_0 consists of stormwater. The behaviour of the incoming flow is modelled based on the Rational method where the relation between rainfall and runoff is assumed with no delays.

Rainfall-Runoff relation

Firstly, precipitation data from the project site or a representable precipitation pattern needs to be retrieved. This research will use five years of hourly data from the city of Rotterdam. This data is deemed representable for urban environments in the Dutch context.

Initial losses are assumed to be 2mm and evaporation is assumed to be 2 mm/day, meaning after 24 hours of no precipitation, the first two millimetres of the next rain event will be subtracted from the precipitation, providing the net precipitation pattern. For every hourly time step, the volume that is still not in use is taken into account as potential initial losses. By applying these operations, the translation from actual precipitation to net precipitation is found, which is given in figure 3.1.

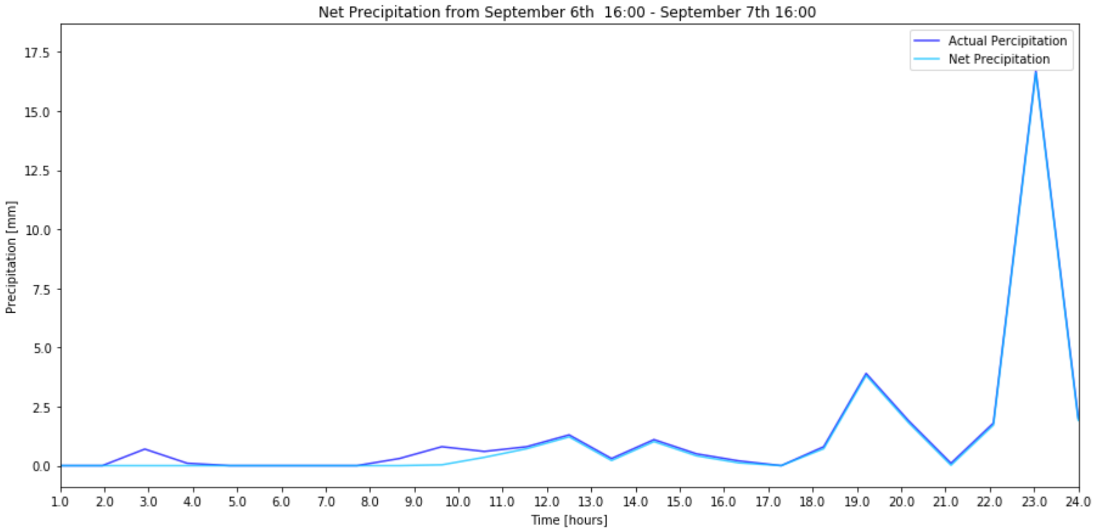


Figure 3.1: Effect of initial losses on a random precipitation event

The precipitation for a specific location does not directly tell anything about the expected drainage capacity needed in the area. The land cover types should be elated to runoff coefficients. Any combination of contributing areas with their respective runoff coefficients can be included. The rainfall data will be multiplied by this weighed average runoff – which is calculated with Equation 3.1 – and area size respectively. The resulting flow into the network is shown in figure 3.2 for the period of five years.

$$C_{average} = \frac{\sum_{i=1}^{N} C_i * A_i}{A_{total}} \tag{3.1}$$

where:

$C_{average}$ [-] = Average runoff coefficient
C_i [-] = Runoff coefficient for catchment area i
A_i [ha] = Size of catchment area i
A_{total} [ha] = Area of the total catchment

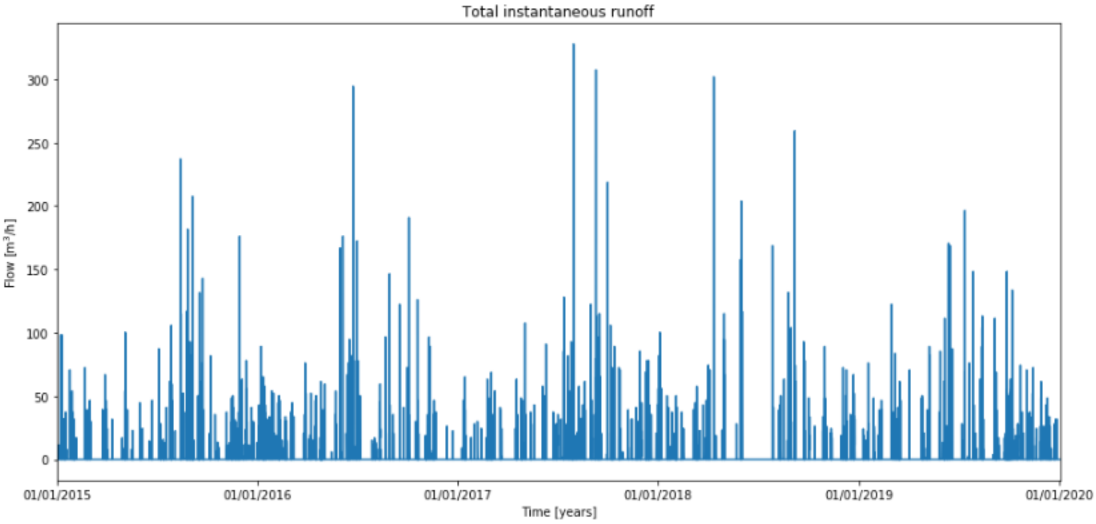


Figure 3.2: Runoff over the entire period of five years

3.2. Attenuation tank

3.2.1. System behaviour

The first component of the Bluebloqs system is the attenuation tank. The behavioural aspects of this component that are to be discussed consist of the water balance of incoming and outgoing flows, and the duration of water being retained in this tank.

Water balance of the incoming and outgoing flows

This component is modelled by creating a water balance between incoming and outgoing flows. The incoming flow consists of the calculate runoff which fills the tank. The outgoing flow can go either of two ways; preferably the water is pumped towards the bio-filter but in case of the attenuation tank being full, the water will be lost in an overflow event. The operation of the attenuation tank component is schematised in Figure 3.3

Determining mean of the maximum water ages in attenuation tank

For the water age in the attenuation tank, the first-in-first-out principle is applied. The performance indicator applied here is the maximum water age in the attenuation tank for each time step that has been considered. This maximum water age is calculated based on the water volume that is present for each time step, and accumulating the water inflows from the previous time step that have contributed to this water volume.

3.2.2. Operations

The operations of the attenuation tank consist of the active control of the pump that discharges the water towards the bio-filter. The incoming flow into the attenuation tank cannot be altered. The flow Q_1, dependent on the prediction horizon, can only be manipulated by adjusting this prediction horizon. The flow Q_2, heading towards the bio-filter, can be adjusted in twofold; either the activation frequency or the pump discharge. It can be considered beneficial to have more feed cycles in periods where the expected volume increase in the attenuation tank is more rapid, which in the Netherlands would occur during the summer months, while slower filling of the tank

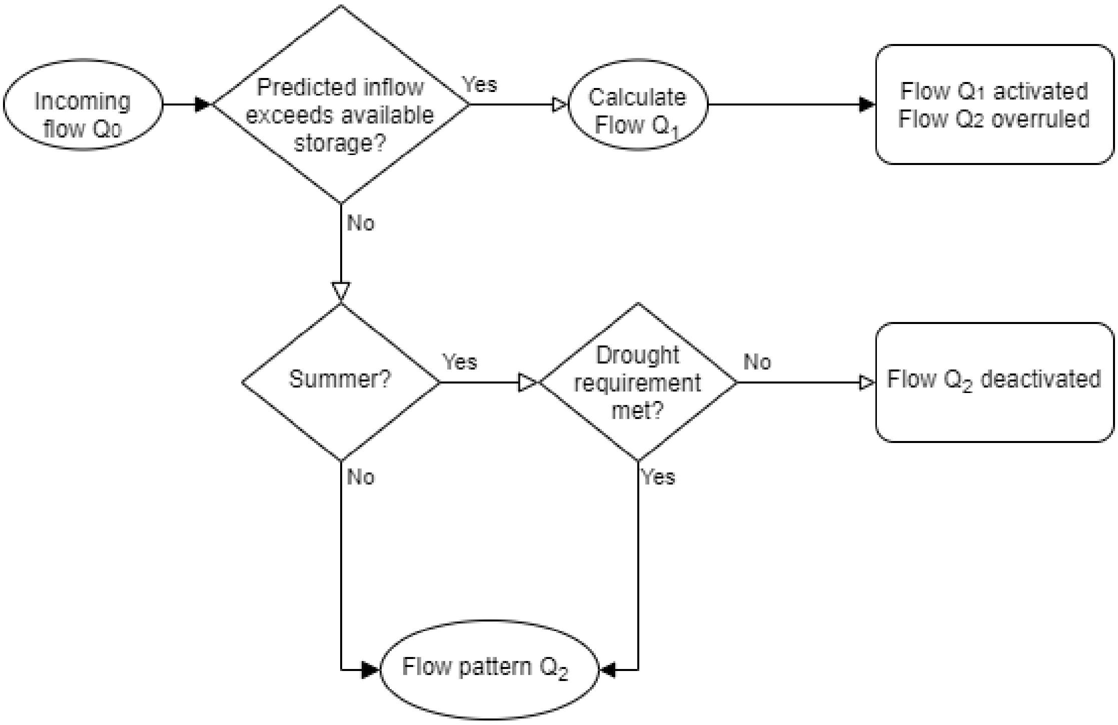


Figure 3.3: Operational considerations for the attenuation tank

can be expected during winter time.

Predictive control

One of the control mechanisms for this component of the system is the predictive control of incoming flow in relation to the available storage volume. If this prediction horizon is set to 0, as is the case in existing Bluebloqs systems, this check simplifies to whether the water level in the attenuation tank exceeds the maximum water level in the tank, and thus whether or not an overflow event will take place in the time step that is being considered. When this prediction horizon is taken for a longer period of time, the accumulated incoming flow and outgoing flow are balanced with the available water volume for each time step. When the available storage volume is not sufficient, the overflow event will be evenly divided over the prediction horizon.

Summer and winter regime

Once the available storage is redundant to deal with the incoming flow, the second control step is to check whether the dry or wet – or summer or winter – season should be considered. However, the model is expected to present a generic overview of the performance of the Bluebloqs system, also when different climates are considered. The summer season applied in this research is based on dates and starts on the first day of June and ends on the last day of September. Within the model, the start of the summer and winter season can be altered to any desired date.

For the Bluebloqs system to ensure self-preservation, a minimum amount of water must be stored in the attenuation tank in the dry season, for the bio-filter to survive in periods of drought.

For the summer period, water scarcity in the urban environment is expected to occur. The system should therefore be in 'hibernation mode'[1] to reduce the risk of increased operational cost as a result of plants dying in the bio-filter. An example of such a long period of drought can be found in Figure 3.2 in the summer period of the year 2018. During the winter season, no such minimum amount of water is necessary for the self-preservation of the system since redundant precipitation is expected to occur in this season.

3.3. Bio-filter

3.3.1. System behaviour

The bio-filter is the first component of the Bluebloqs system that deals with the removal of pollutants from the water. The bio-filter is fed from the top with water from the attenuation tank. The water then infiltrates through the bio-filter, where physical, physio-chemical and biological removal processes filter the water. At the bottom of the system, an irrigation pipe transports the water towards the aquifer.

Geometry of the bio-filter and the relation to the head

The bio-filter is modelled as a large bucket filled with a material for which the permeability and porosity are input parameters. The base width and length of the bio-filter are input parameters as well. The bio-filter is constructed under an angle of 45 °over the length of the bio-filter, as presented in Figure 3.4. This angle is assumed to be 90 °, and thus rectangular, over the width of the bio-filter.

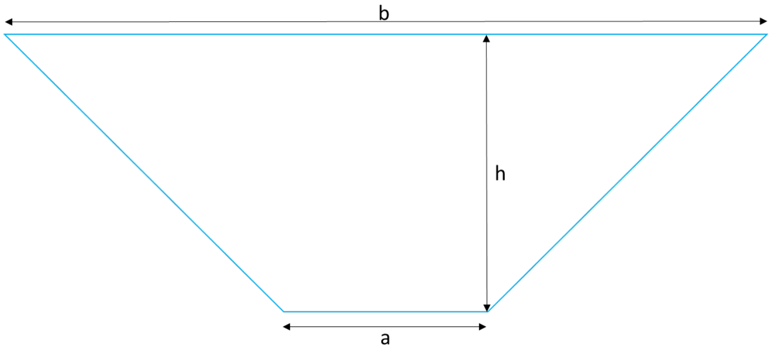


Figure 3.4: Geometry of bio-filter

The geometry of the bio-filter is used to find a function of the head in the bio-filter. Since the shape over the width of the bio-filter is assumed rectangular, the volume of water in the bio-filter can be divided by the length of the bio-filter to find the areal distribution of the water in the porous volume. So, the volume of water in the bio-filter at time step t can be translated to the area of Figure 3.4 filled by applying Equation 3.2.

$$A[t] = \frac{V[t]}{L\mu} \tag{3.2}$$

where:

---

[1] Not dealing with volumes of water for the filtration processes but ensure the root zone of the plants is saturated periodically

A [m^2] = Area needed for volume of water
L [m] = length of bio-filter in meters
μ [%] = Porosity of bio-filter

From the geometry of the bio-filter, a relation between the width and the height of the water level in the bio-filter can be obtained. This is presented in Equation 3.3.

$$h[t] = \frac{-w_0 + \sqrt{w_0^2 + 4 \cdot A[t]}}{2} \tag{3.3}$$

where:

h [m] = head level in bio-filter
w_0 [m] = base width of bio-filter
A [m^2] = Area of bio-filter filled

Outflow towards aquifer

The result of the head level increase in the bio-filter is a pressure build-up that results in the flow Q_3 from the bio-filter to the aquifer. For this flow, a linear laminar flow regime is assumed. Consequently, the pressure gradient is calculated with Equation 3.4.

$$q = -k\frac{\rho g}{\eta}\frac{\delta h}{\delta z} \tag{3.4}$$

where:

k [m/s] = permeability
ρ [kg/m] = water density
g [m/s^2] = gravitational constant
η [m^2/s] = kinematic viscosity of water
$\frac{\delta h}{\delta z}$ [m/m] = head level variation over height of bio-filter

To know the outflow at any given time step, the head level variation in the vertical flow direction through the bio-filter $\frac{\delta h}{\delta z}$ is equal to the head at the given time step, relative to the base level which is set to zero.

Weighted water age in bio-filter

The water age in the bio-filter is calculated based on the first-in-first-out principle, where the weighted average of the water age is used to gain insights in the removal processes occurring in the bio-filter. The water age is calculated based on the following example, which makes use of the values given in Table 3.1.

Table 3.1: Example for the calculation of water age in bio-filter

t	**[hours]**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Q_{in}	[m^3/h]	10	10	10	0	0	10	10	10	0
V	[m^3]	0	10	20	29	23	14	20	30	30
Q_{out}	[m^3/h]	0	0	1	6	9	4	1	10	10
t_j	[hours]	4	3	2	1	0				

To calculate the water age in the bio-filter, it is necessary to find out what incoming flows have contributed to the water volume currently present. When calculating the water age in Table 3.1 for time step 4, the inflows that occurred in preceding time steps are accumulated. This accumulation continues up until the point that the accumulation of incoming water volume is equal to the water volume currently present in the bio-filter, so in the example this would be the water entering in time step 3, 2, 1 and part of time step 0. The volume of incoming flow is then multiplied by the difference in time steps between the one being considered, in this case time step 4, and the time step in which the incoming flow has taken place. So, in the example this would result in $Q_{in}[t_3] \cdot (4-3) + Q_{in}[t_2] \cdot (4-2) + Q_{in}[t_1] \cdot (4-1) + Q_{in}[t_0] \cdot (4-0)$ where only the part of flow $Q_{in}[t_0]$ is considered that contributes to the volume in the bio-filter, so only 3 m^3. The sum of water ages and contributing incoming flows is then divided by the volume of water in the bio-filter, resulting in the average water age. This calculation of the average water age is also presented in Equation 3.5.

$$Water\ Age[i] = \frac{\sum_{j=i-n}^{i} \left(Q_{in,j} \cdot (i-j)\right)}{V_{biofilter}} \tag{3.5}$$

where:

Water age [hrs] = Average water age
Q_{in} [hrs] = Incoming flow Q_2 entering bio-filter
i [-] = time step being considered
n [-] = last time steps contributing to current water volume in biofilter
$V_{biofilter}$ [m^3] = Water volume in bio-filter

Once the average water age for each time step has been determined, it will be related to the flow leaving the bio-filter, flow Q_3. This outgoing flow thus has the average water age of contributing inflows. By multiplying this average water age with the outgoing flow, this average water age is related to the volume of water that has this water age, hence an indication of the volume of water in relation to its retention time in the bio-filter is presented.

