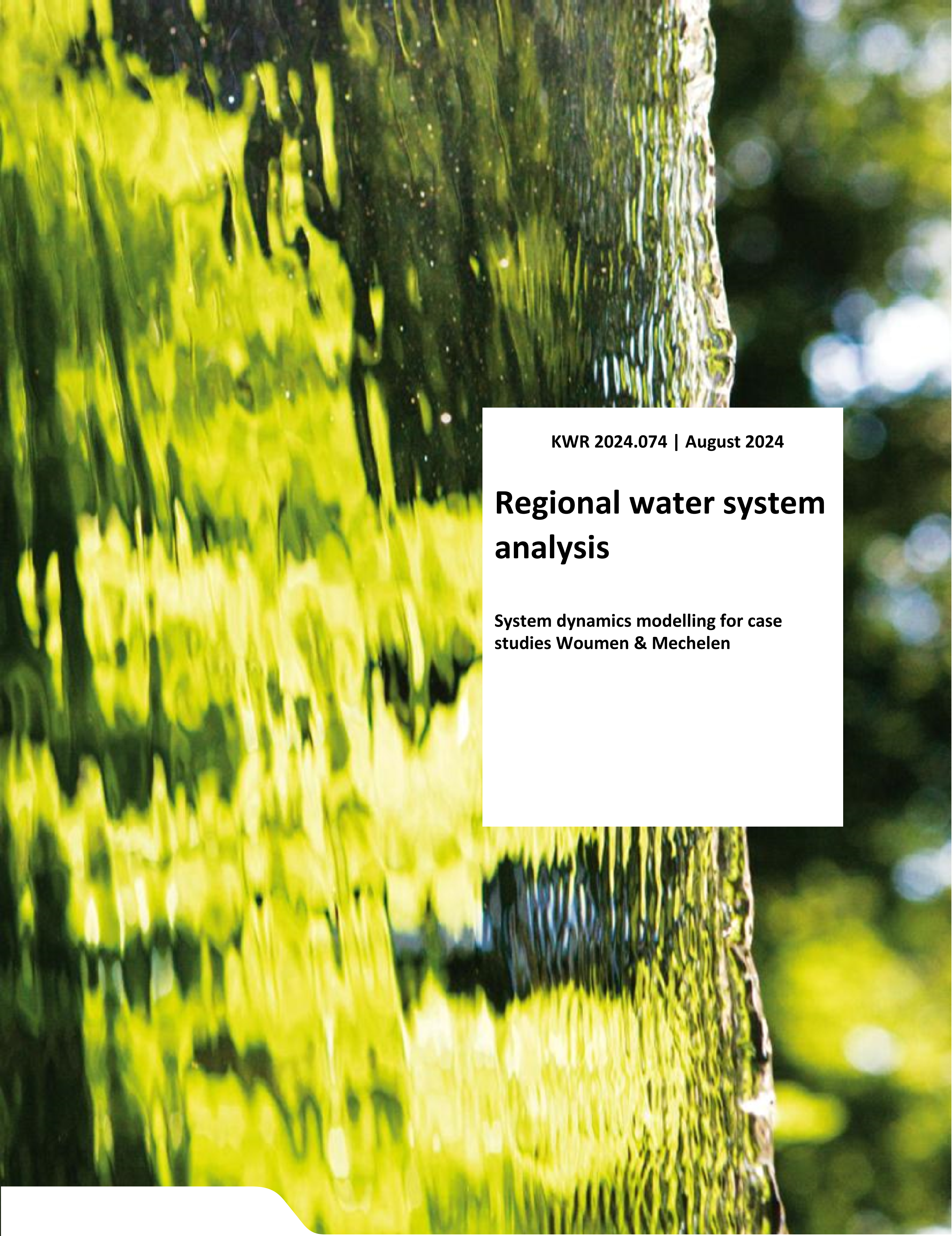

KWR 2024.074 | August 2024

Regional water system analysis

System dynamics modelling for case studies Woumen & Mechelen

Bridging Science to Practice

Report

Regional water system analysis: System dynamics modelling for case studies Woumen & Mechelen

KWR 2024.074 | August 2024

Project number
403664, 402833

Project manager
Klaasjan Raat

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This research was supported by Water in the Circulair Economy (WiCE) research programme (part of the Joint Research Programme with water utilities in the Netherlands and Flanders), and the Delta Programme of the Ministry of Infrastructure and Water Management. The research was conducted in collaboration with B-Watersmart, a European Union Horizon 2020 funded research and innovation programme under grant agreement No. 869171.