3.3.2. Operations

The flow that enters the bio-filter is controlled by a pump. This pump can have different activation frequencies. If the activation frequency is set to zero, a continuous pump regime is found, which is constraint by the availability of water in the attenuation tank. This pump activation frequency can be altered to any desired frequency. If the pump frequency is set to 1 day^{-1}, then the volume of water entering the bio-filter once every day is equal to the pore volume of the bio-filter. The activation frequency of the pump will therefore be the number of bio-filter feeds per day.

3.4. Aquifer Storage and Recovery

3.4.1. System behaviour

The water that has left the bio-filter will be injected into the aquifer through a well. The Bluebloqs system is realised by situating a well in the most shallow aquifer. This aquifer will in reality be characterised as a semi-permeable aquifer where the Bluebloqs system is operated as a transient well.

Introduction to Hantush-Jacob

The infiltration of water into the aquifer results in seepage through the covering clay layer. When more water is extracted than injected, the groundwater table will lower in that time period. The significance thereof should be calculated. The equation to do so was obtained by Hantush and Jacob and is provided in Equation 3.6.

$$h = h^{*} - \frac{Q}{4 \cdot \pi T} \int_{u}^{\infty} \frac{1}{\tau} exp(-\tau - \frac{r^{2}}{4 \cdot \lambda^{2} \tau}) d\tau \tag{3.6}$$

where:

h [m] = head level variation
$h*$ [m] = fixed head above semi-confining layer
Q [m^3/h] = pump discharge
T [m^2/day] = transmissivity of the aquifer
r [m] = distance from well
λ [m/m] = leakage factors
u [-] = lower bound for modified exponential integral of Theis solution

Here, h^{*} presents the head above the aquifer and thus in the case of the Bluebloqs system, operating in the most shallow aquifer, the groundwater table. By assuming h^{*} zero, the head that is calculated with this equation shows the change in the groundwater table at a given moment, as a result of the pump regime that has been ongoing up until the time of interest.

The lower boundary u for the integral comes from the Theis solution, and is given in Equation 3.7. This lower boundary presents the effect of a pump which has been active from t_0 till t.

$$u = \frac{Sr^{2}}{4 \cdot T(t - t_{0})} \tag{3.7}$$

where:

u [-] = lower bound for modified exponential integral of Theis solution
S [m] = storage coefficient of the aquifer
T [m^2/day] = transmissivity of the aquifer
t [hrs] = time step under consideration
t_0 [hrs] = time step of pump activation

Adjusting the implicit time relation

The integral given in Equation 3.6 can be approached numerically. To do so, specific attention must be given to the time scale that is being considered. Since this modelling approach works with an hourly time step for the appropriation of values. However, the Hantush-Jacob function works with daily discharges and also the values for time in Equation 3.7 must be provided in daily values. The integral can only be solved numerically due to the lower bound being dependent on the temporal and spatial domain. Special attention must be given to the λ value in the integral. Although the solution of the integral is dimensionless, the value of λ is given in meters. The actual value found for λ is given by $\lambda = \sqrt{c \cdot T}$ where $T = k \cdot H$. Here, the resistance c is given in days and the hydraulic conductivity k is given in meter/day. The unit of λ is therefore implicitly related to time in days. Adjusting the units of c and k to hours and meters/hour will adjust the value of λ disproportional to time. Therefore, the value for λ will be given implicitly related to time in days and to analyse the equation on an hourly time scale, the integral will be adjusted to the form given in Equation 3.8.

$$E_{1}(u) = \int_{u}^{\infty} \frac{1}{\tau} exp\left(-\tau - \frac{6 \cdot r^{2}}{\lambda^{2} \tau}\right) d\tau \tag{3.8}$$

where:

E_1 [-] = Modified exponential integral of the Theis solution
u [-] = lower bound for modified exponential integral of Theis solution
r [m] = distance from well
λ [m/m] = leakage factor

The discretised solution

In the Bluebloqs configuration, the infiltration rate Q differs for every time step, based on the pressure build-up in the bio-filter. To model this differing discharge for every hourly time step, equation 3.6 must be discretised. However, for this discretisation, the continuing impact of previous pump activities on the current time step needs to be taken into consideration.
Taking the mentioned considerations into account, Equation 3.9 is the discretised form that relates the pumping activities with location-specific characteristics to the groundwater level change.

$$h_t = \sum_{i=1}^{t} \frac{6 \cdot Q_{out,(i-1)}}{\pi T} \left[E_1\left(u_{\Delta t}\right) - E_1\left(u_{t,i}\right)\right] - \sum_{i=1}^{t} \frac{6 \cdot Q_{in,i-1}}{\pi T} \left[E_1\left(u_{\Delta t}\right) - E_1\left(u_{t,i}\right)\right] \tag{3.9}$$

where:

Q_{out} [m^3/h] = extraction rate
Q_{in} [m^3/h] = infiltration rate
T [m^2/day] = transmissivity of the aquifer
E_1 [-] = Modified exponential integral of the Theis solution
$u_{\Delta t}$ [-] = solution to Equation 3.7 for time step of 1 hour
$u_{t,i}$ [-] = solution to Equation 3.7 for time between pump de-activation and time step under consideration

Determining the mean of the maximum water ages in the aquifer

The water age in the aquifer is determined based on the same principle as for the attenuation tank. This means the first-in-first-out principle is applied, where the maximum water age is considered. So, the incoming flow of preceding time steps is subtracted from the water volume for the time step that is being considered. Once this accumulated subtraction reaches zero, the incoming flow that has contributed to the current water volume available in the aquifer is found. The difference in time between this incoming flow and the current time step is then the maximum water age.

The maximum water age is determined for each time step. From these values, the mean and standard deviation are extracted from the model.

3.4.2. Operations

The operations of the ASR component are controlled by the re-use of water from storage. The infiltration of water in the aquifer depends on the infiltration capacity and the rainwater availability. The configuration and operations of the system result in different infiltration volumes. The re-use of water should never exceed the accumulated inflow of water. Moreover, the actual re-use of water from storage is less than the injected volume of water. Naturally occurring processes such as background flow and mixing of the injected freshwater with antecedent groundwater result in a loss of the freshwater source over time. Since these processes are complex and location-specific, this model assumes a recovery efficiency. This recovery efficiency is the amount of water that can be extracted from the aquifer, as percentage of the injected volume:

$$Recovery\ Efficiency = \frac{Maximum\ Extraction\ Volume}{Injected\ Volume} \cdot 100\%$$

4

Results

In this chapter, the model outcomes will be presented and the resulting answers to the research questions will be given. First, the outcome of the model for different dimensions and operations of the system are given, to gain insights into the trade-offs that need to be made when designing the Bluebloqs system and its operations respectively. A proposed outcome, based on these trade-offs, is then provided. This proposed configuration is evaluated to find out what the impact of the Bluebloqs system on its environment would be, in terms of overflows, the discharge thereof, and the effect on the groundwater table.

4.1. Co-designing dimensions and operations

This section will discuss how alterations to the design choices and operations of the Bluebloqs system impact the performance indicators. Alterations of the system are done in the form of a 2D sensitivity analysis, to present the relations that can most significantly impact the performance of the system. For this, the following relations are presented.

The relation between the dimensions of the attenuation tank and the discharge of the pump emptying this tank is analysed. Also, the dimensions of the attenuation tank and the activation frequency of this pump for a given discharge is looked at. Thirdly, this activation frequency is altered to provide the possibility of operating the system with a summer and a winter regime, to better accommodate for expected water volumes that need to be processed by the Bluebloqs system.

4.1.1. Pump regime and buffer dimensions

Initial guess for attenuation tank dimensions and pump discharge

To find out within what range for values of the buffer dimensions and pump discharge appropriate values could be found, the system should first be tested under initial guesses, to find out in what region optimal values can be found. By finding optimal values, a well-balanced trade-off is made between the performance indicators presented in the framework. The initial guesses are presented in Table 4.1 for the attenuation tank, and all consider a pump discharge of 10 m^3 per hour. Not all performance indicators are included in this initial appreciation of the system, but the focus for this first step is to find a system that is first and foremost able to meet its circular performance indicators from a water quantity point of view, hence the volumes of water flowing through the system are presented.

Table 4.1: Initial attenuation tank dimension options

			Overflow: Volume lost (Annual average)	Overflow: Maximum discarge	Infiltrated: Volume (Annual average)	Extracted: Volume (Annual average)
			[m3]	[m3/h]	[m3]	[m3]
Storage capacity	[m3]	200	712.2	491	12108	7507
		800	488.8	489	18741	12063
		1400	98.5	92	19130	12356
		2000	0	0	19230	12426

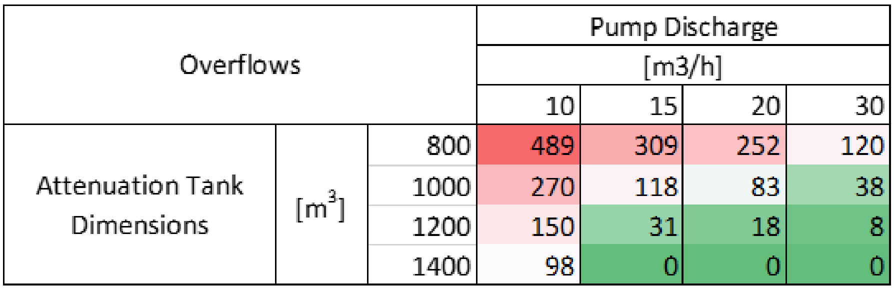
Based on this table, it is decided that the appropriate dimensions that will be considered fall between 800 m^3 and 1400 m^3. This is decided based on the poor performance of the attenuation tank with a capacity of 200 m^3, which has large overflow discharges and is unable to supply a significant volume of water. The attenuation tank with a capacity of 2000 m^3 is considered an over-dimensioned tank, given the fact that these number are related to a pump discharge of 10 m^3 per hour. The next section will go into further detail on the appropriate dimensioning and operations of the attenuation tank and pump discharge specifically.

Finding the appropriate attenuation tank dimensions and pump discharge

The trade-offs that arise when choosing the appropriate dimensions for the attenuation and the discharge for the pump emptying this attenuation tank, are presented in Figure 4.1. These results relate to the assumption of a continuous pump regime, which means whenever water is available in the attenuation tank, the flow towards the bio-filter will occur. The attenuation tank dimensions that are being considered vary from 800 to 1400 m^3 respectively, with steps of 200 m^3. The pump discharges that are considered are 10, 15, 20 and 30 m^3.

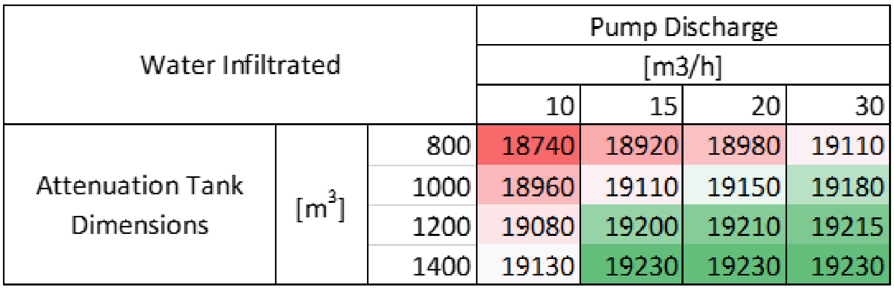
In Figure 4.1a, the average volume of water that is annually lost in overflow events occurring from the attenuation tank – and thus contributing to flow in the downstream stormwater drainage infrastructure – is presented. Figure 4.1b presents the average volume of water that is annually infiltrated in the aquifer. The cells are colour-coded, where the green colour can be interpreted as better performance of the system and red as worse performance. For both the volume of water lost in overflows as well as the volume of water being infiltrated, the performance of the system improves with larger attenuation tank dimensions and a larger pump discharge. What can be noted is that the volume of water that is lost, is equal to the amount of water not being infiltrated. This is in line with expectations, as Figure 2.1 showed that only two flows out of the attenuation tank will occur, either the flow towards the bio-filter which will lead to infiltration into the aquifer, or overflow events.

Another performance indicator for the Bluebloqs system that is influenced by the design of the attenuation tank and the pump discharge is the average volume of water that can be supplied to the end-user on an annual basis. This is presented in Figure 4.2. Here, more storage capacity in the attenuation tank and larger pump discharges positively influence the supply of water. However, the maximum volume of water that is being recovered from the aquifer, can be reached with in multiple configurations in terms of attenuation tank dimensions and pump discharges. With a pump discharge of 30 m^3 per hour, the recovery of water from the aquifer is the same for all attenuation tank dimensions. For a pump discharge of 20 m^3 per hour, a buffer capacity of 1400 m^3 does not add value in terms of this performance indicator.



Overflows			Pump Discharge [m3/h]			
			10	15	20	30
Attenuation Tank Dimensions	[m^3]	800	489	309	252	120
		1000	270	118	83	38
		1200	150	31	18	8
		1400	98	0	0	0

(a) Average volume of water lost in overflow events annually

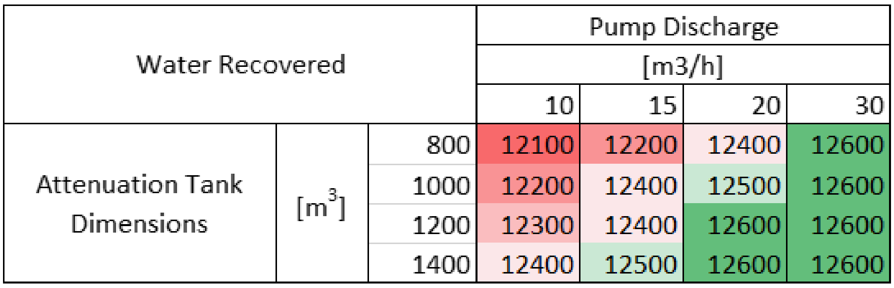


Water Infiltrated			Pump Discharge [m3/h]			
			10	15	20	30
Attenuation Tank Dimensions	[m^3]	800	18740	18920	18980	19110
		1000	18960	19110	19150	19180
		1200	19080	19200	19210	19215
		1400	19130	19230	19230	19230

(b) Average volume of water infiltrated in aquifer annually

Figure 4.1: Bluebloqs system under different combinations of pump discharge and attenuation tank dimensions

Here, it can be noted that the average volume of water supplied annually is reached with an attenuation tank volume of 1200 cubic meters and a pump with a discharge of 20 cubic meters per hour. When these values are related to the volume of water lost in overflow events and water infiltrated, it can be found that for the attenuation tank dimensions being 1200 m^3 and the pump discharge being 20 m^3/h, the annual volume of water lost in overflows is 18 cubic meters and the water infiltrated is 20 cubic meters less than the maximum value that can be found. This means that, if more water is infiltrated, this does not necessarily improve the system performance in terms of supplying additional water to the end-user.



Water Recovered			Pump Discharge [m3/h]			
			10	15	20	30
Attenuation Tank Dimensions	[m^3]	800	12100	12200	12400	12600
		1000	12200	12400	12500	12600
		1200	12300	12400	12600	12600
		1400	12400	12500	12600	12600

Figure 4.2: Average water supplied for different combinations of buffer tank dimensions and pump discharge annually

4.1.2. Activation frequency and buffer dimensions

The control option to activate the pump that discharges the water from the attenuation tank to the bio-filter on a periodic basis has been analysed. This analysis is done based on adjustments to the storage capacity of the attenuation tank and predefined pump activation frequencies. These patterns are presented in Table 4.2. The pump discharge is in this case kept the same for all activation frequencies that are being considered. It is decided to use a discharge of 15 cubic meters per hour. The attenuation tank dimensions vary between 800, 1200 and 1600. The activation frequencies that are considered are 6, ~5 or 4 activations per day, based on one activation filling the pore volume of the bio-filter.

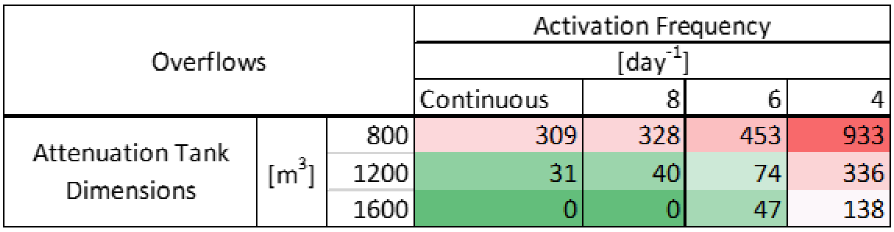
Table 4.2: Activation frequency

		Activation frequency			
		Continuous	6x per day	~5x per day	4x per day
Pump discharge	[m^3/h]	15	15	15	15
Activation duration	hrs	2	2	2	2
De-activation duration	hrs	0	2	3	4

For the filtration of the water, controlling the flow through the bio-filter can improve the removal of pollutants from the water. To get better control of the incoming flow, the pump discharging the water from the attenuation tank to the bio-filter can be set to a certain activation frequency. This will affect the effective storage capacity in the attenuation tank, that is available for incoming stormwater flow. The trade-off between losing water in overflows versus having a periodic pump regime, is presented in Figure 4.4. Here, the average volume of water lost annually in cubic meters is given in Figure 4.4a and the water infiltrated is presented in Figure 4.4b.

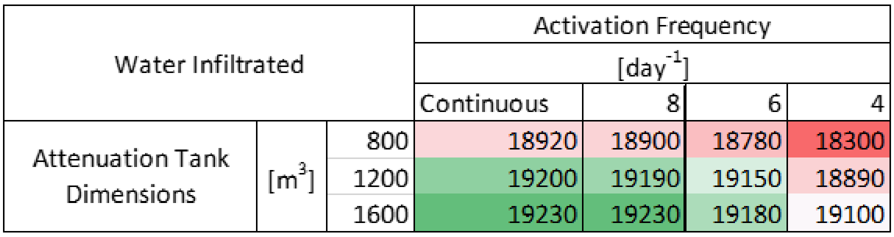
Water quantity performance indicators

The two-dimensional sensitivity analysis on the activation frequency and the attenuation tank dimensions, yield results on the water quantity performance indicators as presented in Figure 4.4. These results show that an attenuation tank of 1600 m^3 with a continuous flow, or an activation frequency of 8 times per day do not result in overflow events and result in the maximum volume of water being infiltrated.



Overflows			Activation Frequency			
			[day^{-1}]			
			Continuous	8	6	4
Attenuation Tank Dimensions	[m^3]	800	309	328	453	933
		1200	31	40	74	336
		1600	0	0	47	138

(a) Average volume of water lost in overflow events annually

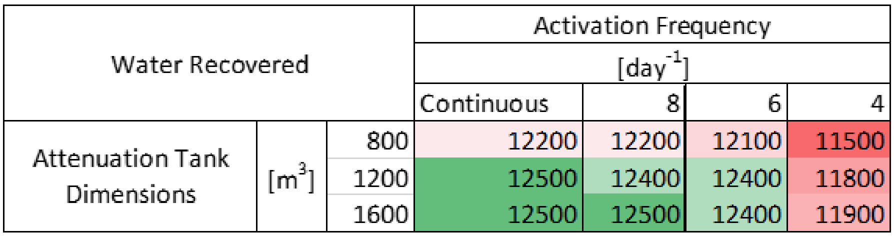


Water Infiltrated			Activation Frequency			
			[day^{-1}]			
			Continuous	8	6	4
Attenuation Tank Dimensions	[m^3]	800	18920	18900	18780	18300
		1200	19200	19190	19150	18890
		1600	19230	19230	19180	19100

(b) Average volume of water infiltrated in aquifer annually

Figure 4.3: Bluebloqs system under different combinations of pump activation frequencies and attenuation tank dimensions

For the recovery of water from the Bluebloqs system, the best performance is found for the 1600 m^3 attenuation tank with either a continuous flow or an activation frequency of 8 times per day. Also, the continuous flow with an attenuation tank of 1200 m^3 find the maximum recovery of water from the aquifer.



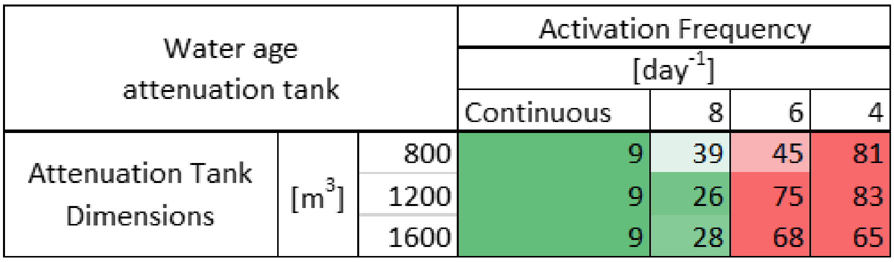
Water Recovered			Activation Frequency			
			[day^{-1}]			
			Continuous	8	6	4
Attenuation Tank Dimensions	[m^3]	800	12200	12200	12100	11500
		1200	12500	12400	12400	11800
		1600	12500	12500	12400	11900

Figure 4.4: Average water supplied for different combinations pump activation frequencies and attenuation tank dimensions

Performance indicators for the removal of pollutants

The reason for considering different operations of the system than the continuous pumping of water over the bio-filter have been discussed in Section 2.5. Here, the consequences of working with different activation frequencies to the maximum water age in the attenuation tank and the weighted water age in the bio-filter are presented.

The average maximum water age in the attenuation tank is presented in Figure 4.5. Here, it can be found that the water is retained for longer periods of time when a lower activation frequency is applied. This is in line with expectations since the controlled pumping of water means that it is not immediately discharged over the bio-filter, as is the case for the continuous pump regime. Long retention in the attenuation tank is assumed to negatively impact the removal of pollutants

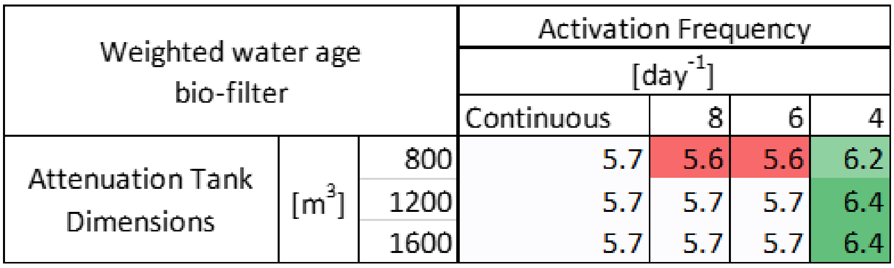


Water age attenuation tank			Activation Frequency [day^{-1}]			
			Continuous	8	6	4
Attenuation Tank Dimensions	[m^3]	800	9	39	45	81
		1200	9	26	75	83
		1600	9	28	68	65

Figure 4.5: Average of maximum water age for each time step in attenuation tank

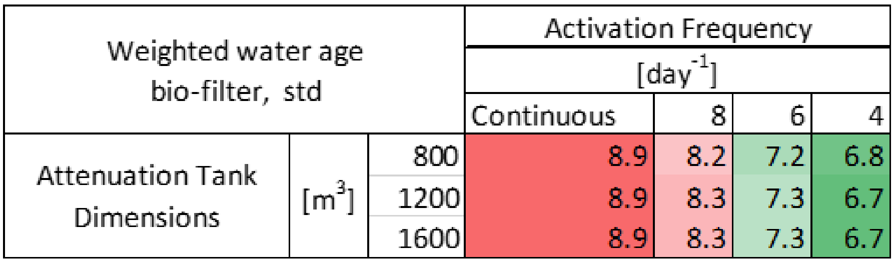
from the water in the Bluebloqs system as a whole.

The mean weighted water age in the bio-filter is presented in Figure 4.6a and the standard deviation of the weighted water is presented in Figure 4.6b. The mean weighted water age is prolonged by decreasing the activation frequency. Also, for larger attenuation tanks, the weighted water age slightly increases. Longer retention of water in the bio-filter means the removal processes can take place for a longer period of time, and therefore a positive relation between the mean weighted water age and the colour-coding of the cells is used.



Weighted water age bio-filter			Activation Frequency [day^{-1}]			
			Continuous	8	6	4
Attenuation Tank Dimensions	[m^3]	800	5.7	5.6	5.6	6.2
		1200	5.7	5.7	5.7	6.4
		1600	5.7	5.7	5.7	6.4

(a) Mean of weighted average retention time



Weighted water age bio-filter, std			Activation Frequency [day^{-1}]			
			Continuous	8	6	4
Attenuation Tank Dimensions	[m^3]	800	8.9	8.2	7.2	6.8
		1200	8.9	8.3	7.3	6.7
		1600	8.9	8.3	7.3	6.7

(b) Standard deviation of weighted average retention time

Figure 4.6: Performance indicators for bio-filter retention

The controlled removal of water in the bio-filter is related to the standard deviation of the weighted water age. If there is a large deviation from the mean water age, more water is retained for different durations and thus the removal efficiency deviates as well. The water quality going out of the bio-filter will then also show larger deviations.

The standard deviation of the weighted water age in the bio-filter shows that lower activation frequencies result in less deviation from the mean value. Also, distinct relation can be found between the attenuation tank dimensions and the activation frequency, other than the slight adjustments that can be found for the 800 m^3 attenuation tank. This is expected to be the result of the availability of water in the attenuation tank to feed the bio-filter.

4.1.3. Seasonality

To prevent the Bluebloqs system from losing water in overflow events, an additional operational adjustment that is analysed is the use of a summer and winter regime. The pump discharge will be the same, however, the activation frequency is adjusted. This adjustment is based on Figure 4.7, which presents the occurrence of overflow events over time for an activation frequency of 4 times per day.

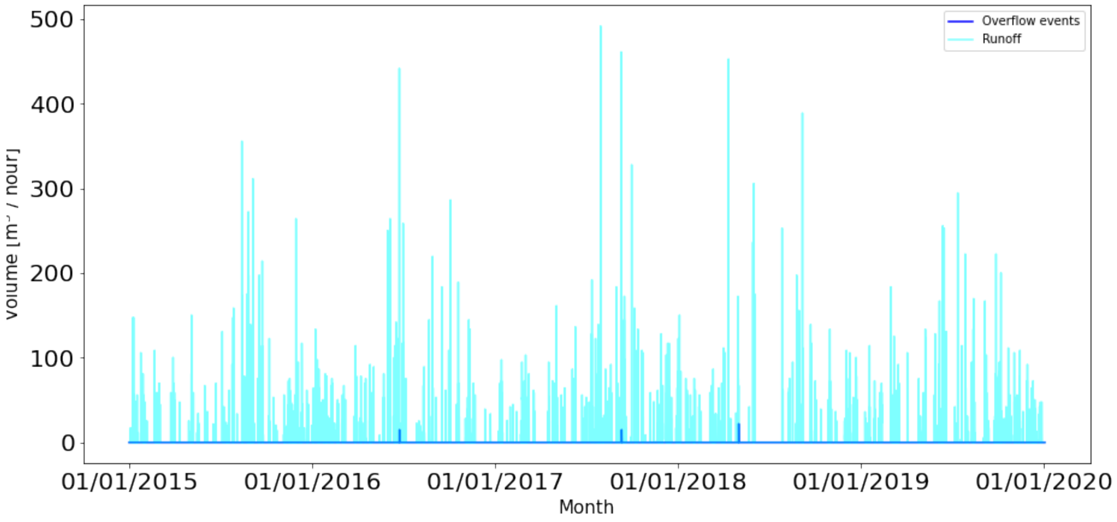


Figure 4.7: Relation between incoming flow and overflows

From this figure, it can be found that the presented overflow events take place in the summer periods. Since there are no overflow events taking place in the winter period, the activation frequency for the winter period is set to 4 activations per day. From Figure 4.3a, it can be found that no overflow events occur for an activation frequency of 8 times per day. The design and operations of the system are presented in Table 4.3.

Table 4.3: Design and operational parameters for adjusted summer and winter regime

Description	**Unit**	**Value**
Attenuation tank dimensions	[m^3]	1600
Bio-filter pore volume	[m^3]	32
Pump discharge	[m^3/h]	15
Summer activation frequency	[day^{-1}]	8
Winter activation frequency	[day^{-1}]	4

This system design and operations yield the results for the performance indicators as given in

Table 4.4. It can be found that no overflow events take place. Also, the volume of water infiltrated in the aquifer reaches the same value as presented in Figure 4.3b for having the activation frequency of 8 times per day, and also the total volume of water recovered from the aquifer meets the maximum values found in Figure 4.4. This means from a water quantity perspective, adjusting the winter pump regime to a lower activation frequency has no consequences to the performance indicators of the system.

The performance indicators that are included to reflect on the water quantity of the supplied water, do change when the winter activation frequency is decreased to 4 times per day, in comparison to having the system operate under 8 activations per day throughout the year. It can be found that the average maximum water age for the attenuation tank goes from 28 hours to 48 hours, meaning that on average, the maximum retention time in the attenuation tank increases by 20 hours.

The mean weighted water age for the bio-filter goes from 5.7 hours to 6.3 hours. For the standard deviation of the water age, the uncertainty interval slightly improves from 8.3 hours to 7.9 hours, which is a decrease of approximately 5 %.

Table 4.4: Performance indicators for the system with summer and winter regime

Description	**Unit**	**Value**
Overflows lost	[m3]	0
Infiltrated	[m3]	19230
Extracted	[m3]	12500
Water age attenuation tank	[hrs]	48
Weighted water age bio-filter	[hrs]	6.3
Standard deviation water age bio-filter	[hrs]	7.9

4.2. The outcome of the configurational trade-offs

Based on the co-design of dimensions and operations of the system, a solution is found for which the input parameters are presented in Table 4.3 and for which some of the performance indicators are presented in Table 4.4. From the previous section, the trade-offs that are affecting the performance of the Bluebloqs system have been presented. The system has been presented as optimal performing solution, where no overflow events occur and the feed cycles of the bio-filter are aligned with the seasonality of incoming flows. Also, the pump discharge leading the water from the attenuation tank to the bio-filter is set to 15 m^3 per hour, rather than the 30 m^3/hour that is now applied. The results that are presented show how the Bluebloqs system in Spangen, Rotterdam could be improved if the system would not yet have been realised.
The system is now only tested on the part of the framework that relates to the supply and drainage of water quantities, as well as the water quality indicators for the attenuation tank and bio-filter. The chosen system dimensions and operations result in no overflow events to occur. Consequently, the infiltrated volume of water equals the volume of water that has entered the system in the form of runoff.

The volume of water extracted from the system never meets the annual water demand. In the provided systems dimensioning and operations, 65 % of the infiltrated water is extracted. Working with a RE of 70 %, this means that there is insufficient water present for uptake. This water scarcity is not the result of the assumptions that underlie the use of the RE. The inability to meet the RE of 70 % means there is a temporal discrepancy between water availability and the water demand.

4.3. Evaluation of Bluebloqs implementation

This section will present the outcomes of the model approach that are related to the impact of implementing the Bluebloqs system. This evaluation will be done by comparing the eventual volume of water that has been supplied to the end user, in relation to the water demand. For this, the configuration that has been found in Section 4.1.3 Also, the implications of seasonal storage of freshwater in the aquifer will be discussed.

4.3.1. Meeting the water demand

Water supply

The supply of water through the system depends on the water demand. Therefore, the water that has been supplied on an annual basis should be related to the water demand. The annual water demand is equal to 17.000 m^3, with a significant larger demand in summer (120 m^3 per day) than in winter (8 m^3 per day). The volume of water extracted from the aquifer on an annual basis is equal to 12.500 m^3, which means approximately 73 % of the annual water demand has been met. One of the main reasons for this low percentage of water demand being met, is that the water demand is modelled to immediately start once the Bluebloqs system is operational. If the water demand is excluded for the initial year, to ensure a sufficient volume of freshwater is available in the aquifer, 88 % of the annual water demand can be supplied. Figure 4.8 shows the water supplied, the water demanded and the incoming runoff that is the source which is used to supply water. The unmet water demand – in the provided scenario where the initial year has no water demand to create storage build-up – takes place after the summer of 2018, when the incoming flow Q_0 shows a long period of drought. During this period of drought, the water in the aquifer that was available for uptake has been fully exploited, resulting in the same problem with the supply of water when no initial build-up period is being considered.