Sent to
This report has been sent to BTO-participants and collaborators. The report is publicly available.

Keywords
Water availability, system dynamics modelling

Year of publishing
2024

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Summary

In the B-Watersmart Living Lab Vlaanderen effects of innovative technological measures on the regional water system are studied. In this report, we used a system dynamics model to identify these effects. A system dynamics model can be used to investigate interactions and feedbacks between different subsystems. In the B-watersmart Living Lab Vlaanderen, two case studies with different landscape characteristics and challenges in the water system are defined, where measures are implemented. In the case study Woumen/De Blankaart an extra purification step is added to the drinking water production to deal with fluctuations in the water quality of the surface water (mainly chloride concentration) and to be able to use effluent from a waste water treatment plant (WWTP) as a source for drinking water production. In the case study Mechelen a stormwater retention basin is build to store urban runoff and re-use it for subirrigation in surrounding agricultural fields. The general research question for both case studies is:

> What is the effect of the measure on the regional water system in normal and dry periods and how does the measure affect the water-smartness of the water system?

In this report we modelled the water system for the two case studies with a specific system dynamic model for each region. We build the models with the software Vensim (https://vensim.com/). In both case studies project partners are performing pilots and technical modelling of subsystems, mainly at small scale and isolated from the regional water system. We explored the effects of the proposed measures on the regional water system and other water users in the region with the system dynamics model.

In Woumen/De Blankaart the implementation of the measure meant that the total drinking water production increased, however, in dry periods there was still not enough water available to maintain the desired production. The measures also affected the surrounding water system. The reuse of WWTP effluent led to less water intake from the IJzer, whereas the installation of the Closed Circle Reverse Osmosis (CCRO) system led to a higher water intake. For this specific case study, a more detailed model is needed to assess the specific effects on the environmental flow in the region and salt water intrusion.

In Mechelen the construction of the stormwater retention basin led to reductions in total runoff and peak runoff to the surface water. The water supplied through subirrigation to the agricultural fields increased groundwater levels and evapotranspiration. The application of subirrigation increased drainage to the surface water, but in this case this extra water did not increase risk of flooding. When implementing the system in a different area, the extra drainage caused by higher groundwater levels should be considered to make sure the risk of flooding is not impacted.

In general, the effects of the implemented measures on the water system could be simulated with the system dynamics model and the preliminary insights are valuable. Detailed analyses of subsystems, however, were not possible. Not all processes are taken into account in the model (e.g. lateral groundwater flow) and some processes are simplified (e.g. percolation to the groundwater). The models gave an overview of the interactions and feedbacks between the subsystems and indications of the changes in the water system. More detailed models are needed to determine, for example, exact changes in groundwater levels or changes in salt water intrusion for specific subsystems. The advantage of the system dynamics model is the limited calculation time, which makes it possible to quickly simulate many scenarios. The insights from the model can then be used in the discussions with stakeholders and help to visualize complex processes.

Contents

1 Introduction

In the B-Watersmart Living Lab Vlaanderen[1] we investigate whether innovative technological measures in subsystems of the water system can make the whole regional water system more robust. To identify the effects of measures on the water system, we use a system dynamics model. A system dynamics model can be used to investigate interactions and feedbacks between different subsystems (Stofberg et al. 2024). They can be applied to derive behaviour within the system, interactions and feedbacks between subsystem, and propagation of effects through the system. When applied to the water system, they give a relatively coarse overview of the whole system compared to detailed hydrological (groundwater) models that usually don't include all subsystems. Spatial differences within a subsystem cannot be determined, because these models use ordinary differential equations per subsystem. Within the program Water in the Circulair Economy (WiCE) smart solutions for the water system are investigated as well. The WiCE project 'A better balance of water demand and supply'[2] focuses on the development of methods to explore the effects of measures and their combinations on the water system (Stofberg et al. 2024).