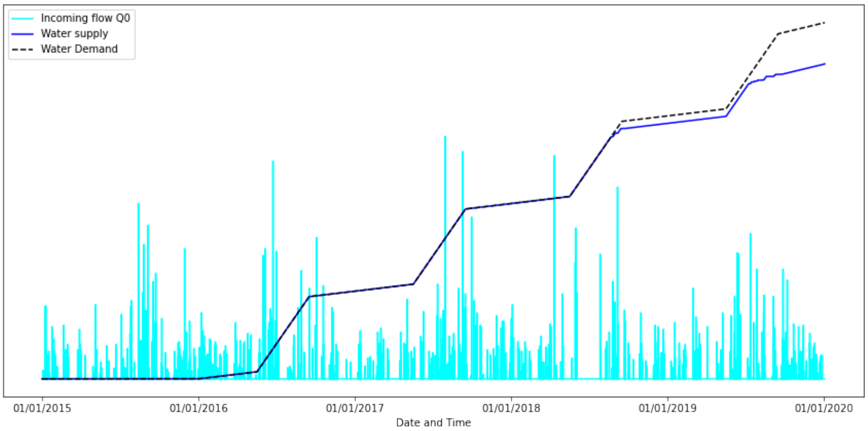


Figure 4.8: Supply of water with initial year as build-up period

The availability of water near the extraction well

The framework has presented the water age in the aquifer as a performance indicator, that can be used to determine where and when the water is to be extracted. The RE is a limitation to the volume of water that can be extracted, which is in part dependent on the background flow taking place in the aquifer. By knowing how long most of the water is retained in the aquifer, the distance between the infiltration well and extraction well can be determined. This is explained here.

For the system dimensions and operations, the mean value for the maximum water ages in the aquifer is found to be equal to 310 hours. The standard deviation related to this set of maximum water ages is found to be equal to 810 hours. Translating these values gives a mean of 13 days with a standard deviation of 33 days.

These values are important indicators regarding the loss of water due to the processes underlying the RE. The freshwater source that is created in the aquifer can only be taken up at one location, the extraction well. If the mean value of the maximum water age is large, then this means the water is often retained for long periods of time.

If the standard deviation of the maximum water ages increases, then the dispersion of the freshwater source in the aquifer becomes larger. Since the extraction of water is constraint by the specific location of the extraction well, having a large standard deviation for the maximum water age means that the water is more dispersed, possibly making the extraction of this water not possible because it has moved away too far from the well.

4.3.2. Aquifer recharge and consequences to phreatic groundwater

Aquifer Recharge

Part of the water that has been infiltrated in the aquifer will be recovered to supply the end-user with water. In Section 4.1.3, it was found that 19.230 m^3 of water are infiltrated annually, and 12.500 m^3 are extracted. This means approximately 65% of the water has been recovered from the water that has been infiltrated, even though a recovery efficiency (RE) of 70% is used. The water that is not recovered from the aquifer, contributes to groundwater recharge. For the situation presented in Section 4.1.3, the annual recharge of groundwater is 35% of the water that has been infiltrated. This is equal to 6.750 m^3 of water on an annual basis.

Impact on the groundwater table

The infiltration of water and temporal storage partially results in the expansion of the aquifer. However the addition of freshwater also causes seepage to occur. This phenomenon causes groundwater table fluctuations. An increase in the groundwater table will occur when more water is infiltrated than is being extracted. The long-term effect of the operations of the Bluebloqs system – related to the storage of water in the aquifer – on the groundwater table is presented in Figure 4.9.

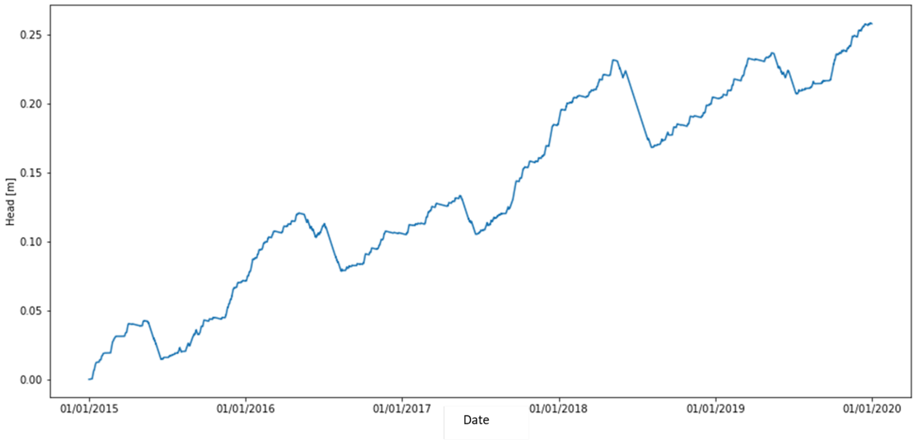


Figure 4.9: Impact of pump regime on groundwater table

A pattern can be distinguished from this figure, which shows that during summer months, the groundwater table rapidly decreases, whereas throughout the rest of the year the groundwater table gradually increases. There is also an upward trend over the entire time period that is being considered. This is the results of the groundwater recharge; the volume of water that is infiltrated but that it not extracted. This figure shows that the groundwater table would increase by 0.25 meters over 5 years for the numbers found for annual infiltration volumes and extraction volumes.

The impact presented in Figure 4.9 shows the behaviour of the groundwater table over time. However, the presented values are related to the well location. The spatial variation of this groundwater table increase is presented in Figure 4.10, where the maximum value of 0.25 meters of groundwater level increase from Figure 4.9 is used.

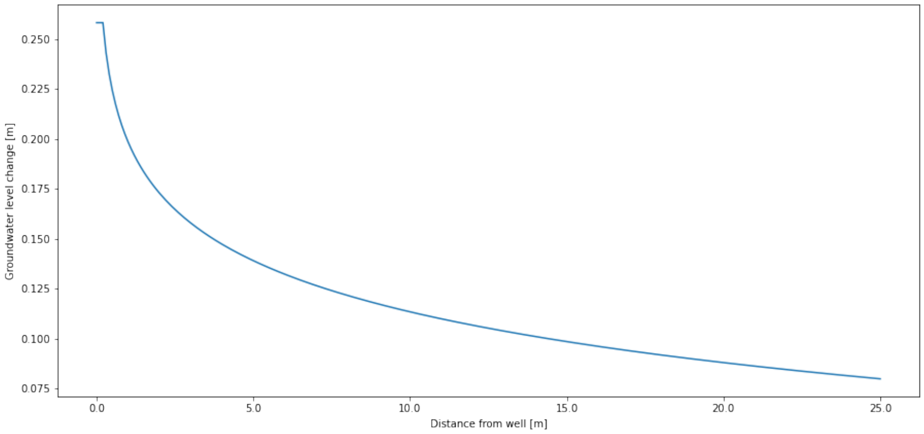


Figure 4.10: Spatial influence of pump regime

There is a significant decrease in the groundwater table when moving away from the well. Having the maximum value for the groundwater table increase presented, it can be found that at a distance of approximately 15 meters, the influence of the Bluebloqs system on the groundwater table has decreased to 0.10 metres, a decrease of 60 % to the impact of the system at the well.

It was noted that Figure 4.9 presents steep declines in the groundwater table in summer months as a result of the operations of the Bluebloqs system in the aquifer. To be able to get a better overview of this impact during the summer, Figure 4.11 shows the same as Figure 4.9 zoomed to the summer period. During the four months of summer, the groundwater table is decreased by approximately 0.05 meters (5 centimetres) due to the 120 m^3 of water that are being extracted on a daily basis. Figure 4.11 does present the impact of the pump regime on the temporal domain to determine the impact at the well, which means that the spatial impact of the Bluebloqs system during this summer period follows the same trend as presented in Figure 4.10.

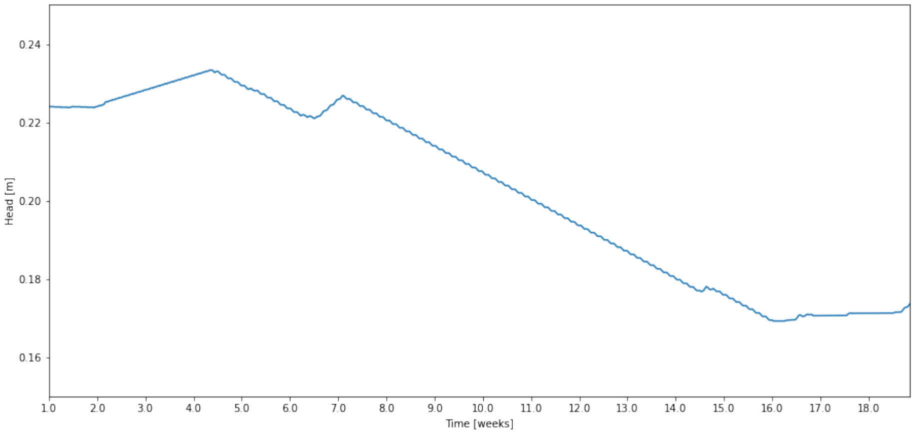


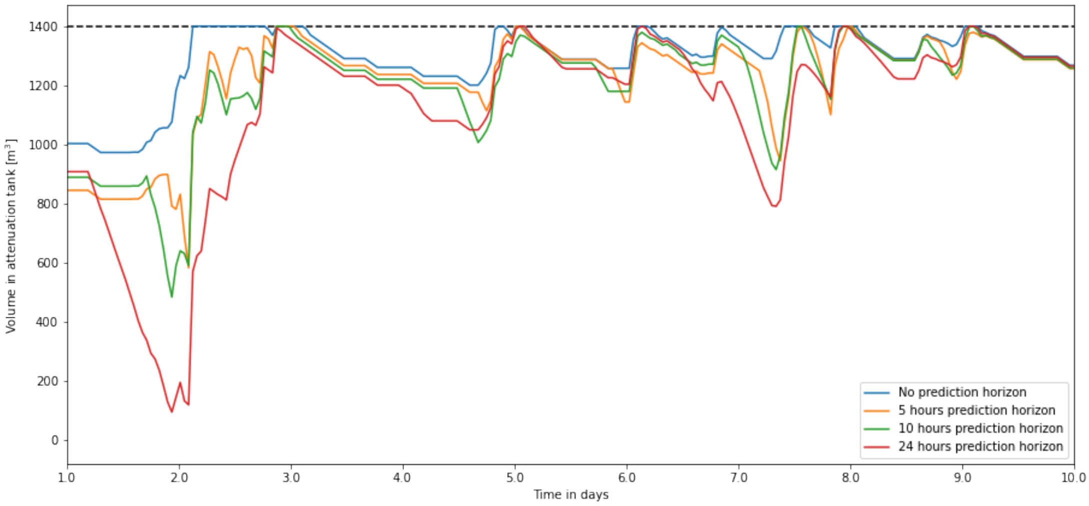
Figure 4.11: Groundwater table depletion during summer

4.3.3. Mitigation of pluvial flood risk

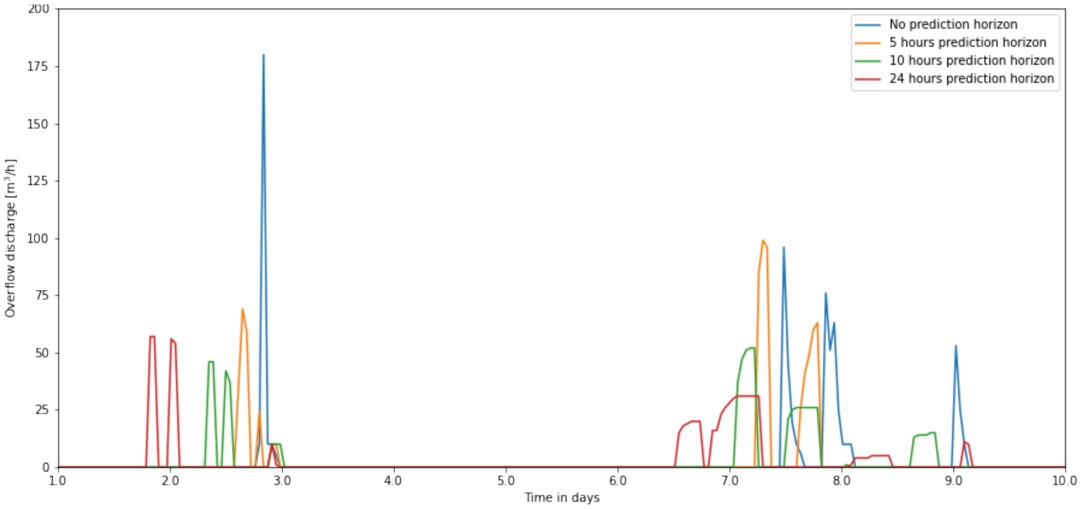
The framework presents two performance indicators that are related to overflow events. The dimensions and operations that are presented up to this point do not result in any overflow events. For the next section, the system dimensions and operations are adjusted. Instead of having a 1600 m^3 attenuation tank, the capacity is decreased to 1400 m^3. The pump discharge is set to 10 m^3 per hour. This is to present a scenario where overflow events do occur, and what control options can be considered to mitigate the pluvial flood risk associated to these overflow events.

Predictive control

To reduce the impact of overflow events, predictive control has been included as operational improvement to the system. The goal of predictive control is to ensure the water is drained out of the attenuation tank – towards the downstream drainage infrastructure – over an extended period of time. Figure 4.12 presents the impact of predictive control for a time horizon of 5, 10 and 24 hours. It can be found that the application of predictive control significantly reduces the discharge with which the attenuation tank overflows.



(a) Attenuation tank fill level for different prediction horizons



(b) Overflow events for different prediction horizons

Figure 4.12: Buffer fill levels and overflow events for different prediction horizons

5

Discussion

The next section will present the main discussion points regarding the results. Here, the interpretation of the results is given as well as the main uncertainties related to these results.

5.1. Circular supply of water and related trade-offs

The circular approach to water management applied by the Bluebloqs system creates direct trade-offs. These trade-offs are discussed here.

5.1.1. The trade-off caused by the circular supply of water

The supply of water from stormwater is dependent on the availability of water in the attenuation tank. How the water is further processed in the system, determines the quality of the water that is delivered.

The optimal buffer dimensions

The capacity needed to reduce the flow in centralised stormwater drainage systems is one condition to which the attenuation tank should adhere. However, it should also periodically feed the bio-filter, which means there is the need for additional storage. In practice, the cost of realising the Bluebloqs system is heavily dependent on the size of the attenuation tank. In urban areas limited space is available for this. Hence, the application of this circular solution is limited by the underground space required.

The pump regime and bio-filter performance

Although this research imposes restrictions on the system, for example by adding feed cycles, it is important to realise that the feed cycles related to optimal removal efficiencies in the bio-filter are not established. Imposing a feed cycle of 8 times a day does improve the water quality indicators. However, the significance of this improvement is not reflected upon. If there is no significant improvement in the removal processes when the water is retained for an additional half hour, then there would be no reason to work with 8 feed cycles per day, if this would cause overflow events to occur.

Water quality deterioration in the attenuation tank

When periodically pumping water out of the attenuation tank towards the bio-filter, the water will remain in the attenuation tank for a longer period of time than when the continuous pump regime is being considered. This will negatively affect the quality of the water which is harmful for the entire removal process of the Bluebloqs system. Preferably, the stormwater quality entering the bio-filter is of the highest quality possible. When retained in the attenuation tank for a prolonged period of time, processes will deteriorate the water quality which may result in anoxic conditions, which makes the filtration process that should occur in the bio-filter less efficient, possibly leading to water quality that is too poor to infiltrate into the aquifer. However, the impact of the water quality deterioration and the additional removal of pollutants from the water should be related to each other.

The use of the first-in-first-out principle is an additional uncertainty regarding the water age in the attenuation tank. In reality, mixing of the water occurs which results in processes that affect the water quality, possibly even more than just the retention of water.

5.1.2. The impact of the Bluebloqs system on the groundwater table

The storage of 35.000 m^3 meters of water in the aquifer results in a maximum increase of 0.25 meters of the groundwater table. Since this is the accumulated effect of groundwater infiltration and extraction over a period of five years, this value is an exaggeration of reality. In this same period, processes such as active groundwater control will have a larger impact on the groundwater table, minimising the effect of the Bluebloqs system. Moreover, as discussed in Section 5.3, the actual storage over the period of five years will not limit itself to one location. Therefore, the movement of the freshwater source created by the Bluebloqs system causes the storage in one specific location to decrease, and therefore also the effect on the groundwater table that has been presented.

The effect of the pump regime during the summer period, resulting in a groundwater table decrease of 5 cm, is expected to be more in line with reality. This is because the time period that is looked at is smaller, and therefore the impact is less correlated to activities such as active groundwater control. Moreover, in summer, the active control of groundwater is limited because there is a water deficit, which decreases the relation even further. The effect of 5 centimetres is the result at the well. This means that the effect asymptotically decreases when one moves away from the well, meaning that the effect of this groundwater table decrease has a limited spatial influence.

5.2. On the applicability of the framework

The model that has been created has presented simulations of possible dimensions and operations of the Bluebloqs system. To determine how these outcomes can be used, the underlying choices that were made to come up with the model are presented in this section. These consist of the assumptions related to how data has been processed and how the Bluebloqs system is simplified in the model approach.

5.2.1. Assumptions related to data processing

The assumptions related to the data used, and how this data has been processed to be aligned with other model parameters, is discussed here.

The catchment size and water supply

By making use of the Rational Method for incoming flows, the water entering the Bluebloqs system is assumed to enter within one hour, which is the presumed time step for the model. By making this assumption, the application of the model is implicitly limited to deal with Bluebloqs systems that have contributing catchments of limited size.

Initial losses and the runoff coefficient

Initial losses are more dynamic than hourly data is able to present, especially with high intensity rainfall which is the most critical for urban water systems. Since this model approaches the dynamics of the system on an hourly basis, there are restrictions to the representation of reality by this model. This same simplification

Precipitation data

For the translation of precipitation data into runoff that is used in this research the handling of information from the KNMI is important to be taken into consideration. The data used in this research is the depth that has been measured by the weather station which is provided on an hourly basis. The duration of these precipitation events is also given. The intensity of the events can then be extracted from these two columns of data by multiplying them. This would give the precipitation intensity of a specific event, given in mm/hour for the specified duration. Since the model approach works with hourly data, the water depth on an hourly basis is used, and not this intensity. The intensity that is used to design the pipe dimensions in centralised infrastructure is not presented in this research, but is important to understand the dynamics of a (design) storm. These intensities can be much larger than the hourly water depth.

5.2.2. Simplifications of the Bluebloqs system that affect the model output

The model has simplified the reality of the Bluebloqs system behaviour. Here, the main ways in which this impacts the model output is discussed.

The performance and behaviour of the bio-filter

The alignment between the design of the bio-filter dimensions and the operations of the pump discharging water over the bio-filter, are important outcomes of this research. However, this relation is flawed by the assumption of having one filter medium, with a single porosity and permeability. Also, no submerged zone is included in the modelled bio-filter, which in reality is an important aspect of the removal of pollutants from the bio-filter. This submerged zone also limits the volume of water that can be discharged per feed cycle.

The recovery efficiency (RE) for the aquifer

By assuming the RE as representation of the processes of groundwater mixing and background flow limits the use of this framework. The goal of this framework is to be applied in the general cases where not much is known about the project site yet. However, the RE impacts the possible supply through this system. To find an RE that is a proper representation of reality is difficult. Therefore, the values found for water re-use by the Bluebloqs system in relation to its RE should be used with caution. The effect of the RE on the water that can be supplied is significant but due to its uncertainty also easy to be misinterpreted, resulting in false promises related to the performance of the Bluebloqs system.

Another notion regarding the recovery efficiency is that one value is taken for the whole data set. Dynamics in the processes that underline the RE, such as the mixing with antecedent water, are not taken into consideration. Since these processes may be correlated to seasonality, the use of one RE for all seasons may be an oversimplification of reality. However, seasonal variation of these processes has not been studied in this research.

Predictive control

Predictive control is able to reduce the impact of overflow events. The longer the prediction horizon applied, the lower the discharge will be. However, it must be noted that an extended prediction horizon will reduce the certainty with which the weather is forecasted. This assumption is not considered in this research, where a perfect prediction horizon is considered. In reality, the uncertainties related to this weather forecast can lead to additional water being lost in overflow events, or predictive control not decreasing the impact of an extreme rainfall event.

5.2.3. The framework for other water solutions

The framework that has been elaborated upon in Section 2.3 could arguably also be used for other solutions that are arising in the transition of urban water systems. It must be noted that the framework is tailored to the Bluebloqs system, being a circular solution. For other solutions, this means parts of the framework can be used whereas other parts cannot.

The interactions with centralised infrastructure present the performance indicators that are expected to be of interest for many new solutions. For this group, it only matters what kind of alternative system is being considered. If, for example, blue-green roofs are considered, then the interactions with centralised infrastructure solely occur with the stormwater drainage system. This means that only one performance indicator of the group that regards the interactions with centralised infrastructure will be considered. For the group of water quality indicators, the components of the Bluebloqs system are specified. The retention time in blue-green roofs could also be included. However, it is not interesting to take this group of performance indicators into consideration since blue-green roofs do not supply the water for high-quality non-potable re-use.

The use of the framework for other solutions is thus not directly attractive. However, the use of the framework does show the distinct traits the Bluebloqs system can provide. The framework presents the additional features of the Bluebloqs system as local, circular solution in the transition of urban water systems.

5.3. The recovery efficiency in relation to the recharge of groundwater

The recovery efficiency (RE) used as assumption to present the reduction in water available for extraction is a simplification of reality. However, this simplification does align with reality in the sense that it limits the amount of water that is lost in between infiltration and extraction.

Nonetheless, this does not mean that the filtered stormwater in the aquifer has lost its functionality. It may not be available for the Bluebloqs system itself, however, it does contribute to the desalination of groundwater. Especially in deltas, the groundwater quality deterioration as a result of seawater intrusion is a threat that, in relation to climate change and sea level rise, is expected to increase. Although a low RE makes the application of the Bluebloqs system seem less viable, it should be taken into consideration to regard its effect on groundwater recharge as an additional positive trait.

5.4. Bluebloqs in relation to other water solutions

This research shows the Bluebloqs system and the interactions that take place with existing centralised infrastructure. However, the Bluebloqs system is not the only upcoming solution that provides a solution to make cities more climate-resilient. The most prevalent solutions can be divided in two groups, the group that mitigates the risk of pluvial flooding and the group that cleans foul water sources and re-uses these. The Bluebloqs system, being a circular solution, establishes itself in the middle of these two groups. This research presents the trade-offs for the Bluebloqs system, and this circular approach is also the main limiting factor of the Bluebloqs system. This does not mean that it is less effective than other solutions, but there is a distinct design difference that will be discussed here.

The solutions related to the mitigation of flood risk often focus on the attenuation of flow. Permeable pavement, green roofs and storage tanks all reduce the discharge that the piped network has to deal with. However, they are all built on the principle of draining out the water. These solutions complement the drainage system in its existing function. Other solutions need to be included to make this system circular.

Solutions that create a water source from foul water, such as small-scale treatment plants for greywater, also follow the linear approach to urban water management. These solutions do break the supply chain, where the water does not need to be conveyed to a receiving water body, and go through the water cycle for it to become a water source for the urban context again. In that sense, these types of solutions can significantly reduce the pressure on centralised treatment plants. Especially the solutions that treat grey water locally can be beneficial for the treatment processes going on in the centrally located treatment facilities, which can be optimised to deal with heavily polluted water (blackwater and industrial wastewater) specifically.

Both the groups of solutions regarding the attenuation of flow and the re-use of grey or even black water can be combined with the Bluebloqs system. The Bluebloqs system provides a solution that connects the objectives of the drainage system and the supply of water. The dimensions of the attenuation tank can possibly be reduced when permeable pavement or blue-green roofs are used to spread the peak discharge over multiple hours. The focus has thus far been on re-using stormwater but once the infrastructure of possibly multiple Bluebloqs systems are realised within one urban area, the interactions between these systems can result in a more complex yet truly circular solution. Having attenuation tanks connected to different parts of the stormwater drainage system will help reduce the investments necessary to maintain the centralised infrastructure. The inclusion of greywater collection systems that lead to separate attenuation tanks is possible. This water then needs additional treatment steps, besides the bio-filter, but can be infiltrated into the aquifer, just like the stormwater. By doing so, a larger freshwater source is created, which can supply more households or facilities in the urban area. Treatment steps after the aquifer storage and recovery can also be considered, to deliver potable water. In conclusion, the Bluebloqs system is a water solution that needs physical implementation. However, its most significant contribution to urban water systems is the principle it follows of creating true circularity within the urban water services.

5.5. Implications of the results on the Bluebloqs system in Spangen, Rotterdam

The system that is realised in Spangen, Rotterdam already has physical design and operational choices that limit the possibilities of improving the performance of the system at this location. An example is the attenuation tank dimensions, which are set to 1400 m^3. The suggested solution would work with a larger attenuation tank and have feed cycles for the bio-filter, to see how much the removal efficiency would improve. Although there is already this 1400 m^3 attenuation tank, it is still suggested to work with a feed cycle of 8 activations per day in summer and 4 activations per day in winter. The reason for still choosing these settings is related to the runoff coefficient. This research has made use of an average runoff coefficient of 0.75, whereas other research on the system in Spangen mentioned a value of 0.55. This lower runoff coefficient means less stormwater enters the system and therefore the feed cycles can arguably safely be applied.

These feed cycles are the most important adjustment that would be suggested as an improvement to the current settings to the system. Also, the discharge of the pump would preferably be set to 15 m^3 per hour instead of the 30 m^3 per hour to which it is set now. However, it is uncertain whether this pump discharge can be adjusted.

By making these adjustments, the system in Spangen, which is a pilot project, can help research progress. If the bio-filter is fed 8 times per day in summer and 4 times in winter, data logging can help provide the necessary information regarding the removal efficiency of the bio-filter. By working with different feed cycles for summer and winter, the removal efficiency of the bio-filter under these different operations can be analysed. Once this is done, future systems can be optimised based on this knowledge, which will eventually present ideal feed cycles.

Also, the feed cycles provide a better understanding of the deterioration processes going on in the bio-filter. The bio-filter may need to be replaced after it has had a number of feed cycles. This number is still uncertain, yet working with these types of feed cycles will make the analysis of long-term deterioration of the bio-filter more convenient. Now, it is uncertain whether the performance of the bio-filter worsens due to the prolonged feed of water, or due to the deterioration of the system itself.

6

Conclusions

In this chapter, the conclusions that can be drawn from the research are presented. First, the performance of the Bluebloqs system as circular solution is concluded upon. Then, the main research question is answered extensively, after which the sub-questions are answered one by one.

6.1. Bluebloqs as a circular urban water solution

This research has presented a model of the Bluebloqs system. This model describes the physical behaviour of processes going on in the Bluebloqs system, with a focus on the water quantity perspective. The outcome of this model are the performance indicators, which grouped together form a framework. This framework can be seen as an overview of the performance of the Bluebloqs system, based on three groups. These groups are the interactions that the Bluebloqs system has with centralised infrastructure, the water quality indicators and the environmental impact of the Bluebloqs system. Based on these groups, it has been determined that the adjustments made in the model can present the performance of the Bluebloqs system as a circular water solution. The objectives on both the drainage and supply side can be met when the right design and operational choices are made. For the system in Spangen, Rotterdam, these design and operational choices are presented in the results. In the discussion it is noted that some of the adjustments made are not feasible, since this system is already realised. However, this shows the function of the model and framework as design tool, and that it can best be applied in the design phase.

The Bluebloqs system can function as circular solution. It can mitigate the risk of pluvial flooding to no occurrences, yet this would imply building an attenuation tank of 1600 m^3, which can be considered an over-dimensioned system. The occurrence of overflows of the attenuation tank do not necessarily result in a surcharged piped network downstream, and even if overflows are taken into consideration, the risk of pluvial flooding is reduced.
The Bluebloqs system is able to provide, in the given case study, 12.500 m^3 of high-quality water, which was determined to be 73 % of the annual demand. If an initial build-up period is included, 88 % of the annual demand can be supplied. As presented in the results, this can deliver a football stadium with irrigation water for multiple years. Only during the summer of 2018, when a long dry period occurred, the supply of water was insufficient at the end of the dry period. Moreover, the model and framework can be used to beforehand show how much water can be

delivered, and give predictions on what periods of drought can be overcome by the system and which are not.
In conclusion, the Bluebloqs system can function as a true circular solution within urban environments. It can be combined with other solutions, such as blue-green roofs and grey-water treatment facilities to make the entire urban water system more circular.

6.2. How can co-designing the Bluebloqs systems design and operations improve its function as a circular urban water system

This section will present how different improvements to the system will result in better performances of the Bluebloqs system. The same order will be used as in the results section, where first the relation between attenuation tank dimensions and pump discharge were discussed. Then activation frequencies are reflected upon after which predictive control of the attenuation tank is presented as improvement to the system.

6.2.1. The relation between attenuation tank dimensions and pump discharge

This research has provided a framework that can be used to find dimensions and operations of the Bluebloqs system that can improve its functionality as local water solution. The volume of water lost in overflow events and the volume of water that can be infiltrated are presented in relation to different attenuation tank dimensions and pump discharges. When an attenuation tank is applied that is very small, a large volume of water is lost in overflow events. If a very large attenuation tank is applied, no overflow events will occur, which would mean the Bluebloqs system could reach its optimal performance. However, the water demand becomes saturated, which means the infiltration of additional water will not increase the performance of the Bluebloqs system. This means that, at some point, providing additional storage in the form of a larger attenuation tank is useless.

6.2.2. The inclusion of activation frequencies

By imposing feed cycles on the bio-filter rather than the continuous discharge of water from the attenuation tank over the bio-filter, a more controlled flow through the bio-filter can be created. When a feed cycle is considered, the effective storage capacity of the attenuation tank is affected. Under continuous flow conditions, the attenuation tank solely has the function to attenuate the flow. This means that, when water is available in the attenuation tank after a storm event, the attenuation tank will be completely emptied directly afterwards. With feed cycles, this water is retained for a longer period of time, resulting in better filtration in the bio-filter. The purpose of doing this is to have a higher quality of the water that is supplied by the Bluebloqs system to the end-user. However, the attenuation tank is less effective in storing upcoming storm events.

6.2.3. Fitting the activation frequencies on expected water inflows

By using activation frequencies, the system is prone to have less effective storage. This can be improved by fitting the activation frequencies to the expected stormwater flows, based on seasonal patterns. The results presented show that an activation frequency of 8 times per day in the summer period – when intense precipitation events are expected to occur – and an activation frequency of 4 times per day in winter, create a solution that has no overflow events for an attenuation tank of 1600 m^3 and a pump discharge of 15 m^3 per hour. These operations present a system that is both able to meet high standards with regard to the drainage objectives, whilst having the a decreased standard deviation for the weighted water age in the bio-filter. This means that less often, there are extended periods of not feeding the bio-filter. Also, the mean weighted water age is slightly longer, which means the water can be filtered for a longer period of time.

6.2.4. Predictive control of the attenuation tank

Allowing overflow events to occur is not necessarily problematic since a hybrid water system is being considered. This means there is a downstream piped infrastructure that is able to deal with flows to occur. However, if overflow events occur, these are not attenuated, which means the overflow event would take place at the same time step as the stormwater runoff enters the system. This is the time step during which the Bluebloqs system should reduce the flow through the downstream network. Hence, predictive control can be applied to let this overflow happen over an extended period of time, when the flow in the downstream network is not yet large.

6.3. Outcome of methodological approach

This section will go through each of the sub-questions, to present how the research has found answers to these questions.

6.3.1. What performance indicators should be included in the framework?

The performance indicators applied in this research represent the behaviour of the Bluebloqs system in different ways. The significance of some of the performance indicators, such as the volume of water lost in overflow events, are more important than others, such as the water age in the attenuation tank. Although some may not be as important as others to find the proper dimensions and operations of the system on the scale that has been focused on in this research, they do need to be included in the framework, since they are important parameter
The Bluebloqs system has been tested on a framework to determine its functionality with regard to support centralised water systems. Therefore, the performance indicators are inclined to present the Bluebloqs system in relation to urban water systems. The framework furthermore focuses on the water quantity aspects of the system, therefore the performance indicators included are the volume of water lost in overflow events annually, the water volume infiltrated in the aquifer and the volume of water supplied to the end-user. These indicators present the circular behaviour of the system.

The framework also provides information on the internal physical behaviour of the Bluebloqs system, and how design and operational adjustments affect this physical behaviour. The indicators that are used to present this are the maximum water age in the attenuation tank and the mean and standard deviation of the weighted water age in the bio-filter respectively.

For the impact of the Bluebloqs system on its environment, the framework also presents the groundwater level fluctuations as indicator.

6.3.2. Which additions to the current control of the Bluebloqs system should be considered?

Current control of the Bluebloqs system could be improved by applying an activation frequency instead of having the continuous feeding of the bio-filter. This allows for better control of the water volumes being fed to the bio-filter.

By applying different activation frequencies for different periods in the year, the trade-off between having sufficient storage capacity available in the attenuation tank and improving the removal efficiency in the bio-filter can be fit more accurately to incoming flow volumes. Adjusting this feed cycle based on expected incoming flow volumes can help to improve the performance of the bio-filter in terms of removing pollutants from the water.

If the storage capacity of the attenuation tank is exceeded, the impact of the overflow events should me minimised to decrease the environmental impact. This can be accomplished by applying predictive control. Looking at what incoming flows can be expected to enter the system will result in the gradual discharge of water towards the downstream water infrastructure, rather than discharging the peak flow in a small time frame.

6.3.3. Which physical aspects of the Bluebloqs system should be modelled?

The Bluebloqs system consists of three components, being the attenuation tank, the bio-filter and the Aquifer Storage and Recovery (ASR) system.
The attenuation tank is modelled as storage volume from which water is discharged towards the bio-filter or lost in overflow events. The volume of water available in the attenuation tank over time, the number of overflow events taking place, the discharge with which the maximum overflow event takes place and the volume of water lost on an annual basis are the important aspects that should be modelled regarding the physical behaviour of the attenuation tank.

The bio-filter is simplified to a trapezoidal bucket filled with a predefined medium for which the average porosity and permeability should be known. The physical behaviour of the water in the bio-filter is simplified by making use of Darcy's Law, where linear flow paths are considered. No preferential flow paths are included nor the use of a submerged zone is considered. The weighted water age for the water leaving the bio-filter is used as performance indicator. This outgoing flow is assumed to follow the first-in-first-out principle.

The ASR system comprises of an infiltration well, allowing the flow of the bio-filter to enter, and an extraction well, which is set to meet the pre-defined water demand set for the end-user. The physical behaviour of the water in the aquifer is further simplified by making use of a Recovery Efficiency (RE) to simplify the processes of mixing with antecedent groundwater and background flow.

6.3.4. What adjustments can most significantly improve the supply of water through the Bluebloqs system?

The pump discharge and attenuation tank dimensions play an important role in the functioning of the Bluebloqs system based on the performance indicators that are related to water quantity. The higher the pump discharge, the less water is lost in overflow events. Also, if a larger attenuation tank is included in the design of the system, less water is lost in overflow events.

Including an activation frequency will extend the retention of water in the attenuation tank, which decreases the mitigation of flood risk. However, the feed cycle for the bio-filter does improve, which can be concluded from the decrease in the standard deviation of the weighted water age in the bio-filter.

The adjustment of the activation frequency based on the seasonality of expected stormwater volumes can further improve the system. By working with higher activation frequencies, the volume of water fed to the bio-filter in a day will be more and thus the effective storage capacity of the attenuation tank increases.

6.3.5. What is the impact of the Bluebloqs system on its environment?

The Bluebloqs system has a minimal negative impact on the groundwater table. Over a period of 5 years, the groundwater table has decreased 25 centimetres. This is the maximum change to the groundwater level found in the time series analysed.

The impact that overflow events may impose on the environment, can be minimised by working with a larger attenuation tank, or a higher discharge. Also, the catchment scale that is connected to the Bluebloqs system can be decreased, resulting in less runoff entering the system. If overflow events do occur, there is the option to include predictive control, which distributes the volume of water lost in an overflow event over the prediction horizon. This can further decrease the impact of overflow events.

6.3.6. What limitations do the modelling assumptions impose on the application of the model?

The model works with hourly time steps, which limits the insights regarding the behavioural aspects that occur on a smaller time scale. This has limited the ability to present the behaviour of the water in the bio-filter. Moreover, the exclusion of a submerged zone, assuming one type of filter medium for the entire bio-filter and no preferential flow paths further limit the application of the model for monitoring purposes. However, it has not been the purpose of this research to build a model for these purposes.

The simplification of the processes taking place in the aquifer have limited the use of the model. The recovery efficiency (RE) is often not known beforehand in a specific location, yet significantly influences the performance of the Bluebloqs system in supplying water. This limitation thus significantly impacts the accuracy of the model in presenting reality.

7

Further research

7.1. From drainage to retention

The use of traditional storage tanks, or attenuation tanks as provided in the configuration for Bluebloqs, present a significant reduction in the occurrence of flow through the downstream water drainage system. The design of this downstream drainage system can consequently be altered. The objective of the centralised drainage system will change from conveying all stormwater to receiving water bodies to ensuring overflow events are conveyed to receiving water bodies. The occurrence of flows and accumulation of flow in the piped network will not follow the traditional accumulation of upstream discharges. Especially when multiple attenuating tanks are realised upstream, the impact of this on the downstream design is worth looking into.

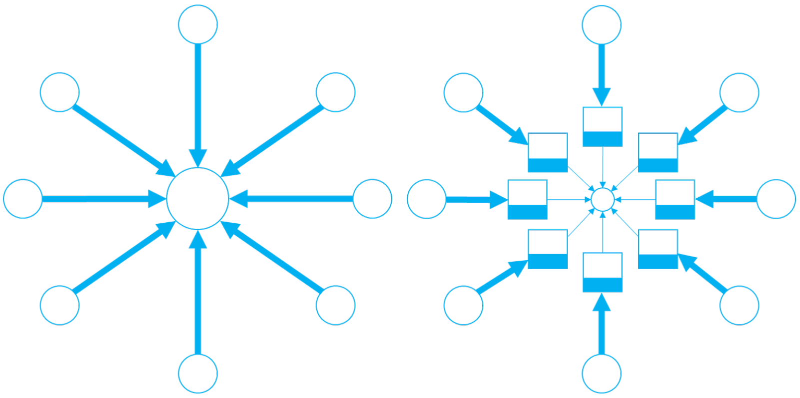

(a) Traditional system (b) System with multiple attenuation tanks

Figure 7.1: Composition of flows in traditional system approach and with the inclusion of attenuation tanks

7.2. Optimising the Bluebloqs configuration

This research has laid out a framework and modelling approach to increase the knowledge that underline the trade-offs which most significantly impact the performance of the Bluebloqs system. The circular approach that this system applies makes the relation between control and design important, because the dimensions of the system should ensure the performance of the system is in line during extreme weather situations, whereas the operations are supposed to create as much homogeneity in the system flows as possible. To make this happen, there are two optimisation tasks that further research should look into. One is finding the optimal configuration of the Bluebloqs system, where a cost-estimation is included. This optimisation should work with the cost of adding additional infiltration wells, the relation between cost and dimensions of the attenuation tank, and how the loss of water in overflow events increases flood risk, and what costs are associated to this. Also, the supply of water through the Bluebloqs system can be related to the cost of having other water resources that the end-user has access to. This optimisation could make use of the schematic representation of the Bluebloqs system, presented in Figure 7.2, where the relations are presented. A modelling approach has also been set up for this problem, which is provided in Appendix C.

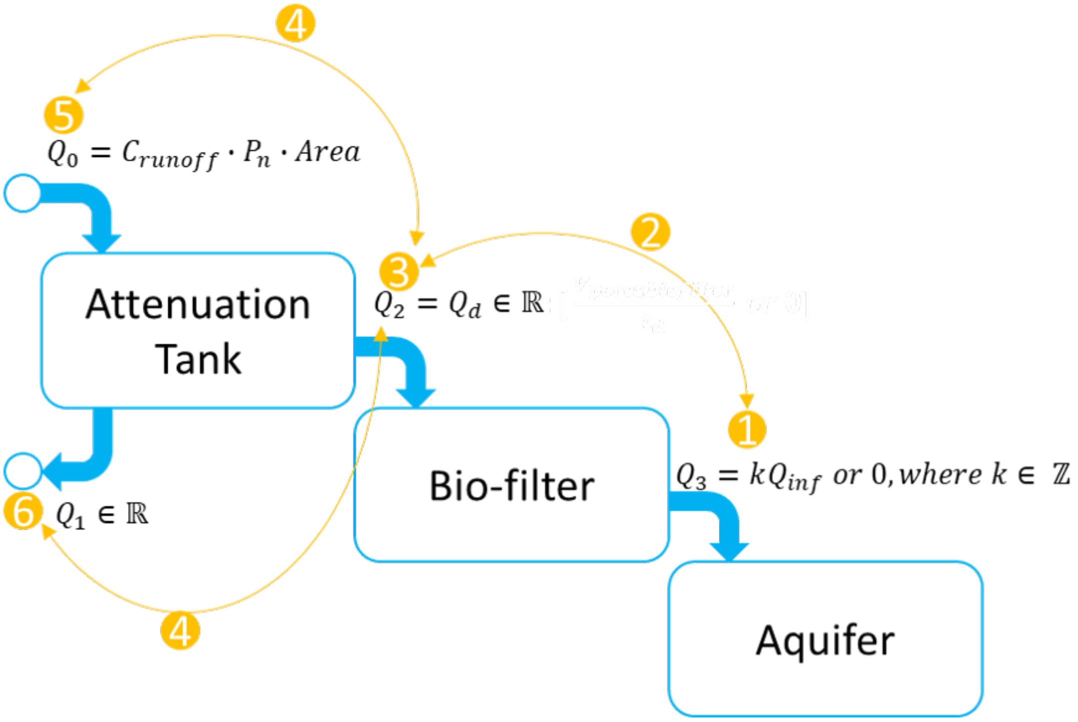


Figure 7.2: Schematic overview of Bluebloqs system for optimisation of configuration

7.3. Optimising the Bluebloqs real-time control

This research has shown the potential of applying predictive control in decreasing the discharge with which overflow events take place. Also, it has been shown how the activation frequencies affect the effective storage of water in the attenuation tank, for which seasonality plays an important role. New research that optimises the real-time control of the Bluebloqs system, based on findings that have been provided in this research regarding predictive control. Combining this research with the real-time control of multiple attenuation tanks, to create a system as presented in Section 7.1.

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A

Rainfall Runoff Relation

```python
#!/usr/bin/env python
# coding: utf-8

import pandas as pd
import numpy as np

Runoff_coefficient = ([0.9, 0.8, 0.6])
Area  = ([0.6, 1.8, 1.3])

data = pd.read_csv('Rainfall_Rotterdam_2015_2020.txt', skiprows=12,
                    sep=',', skipinitialspace=True,
                    parse_dates=[['YYYYMMDD', 'HH']], index_col=0)

data.rename(columns={'DR':'Duration',
                    'RH' :'Depth',
                     '# STN':'Station',
                    'YYYYMMDD_HH' : 'Date'}, inplace=True)

data.loc[data.Depth < 0, 'Depth'] = 0
data.Depth = 0.1 * data.Depth
data.Duration = 0.1 * data.Duration

data.drop(columns='Station', inplace=True)
data.drop(index='nan nan', inplace=True)
data.rename_axis(”Date and Time”, axis='index', inplace=True)

data['Intensity'] = 0

for i in range(len(data)):
    if data.Depth[i] > 0:
        if data.Duration[i] > 0:
            data.Intensity = (data.Depth / data.Duration)

```

```
AREA = 0
CA = 0

for j in range(len(Runoff_coefficient)):
        AREA += Area[j]
        CA += Runoff_coefficient[j] * Area[j] * 10 ** 4

RUNOFF_COEFF = CA / (AREA * 10 ** 4)

print ('The average Runoff Coefficient for this region is:',
        round(RUNOFF_COEFF, 2)  )
print ('The area has a total size of', AREA, 'ha')


# In[10]:


def Q0(Precipitation = data.Depth, C = RUNOFF_COEFF, A = AREA):
    V_max = 2
    evap = (2 / 24)
    Q = np.zeros(len(data)) #Flow in cubic meters per hour
    P_n = np.zeros_like(Q) #Net precipitation in mm
    V = np.zeros_like(Q)

    for i in range(len(data)):
        P = Precipitation[i]
        V[i] = min((V[i-1] + P), V_max)
        if V[i] > 0:
            V[i] += -evap
        elif V[i] <= 0:
            V[i] = 0


        P_n[i] = max(0, (P - max(0, (V_max - V[i]))))


        Q[i] = C * P_n[i] * 10**-3 * A * 10**4


    return P_n, Q, V

data['Pn'] = Q0()[0]
data['Q0'] = Q0()[1]
```

B

Code for Bluebloqs System Model

```
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
import pandas as pd
import datetime
import math
import time
from sympy import symbols, Eq, solve
from scipy.special import exp1
from scipy.special import k0
from scipy.integrate import quad
import timeit
from mpl_toolkits import mplot3d
from tqdm import tqdm

pd.options.mode.chained_assignment = None  # default='warn'
```

Data Dashboard

```
##Design Parameters

Runoff_coefficient = ([0.9, 0.8, 0.6])
Area  = ([0.6, 1.8, 1.3])
print ('Check this is equal:', round((0.9*0.6 + 0.8*1.8 + 0.6*1.3)
        / (np.sum(Area)), 2), np.sum(Area))


%run Rainfall.py
print ('The average annual rainfall is equal to',
        round((data.Depth.sum() / len(data)) * (24*365), 2),'mm')

# Dimensions of the attenuation tank
```

```
L_BUFFER        = 40    # Length of buffer [m]
W_BUFFER        = 25    # Width of buffer [m]
HMAX_BUFFER     = 1.4   # Maximum height in the buffer tank [m]
BUFFER_VOLUME   = L_BUFFER * W_BUFFER * HMAX_BUFFER



# Dimensions of the bio-filter
VOLUME_SELFSUFFICIENCY = 100

W_BIOFILTER = 4
L_BIOFILTER = 13

ANGLE_BIOFILTER = 45    #fixed
HMAX_BIOFILTER  = 1     #fixed
MU_BIOFILTER    = 0.4   #fixed



def dimensions_biofilter(hmax_biofilter = HMAX_BIOFILTER,
        w_biofilter = W_BIOFILTER, angle = ANGLE_BIOFILTER,
        mu = MU_BIOFILTER, L_biofilter = L_BIOFILTER):
    V_biofilter = (hmax_biofilter * (w_biofilter +  hmax_biofilter
            * math.tan(90 - angle)) * (hmax_biofilter *
            (L_biofilter +  hmax_biofilter * math.tan(90 - angle)))
            * mu
    A_biofilter = (w_biofilter + 2 * hmax_biofilter
            * math.tan(90 - angle)) * L_biofilter
    return V_biofilter, A_biofilter

biofilter = dimensions_biofilter()
print ('Volume of the pores in the biofilter:',
        round(int(biofilter[0]), 0))
print ('Surface area of the biofilter:', round(int(biofilter[1]),-1))
```

```
 ## Operational Parameters

 # Flow between buffer and bio-filter
Q2_BREAK_SUMMER     = 4  # Time between bio-filter runs [hrs]
Q2_DISCHARGE_SUMMER = 10 # Inflow rate of irrigation [m3/h]
Q2_DURATION_SUMMER  = 3  # Duration of flow [hrs]

Q2_BREAK_WINTER     = 4  # Time between bio-filter runs [hrs]
Q2_DISCHARGE_WINTER = 10 # Inflow rate of irrigation [m3/h]
Q2_DURATION_WINTER  = 3  # Duration of flow [hrs]


#Operations of the buffer tank
MIN_BUFFER_FILL = VOLUME_SELFSUFFICIENCY #minimum water level
```

```
MAX_BUFFER_FILL = 0.95 * BUFFER_VOLUME    #maximum water level
PREDICTION_DURATION = 0                   #prediction horizon


# Flow to the end-user
Q4_BREAK_SUMMER     = 12  # Time between aquifer runs [hrs]
Q4_DISCHARGE_SUMMER = 10  # Inflow rate aquifer [m3/h]
Q4_DURATION_SUMMER  = 12  # Duration of flow [hrs]

Q4_BREAK_WINTER     = 23  # Time between aquifer runs [hrs]
Q4_DISCHARGE_WINTER = 10  # Inflow rate aquifer [m3/h]
Q4_DURATION_WINTER  = 1   # Duration of flow [hrs]

# Aquifer efficiency
RECOVERY_EFFICIENCY = 100
```

```
 ## System Constraints

 year = int((24*365))

# Dimensions of the bio-filter
PERMEABILITY = 34.6 * 10 ** -6
VISCOSITY = 1000
DENSITY = 1000



#Dimensions of the aquifer
rw = 0.2                # diameter of the well [m]
k = 40                  # hydraulic conductivity [m/d]
H = 10.75               # aquifer thickness [m]
T = k * H               # transmissivity [m2 /d]
c = 200                 # resistance of the covering clay layer [days]
lab = np.sqrt(c * T)    # lambda [m]
Ss = 1e-5               # specific storage [m3/m]
S = Ss * H              # storage [m3]


r = np.linspace(rw, 3*lab, 100)
```

Flow pattern for flow from attenuation tank to bio-filter

```
 def Q2(break_duration_summer = Q2_BREAK_SUMMER,
        break_duration_winter = Q2_BREAK_WINTER,
        summer_inflow = Q2_DISCHARGE_SUMMER,
        winter_inflow = Q2_DISCHARGE_WINTER,
        irrigation_duration_summer = Q2_DURATION_SUMMER,
        irrigation_duration_winter = Q2_DURATION_WINTER):
    Q2 = np.zeros(len(data))
```

```

    for i in range(0, len(Q2), year):
        for j in range(int((5/12)*year),
        int((9/12)*year),
        (irrigation_duration_summer + break_duration_summer - 1)):
            for k in range(irrigation_duration_summer):
                if i+j+k < len(Q2):
                    Q2[i+j+k] = summer_inflow
                    data['season'] = ”summer”

    for i in range(-year, len(Q2), year):
        for j in range(int((9/12)*year + irrigation_duration_summer),
        int((17/12)*year - irrigation_duration_winter),
        (irrigation_duration_winter + break_duration_winter )):
            for k in range(irrigation_duration_winter):
                if i+j+k < len(Q2):
                    Q2[i+j+k] = winter_inflow
                    data['season'] = ”winter”
    return Q2

data['Q2'] = Q2()
#data['Q2'] = 0
```

Predictive Control of Attenuation Tank

```
data['rain_time_series'] = data['Q0'].rolling(
   window=PREDICTION_DURATION).sum().shift(-PREDICTION_DURATION)
   -data['Q2'].rolling(
   window=PREDICTION_DURATION).sum().shift(-PREDICTION_DURATION)
```

Attenuation Tank Design And Operations

```
def Buffer(rain_time_series, prediction_duration):
   V = np.zeros(len(data))
   Volume = 0
   data['Q1'] = 0

   for i in tqdm(range(len(data))):

       if rain_time_series[i] > BUFFER_VOLUME - V[i-1] - data.Q2[i]:
           lost = 0
           for j in range(prediction_duration):
               data.Q1[i+j] = (rain_time_series[i] - V[i]) /
               prediction_duration
               lost += data.Q1[i+j]


       if data.season[i] == ”summer”:
           if V[i-1] <=  + 100 :
```

```
                data.Q2[i+j] = 0
            if V[i-1] > MAX_BUFFER_FILL:
                for j in range(Q2_DURATION_SUMMER):
                    data.Q2[i+j] = Q2_DISCHARGE_SUMMER


        if data.season[i] == ”winter”:
            if V[i-1] <= Q2_DISCHARGE_WINTER: #* Q2_DURATION_WINTER:
                data.Q2[i] = 0
            if V[i-1] > MAX_BUFFER_FILL:
                for j in range(Q2_DURATION_WINTER):
                    data.Q2[i+j] = Q2_DISCHARGE_WINTER

        if V[i-1] + data.Q2[i-1] > BUFFER_VOLUME:
            data.Q1[i] = data.Q2[i-1] + V[i-1] - BUFFER_VOLUME



        Volume += data.Q0[i] - data.Q2[i] - data.Q1[i]
        V[i] = Volume

        if V[i] >= BUFFER_VOLUME:
            data.Q1[i] += V[i] - BUFFER_VOLUME
            V[i] = BUFFER_VOLUME


    return V, data.Q1

#-----------------------------
values = Buffer(rain_time_series=data.rain_time_series,
                prediction_duration = PREDICTION_DURATION)

data[”Buffer_level”] = values[0]
data[”Overflows_Buffer”] = values[1]
```

```
 PREDICTION_DURATION = 5
data['rain_time_series_5hrs'] =
data['Q0'].rolling(window=PREDICTION_DURATION).sum()
.shift(-PREDICTION_DURATION) -
data['Q2'].rolling(window=PREDICTION_DURATION).sum()
.shift(-PREDICTION_DURATION)

data[”Buffer_level_5hrs”] =
Buffer(rain_time_series=data.rain_time_series_5hrs,
prediction_duration = PREDICTION_DURATION)[0]

data['Overflows_5hrs'] =
Buffer(rain_time_series=data.rain_time_series_5hrs,
prediction_duration = PREDICTION_DURATION)[1]
```

```


PREDICTION_DURATION = 10
data['rain_time_series_10hrs'] =
data['Q0'].rolling(window=PREDICTION_DURATION).sum()
.shift(-PREDICTION_DURATION) -
data['Q2'].rolling(window=PREDICTION_DURATION).sum()
.shift(-PREDICTION_DURATION)

data[”Buffer_level_10hrs”] =
Buffer(rain_time_series=data.rain_time_series_10hrs,
prediction_duration = PREDICTION_DURATION)[0]

data['Overflows_10hrs'] =
Buffer(rain_time_series=data.rain_time_series_10hrs,
prediction_duration = PREDICTION_DURATION)[1]


PREDICTION_DURATION = 24
data['rain_time_series_24hrs'] =
data['Q0'].rolling(window=PREDICTION_DURATION).sum()
.shift(-PREDICTION_DURATION) -
data['Q2'].rolling(window=PREDICTION_DURATION).sum()
.shift(-PREDICTION_DURATION)

data[”Buffer_level_24hrs”] =
Buffer(rain_time_series=data.rain_time_series_24hrs,
prediction_duration = PREDICTION_DURATION)[0]

data['Overflows_24hrs'] =
Buffer(rain_time_series=data.rain_time_series_24hrs,
prediction_duration = PREDICTION_DURATION)[1]
```

Bio-filter operations

```
def bio_filter(Q2 = data.Q2, w = W_BIOFILTER, L = L_BIOFILTER,
               hmax = HMAX_BIOFILTER, mu = MU_BIOFILTER,
               k = PERMEABILITY, rho = DENSITY, eta = VISCOSITY):
    Qin = data.Q2
    w0 = w
    a = w0
    g = 9.81

    V = np.zeros(len(data))
    Vp = np.zeros_like(V)
    Qout = np.zeros_like(V)
    A = np.zeros_like(Qout)
    h = np.zeros_like(A)

```

```
    Vin = 0
    Vout=0
    h_0 = 0
    no_flow = 0

    for i in range(len(data)):
        V[i] = (Qin[i] - Qout[i-1] + V[i-1])
        Vp[i] = V[i] / mu
        A[i] = Vp[i] / L
        h[i] = (-a + np.sqrt(a**2 + 4 * A[i])) / 2
        Qout[i] = ((k * ((rho * g) / eta) * h[i])) * (A[i] * 3600)
        Vout += Qout[i]
        if Qout[i] == 0:
            h_0 += 1
            no_flow +=1

    return h, Qout, A


values = bio_filter()
data['water_level_biofilter'] = values[0]
data['Q3'] = values[1]
```

Demand Flow Pattern

```
def Q4(break_duration_summer = Q4_BREAK_SUMMER,
        break_duration_winter = Q4_BREAK_WINTER,
        summer_outflow = Q4_DISCHARGE_SUMMER,
        winter_outflow = Q4_DISCHARGE_WINTER,
        irrigation_duration_summer = Q4_DURATION_SUMMER,
        irrigation_duration_winter = Q4_DURATION_WINTER):
    Q4 = np.zeros(len(data))

    for i in range(0, len(Q4), year):
        for j in range(int((4.5/12)*year), int((8.5/12)*year),
        (irrigation_duration_summer + break_duration_summer - 1)):
            for k in range(irrigation_duration_summer):
                if i+j+k < len(Q4):
                    Q4[i+j+k] = summer_outflow


    for i in range(-year, len(Q4), year):
        for j in range(int((8.5/12)*year +
        irrigation_duration_summer),
        int((16.5/12)*year - irrigation_duration_winter),
        (irrigation_duration_winter + break_duration_winter - 1)):
            for k in range(irrigation_duration_winter):
                if i+j+k < len(Q4):
                    Q4[i+j+k] = winter_outflow
```

```
    for i in range(0, int((3/12)*year)):
        Q4[i] = 0

    return Q4



data['Q4'] = Q4()
```

Constrain supply to water availability in aquifer

```
 def Extraction(min_water_need):
    a = 0
    for i in tqdm(range(len(data))):
        a += data.Q3[i] - data.Q4[i]
        if a <= 0:
            data.Q4[i] = 0
            a = 0
    data['Q4_sum'] = data.Q4.cumsum()
    return

Extraction((100 - RECOVERY_EFFICIENCY) * data.Q3_sum)

data['Bell'] = data.Q3_sum - data.Q4_sum
```

Behaviour of water in aquifer

```
 r = 0.2
def E1_func(tau, r, T, lab):
    #print (tau)
    return (1/tau) * np.exp(-tau - (r**2 / (4 * lab**2 * tau)))

def Integral(u):
    return quad(E1_func, u, np.inf, args=(r, T, lab))[0]

def u_t(r, t_end):
    E1 = []
    add_ons = 6 * S * r**2 / T
    for i in range(t_end):
            u  = (add_ons / (t_end - i))
            E1.append(Integral(u))
    return E1

E1_t = (u_t(r=0.2, t_end=24*365))
```

Injection of water and effect on aquifer

```
h_injection = np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection))):
```

```
    for j in range(i):
        h_injection[i] += - (6 * data.Q3[j]) / (np.pi * T) *
        (E1_t[-1] - E1_t[j-i])

h_injection_year2 = np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection_year2))):
    for j in range(i):
        h_injection_year2[i] += - (6 * data.Q3[365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])

h_injection_year3 = np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection_year2))):
    for j in range(i):
        h_injection_year3[i] += - (6 * data.Q3[2*365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])

h_injection_year4 = np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection_year2))):
    for j in range(i):
        h_injection_year4[i] += - (6 * data.Q3[3*365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])

h_injection_year5 = np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection_year2))):
    for j in range(i):
        h_injection_year5[i] += - (6 * data.Q3[4*365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])
```

Extraction of water and effect on aquifer

```
 h_extraction = np.zeros(len(E1_t))
for i in tqdm(range(len(h_extraction))):
    for j in range(i):
        h_extraction[i] += - (6 * -data.Q4[j]) /\
        (np.pi * T) *\
        (E1_t[-1] - E1_t[j-i])

h_extraction_year2 = np.zeros(len(E1_t))
for i in tqdm(range(len(h_extraction_year2))):
    for j in range(i):
        h_extraction_year2[i] += - (6 * -data.Q4[365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])

h_extraction_year3 = np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection_year2))):
    for j in range(i):
        h_extraction_year3[i] += - (6 * -data.Q4[2*365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])

```

```
h_extraction_year4 = np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection_year2))):
    for j in range(i):
        h_extraction_year4[i] += - (6 * -data.Q4[3*365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])

h_extraction_year5 =np.zeros(len(E1_t))
for i in tqdm(range(len(h_injection_year2))):
    for j in range(i):
        h_extraction_year5[i] += - (6 * -data.Q4[4*365*24+j]) /
        (np.pi * T) * (E1_t[-1] - E1_t[j-i])
```

Groundwater change over entire period

```
 h_groundwater = np.ones(len(data))

h_groundwater[0:len(h_injection)] = h_injection + h_extraction
h_groundwater[len(h_injection):2*len(h_injection)] =
    h_groundwater[len(h_injection)-1] + h_injection_year2 +
    h_extraction_year2
h_groundwater[2*len(h_injection):3*len(h_injection)] =
    h_groundwater[2*len(h_injection)-1] + h_injection_year3 +
    h_extraction_year3
h_groundwater[3*len(h_injection):4*len(h_injection)] =
    h_groundwater[3*len(h_injection)-1] + h_injection_year4 +
    h_extraction_year4
h_groundwater[4*len(h_injection):5*len(h_injection)] =
    h_groundwater[4*len(h_injection)-1] + h_injection_year5 +
    h_extraction_year5

print (h_groundwater[np.argmax(h_groundwater)])

plot(h_groundwater, my_label_years, my_ticks_years)

plt.ylabel('Groundater head variation [m]')
plt.xlabel('Date')
```

Spatial effect of pump regime at maximum water level change

```
def Integral2(u, r):
    return quad(E1_func, u, np.inf, args=(r, T, lab))[0]

def u_r(r_well, t_interest):
    E1 = []
    for i in range(len(r_well)):
        r = r_well[i]
        add_ons = 6 * S * r**2 / T
        u  = (add_ons / (t_interest))
        E1.append(Integral2(u, r))
```

```python
    return E1

R = np.linspace(0, 25, 251)
R[0] = 0.2
R[1] = 0.2

x = u_r(r_well = R, t_interest = np.argmax(h_groundwater))[0] /
        h_groundwater[np.argmax(h_groundwater)]

groundwater_distance = u_r(r_well = R,
                           t_interest = np.argmax(h_groundwater)) /
                           x
```

C

Code for the optimisation of the Bluebloqss ystem configuration

Provide necessary packages.

```
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
import pandas as pd
import pyomo.environ as pyo
import time
```

```
Q_overflow = np.inf
S_max      = np.inf
Wells_max  = 4

k_well   = 40
H_well   = 10.75
T_well   = k_well * H_well
H_filter = 1.2
Q_inf    = H_filter * T_well / 24

k_biofilter = 34.6 * 10 ** -6
rho         = 1000
g           = 9.81
eta         = 1000
mu          = 0.4
h_bio_max   = 1

delta_pump  = 1e-3
delta_head  = 1e-3
print ('The infiltration capacity of one well in the location
is:', round(Q_inf,1) , 'cubic meters per hour')
```

```python
model = pyo.AbstractModel()

# Sets
model.t    = pyo.Set(dimen  = 1)
model.x    = pyo.Set(within = model.t)


# Indexed Parameters
model.Q0      = pyo.Param(model.t, within = pyo.NonNegativeReals)

# Non-indexed Variables
model.V_max   = pyo.Var(within = pyo.NonNegativeReals,
initialize = 0)
model.Q2_dis  = pyo.Var(domain = pyo.NonNegativeReals)
model.Att_max = pyo.Var(domain = pyo.NonNegativeReals)
model.L_bio   = pyo.Var(domain = pyo.PositiveIntegers,
bounds = (5, 30))
model.w_bio   = pyo.Var(domain = pyo.PositiveIntegers,
bounds = (1, 10))
#Constraint for area of bio-filter

# Indexed Variables
model.V_att   = pyo.Var(model.t, within = pyo.NonNegativeReals,
bounds = (0, S_max))
model.Q2      = pyo.Var(model.t, within = pyo.NonNegativeReals)
model.Q2_pump = pyo.Var(model.t, domain = pyo.NonNegativeReals,
initialize = 1)
model.Q3      = pyo.Var(model.t, domain = pyo.NonNegativeReals,
bounds = (0, Q_inf))
model.h_bio   = pyo.Var(model.t, domain = pyo.NonNegativeReals,
bounds = (0, h_bio_max))
model.V_bio   = pyo.Var(model.t, domain = pyo.NonNegativeReals)
model.Volume  = pyo.Var(model.t, domain = pyo.NonNegativeReals)
```

```python
# Water balance for attenuation tank
def Attenuation_Tank(model, t):
    if t == 0:
        return model.V_att[t] == Vatt_init
    if t == len(model.t) - 1:
        return model.V_att[t] == Vatt_init
    else:
        return model.V_att[t] == model.V_att[t-1] + model.Q0[t-1] -
        model.Q2[t-1]


# Binary pump
def Pump_binary(model, t):
    return np.abs(model.Q2_pump[t] * ( 1 - model.Q2_pump[t])) <=
```

```
    delta_pump

# Composition of flow Q2
def FlowQ2(model, t):
    if t == 0:
        return model.Q2[t] == 0
    else:
        return model.Q2[t] == model.Q2_pump[t] * model.Q2_dis

# Bio-filter volume
def V_biofilter(model, t):
    if t == 0:
        return model.V_bio[t] == Vbio_init
    else:
        return model.V_bio[t] == (model.Q2[t-1] - model.Q3[t-1]) +
        model.V_bio[t-1]

# Composition of flow Q3
def FlowQ3(model, t):
    if t == 0:
        return model.Q3[t] == 0
    else:
        return model.Q3[t] == (k_biofilter * (rho * g / eta) *
        model.h_bio[t-1]) * (model.V_bio[t-1] / model.L_bio) *
        (60*60)


# Water level in bio-filter
def h_biofilter(model, t):
    return model.L_bio * model.w_bio * model.h_bio[t] ==
    model.V_bio[t]
```

```
# Constraints
model.attenuation_tank = pyo.Constraint(model.t,
rule = Attenuation_Tank)
model.flowQ2            = pyo.Constraint(model.t, expr = FlowQ2)
model.flowQ3            = pyo.Constraint(model.t, expr = FlowQ3)
model.volume_biofilter = pyo.Constraint(model.t, expr = V_biofilter)
model.head_biofilter    = pyo.Constraint(model.t, expr = h_biofilter)
model.binary_pump       = pyo.Constraint(model.t, expr = Pump_binary)
```

```
# Minimize attenuation tank volume

def MinAtt(model):
    return pyo.summation(model.V_att)

model.objective1 = pyo.Objective(rule=MinAtt, sense = pyo.minimize)
```

```
time_frame = 50
```

```python

inflow = {}
for i in range(0, time_frame):
    inflow[i] = data.Q0[21300 + i] #20000

t = np.arange(0, time_frame)


opt_dict = {None: {
    't' : {None: t},
    'Q0' : inflow,
}}

Vatt_init = 50
Vbio_init = 0


#print (opt_dict)
opt        = pyo.SolverFactory('ipopt')
opt.options['max_iter'] = 10000
opt.options['tol']      = 1e-1
```

```python
instance1 = model.create_instance(opt_dict)
start = time.time()
opt.solve(instance1)
stop = time.time()

print ('Time to solve:', stop - start);
```

```python
def FlowQ3Max(model):
    return pyo.summation(model.Q3)

model.objective3 = pyo.Objective(rule=FlowQ3Max,
sense = pyo.maximize)
model.objective1.deactivate()
instance3 = model.create_instance(opt_dict)
```

```python
start = time.time()
opt.solve(instance3);
stop = time.time()
print ('Time to solve:', stop - start)
```

D

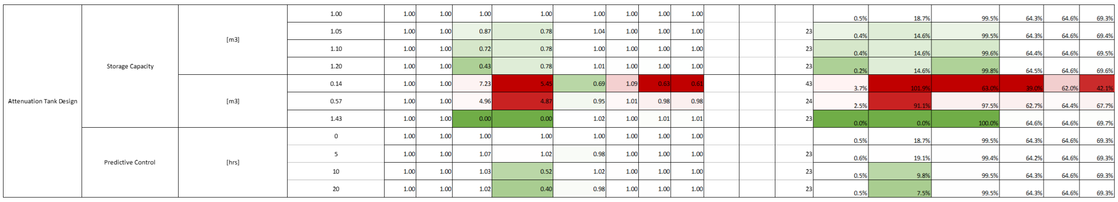
Sensitivity Analysis

The tables below present the sensitivity analysis that has been performed in more detail. Here, the tables are divided in five groups. The first group focuses on input parameters related to the incoming flow, such as the catchment size and runoff coefficient. The second group presents the performance indicators for adjustments made to the attenuation tank dimensions. The third group gives insights on how adjustments to the control of the pump, discharging the water from the attenuation tank to the bio-filter, change the performance indicators. The fourth table reflects on the impact of the recovery efficiency. Lastly, the demand pattern is adjusted to find out what performance indicators are affected by this.

The water age in the aquifer is not calculated for most of the calculated values in the sensitivity analysis presented here. Reason for this is the runtime of the model significantly increases when this parameter is to be determined. Since it also is a performance indicator that is not leading in the design choices and operational considerations of the system, it is decided that it is excluded from this table. For the results presented in the research, the water age in the aquifer is calculated.

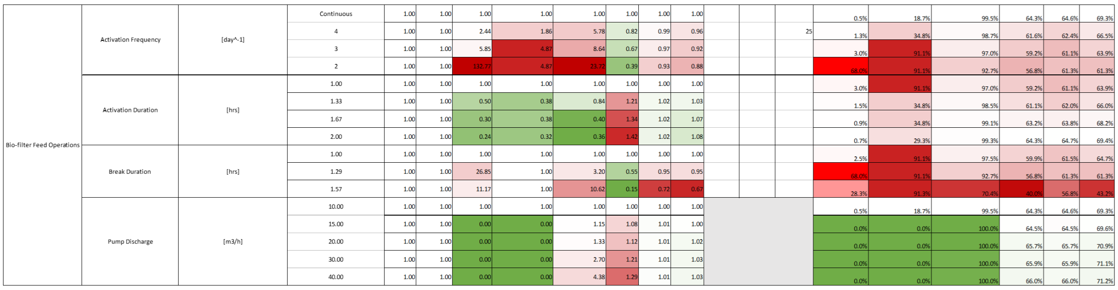
			Percentage Change Compared to Base Situation	Average Annual Runoff	Maximum Incoming Runoff	Average Annual Volume Lost Overflows	Maximum Discharge Overflow Event	Mean Water Age Attenuation Tank	Mean Water Age Bio-filter	Volume Infiltrated	Volume Extracted	Minimum Water Age Aquifer	Mean Water Age Aquifer	Unmet Demand	Overflow Lost of Incoming Flow	Impact of Maximum Overflow Event	Volume Infiltrated of Water Received	Volume Extracted of Incoming Flow	Volume Extracted of Infiltrated	Volume of Demand Supplied
				m3	m3/h	m3	m3/h	hrs	hrs	m3	m3	hrs	hrs	days	%	%	%	%	%	%
Incoming Flow	Runoff Coefficient	[-]	0.73	0.73	0.73	0.00	0.00	1.19	1.07	0.74	0.73			37	0.0%	0.0%	100.0%	64.0%	64.0%	50.6%
			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			1.05	1.05	1.05	1.45	1.96	0.85	1.00	1.05	1.06				0.7%	34.8%	98.7%	64.4%	65.2%	73.2%
			1.10	1.11	1.11	1.87	2.04	0.95	0.98	1.10	1.11				0.9%	34.6%	99.1%	64.4%	64.9%	76.9%
			1.16	1.20	1.20	3.04	2.21	1.20	0.98	1.19	1.20				1.3%	34.4%	98.7%	64.5%	65.3%	83.5%
	Catchment Size	[ha]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			1.05	1.05	1.05	1.42	1.95	0.89	0.99	1.05	1.05				0.7%	34.6%	99.3%	64.4%	64.9%	73.1%
			1.10	1.10	1.10	1.82	2.03	1.00	0.99	1.10	1.10				0.8%	34.6%	99.1%	64.4%	64.9%	76.4%
			1.20	1.20	1.20	3.04	2.21	1.19	0.98	1.19	1.20				1.3%	34.4%	98.7%	64.5%	65.3%	83.5%
	Initial Losses		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			1.50	0.94	1.00	0.94	0.78	1.44	1.12	0.94	0.94				0.5%	14.6%	99.5%	64.6%	64.9%	65.4%
			2.00	0.89	1.00	0.95	0.78	1.35	1.30	0.89	0.90			29	0.5%	14.6%	99.4%	64.8%	65.2%	62.4%
			2.50	0.86	1.00	0.93	0.78	1.33	1.50	0.86	0.87			30	0.6%	14.6%	99.4%	65.0%	65.4%	60.3%
	Evaporative Losses	[mm/h]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			1.50	0.93	1.00	0.78	0.77	1.02	1.04	0.93	0.93			26	0.4%	14.5%	99.6%	64.4%	64.7%	64.7%
			2.00	0.88	1.00	0.53	0.76	1.12	1.06	0.88	0.88			30	0.3%	14.3%	99.7%	64.6%	64.8%	61.2%
			2.50	0.83	0.99	0.40	0.75	1.19	1.09	0.83	0.84			32	0.2%	14.1%	99.7%	64.8%	64.9%	58.0%

(a) Incoming flow



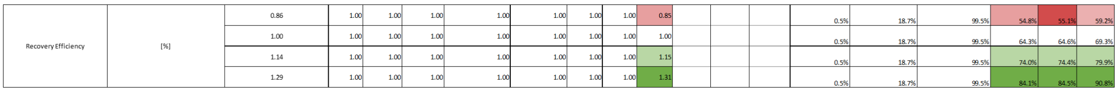
Attenuation Tank Design	Storage Capacity	[m3]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			1.05	1.00	1.00	0.87	0.78	1.04	1.00	1.00	1.00			23	0.4%	14.6%	99.5%	64.3%	64.6%	69.4%
			1.10	1.00	1.00	0.72	0.78	1.00	1.00	1.00	1.00			23	0.4%	14.6%	99.6%	64.4%	64.6%	69.5%
			1.20	1.00	1.00	0.43	0.78	1.01	1.00	1.00	1.00			23	0.2%	14.6%	99.8%	64.5%	64.6%	69.6%
		[m3]	0.14	1.00	1.00	7.23	5.45	0.69	1.09	0.63	0.61			43	3.7%	101.9%	63.0%	39.0%	62.0%	42.1%
			0.57	1.00	1.00	4.96	4.87	0.95	1.01	0.98	0.98			24	2.5%	91.1%	97.5%	62.7%	64.4%	67.7%
			1.43	1.00	1.00	0.00	0.00	1.02	1.00	1.01	1.01			23	0.0%	0.0%	100.0%	64.6%	64.6%	69.7%
	Predictive Control	[hrs]	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			5	1.00	1.00	1.07	1.02	0.98	1.00	1.00	1.00			23	0.6%	19.1%	99.4%	64.2%	64.6%	69.3%
			10	1.00	1.00	1.03	0.52	1.02	1.00	1.00	1.00			23	0.5%	9.8%	99.5%	64.3%	64.6%	69.3%
			20	1.00	1.00	1.02	0.40	0.98	1.00	1.00	1.00			23	0.5%	7.5%	99.5%	64.3%	64.6%	69.3%

(b) Attenuation tank design



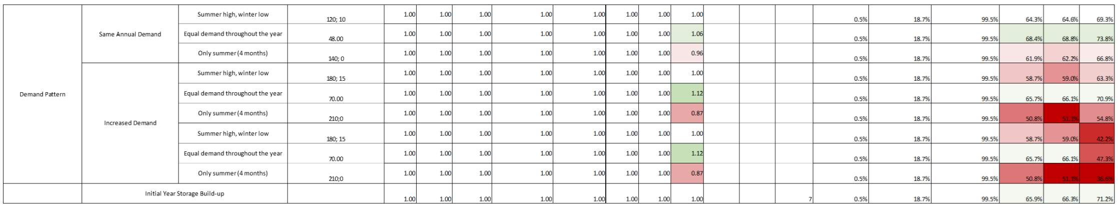
Bio-filter Feed Operations	Activation Frequency	[day^-1]	Continuous	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			4	1.00	1.00	2.44	1.86	5.78	0.82	0.99	0.96			25	1.3%	34.8%	98.7%	61.6%	62.4%	66.5%
			3	1.00	1.00	5.85	4.87	8.64	0.67	0.97	0.92				3.0%	91.1%	97.0%	59.2%	61.1%	63.9%
			2	1.00	1.00	132.77	4.87	23.72	0.39	0.93	0.88				68.0%	91.1%	92.7%	56.8%	61.3%	61.3%
	Activation Duration	[hrs]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				3.0%	91.1%	97.0%	59.2%	61.1%	63.9%
			1.33	1.00	1.00	0.50	0.38	0.84	1.21	1.02	1.03				1.5%	34.8%	98.5%	61.1%	62.0%	66.0%
			1.67	1.00	1.00	0.30	0.38	0.40	1.34	1.02	1.07				0.9%	34.8%	99.1%	63.2%	63.8%	68.2%
			2.00	1.00	1.00	0.24	0.32	0.36	1.42	1.02	1.08				0.7%	29.3%	99.3%	64.3%	64.7%	69.4%
	Break Duration	[hrs]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				2.5%	91.1%	97.5%	59.9%	61.5%	64.7%
			1.29	1.00	1.00	26.85	1.00	3.20	0.55	0.95	0.95				68.0%	91.1%	92.7%	56.8%	61.3%	61.3%
			1.57	1.00	1.00	11.17	1.00	10.62	0.15	0.72	0.67				28.3%	91.3%	70.4%	40.0%	56.8%	43.2%
	Pump Discharge	[m3/h]	10.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
			15.00	1.00	1.00	0.00	0.00	1.15	1.08	1.01	1.00				0.0%	0.0%	100.0%	64.5%	64.5%	69.6%
			20.00	1.00	1.00	0.00	0.00	1.33	1.12	1.01	1.02				0.0%	0.0%	100.0%	65.7%	65.7%	70.9%
			30.00	1.00	1.00	0.00	0.00	2.70	1.21	1.01	1.03				0.0%	0.0%	100.0%	65.9%	65.9%	71.1%
			40.00	1.00	1.00	0.00	0.00	4.38	1.29	1.01	1.03				0.0%	0.0%	100.0%	66.0%	66.0%	71.2%

(c) Bio-filter feed operations



Recovery Efficiency	[%]	0.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85				0.5%	18.7%	99.5%	54.8%	55.1%	59.2%
		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
		1.14	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.15				0.5%	18.7%	99.5%	74.0%	74.4%	79.9%
		1.29	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.31				0.5%	18.7%	99.5%	84.1%	84.5%	90.8%

(d) Aquifer recovery efficiency



Demand Pattern	Same Annual Demand	Summer high, winter low	120; 10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	64.3%	64.6%	69.3%
		Equal demand throughout the year	48.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.06				0.5%	18.7%	99.5%	68.4%	68.8%	73.8%
		Only summer (4 months)	140; 0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96				0.5%	18.7%	99.5%	61.9%	62.2%	66.8%
	Increased Demand	Summer high, winter low	180; 15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	58.7%	59.0%	63.3%
		Equal demand throughout the year	70.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.12				0.5%	18.7%	99.5%	65.7%	66.1%	70.9%
		Only summer (4 months)	210;0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87				0.5%	18.7%	99.5%	50.8%	51.1%	54.8%
		Summer high, winter low	180; 15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				0.5%	18.7%	99.5%	58.7%	59.0%	42.2%
		Equal demand throughout the year	70.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.12				0.5%	18.7%	99.5%	65.7%	66.1%	47.3%
		Only summer (4 months)	210;0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87				0.5%	18.7%	99.5%	50.8%	51.1%	36.6%
	Initial Year Storage Build-up			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00			7	0.5%	18.7%	99.5%	65.9%	66.3%	71.2%

(e) Demand pattern

Figure D.1: Parameters affecting the performance indicators