In the B-watersmart Living Lab Vlaanderen, two case studies with different landscape characteristics and challenges in the water system are defined. In both case studies measures are implemented to make the water system more robust. In the case study Woumen/De Blankaart an extra purification step is added to the drinking water production to deal with fluctuations in the water quality of the surface water (mainly chloride concentration) and to be able to use effluent from a waste water treatment plant (WWTP) as a source for drinking water production. In the case study Mechelen a reservoir is build to store urban runoff and re-use it for subirrigation in surrounding agricultural fields.

In both case studies project partners are performing pilots and technical modelling of the subsystems, mainly at small scale and isolated from the regional water system. We explored the effects of the proposed measures on the regional water system and other water users in the region with the system dynamics model.

The general research question for both case studies is:

> What is the effect of the measure on the regional water system in normal and dry periods and how does the measure affect the water-smartness of the water system?

In chapter two we will describe the general approach. In chapter three and four the specific case studies are described. Chapter five contains a reflection on the method and general conclusions.

[1] https://b-watersmart.eu/living-lab/flanders-belgium/

[2] https://www.kwrwater.nl/en/projecten/connecting-the-water-cycle-and-the-water-system-for-a-better-balance-of-water-demand-and-supply/

2 General method

We used a System Dynamics Model for each case study to investigate the effects of the measures. System dynamics models can be used to describe all sorts of systems according to systems thinking. According to Arnold en Wade (2015) an objective definition of system thinking is: “Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects. These skills work together as a system.”

A system dynamics model can be used to investigate interactions and feedbacks between different subsystems. They can be applied to derive behaviour within the system, like propagation of effects of measures. When applied to the water system, they give a relatively coarse, but holistic, overview of the system compared to detailed hydrological (groundwater) models. Spatial differences within a subsystem cannot be determined, because these models use ordinary differential equations per subsystem. Detailed models on the other hand usually include a limited number of subsystems.

System dynamics models are applied at a strategic level to understand the water system and interactions within the system (Phan et al. 2021). Compared to detailed hydrological (groundwater) models, the calculation time is relatively short. Therefore, it is possible to perform many sensitivity analyses and scenarios to understand the behaviour of the system without the limitation of long calculation times. System dynamics models are not limited to the water system, but can be extended with economic or social processes that affect the water system. It is also possible to combine the natural or semi-natural hydrological system with the anthropogenic water system. Natural groundwater processes, for example, can be included in the same system dynamics model as drinking water production or waste water treatment plants. This way, different types of subsystems and feedbacks between these systems can be analysed.

In this report we modelled the water system for the two case studies with a specific system dynamic model for each region. We build the models with the software Vensim (https://vensim.com/). A detailed description of the models is given in the next chapters.

3 Woumen/De Blankaart

3.1 Case study description

3.1.1 Overview

This case study comprises the drinking water production centre De Blankaart and wastewater treatment plant (WWTP) Woumen, both located in the Blankaartpolder in the middle-west of Flanders (Figure 3-1). At drinking water production centre De Blankaart, De Watergroep produces drinking water from local surface water (Figure 3-2). The main source for drinking water is the IJzer river; in addition, a small amount of water is taken from the Blankaartvijver to the east of the production centre. Intake water is stored in the Blankaart reservoir before being treated to drinking water quality at the production centre.

WWTP Woumen, managed by Aquafin, is located to the north of the reservoir. Incoming wastewater from the Houthulst-Diksmuide area is treated and discharged on the Houtensluisvaart, from where it is directly discharged to the IJzer.

Both the water production centre and the WWTP are located in the Blankaart basin (Figure 3-3). The western part of the basin is a low-lying polder area consisting of mainly clayey soils with managed water levels. Here the nature area "Blankaartvijver" is located. In addition, the whole area is designated as bird habitat (Ramsar, Natura 2000), for which purpose water levels have been raised in recent years. To the east of the polder is a higher sandy area, from which several brooks drain towards the Blankaart system. The Blankaart system drains mostly through the Stenensluisvaart pumping station (Figure 3-3). The northern part of the polder, including the WWTP, is separated from the rest of the polder and discharges directly to the IJzer.

The IJzer is a rain-fed river with a catchment area in northern France and western Flanders. Over much of its course in Flanders the water level is managed; in periods of high sea levels or low river levels discharge can stagnate. The river is suffering increasingly from low discharges in summer and water quality issues, especially high salinity levels, resulting from sea water intrusion and discharge from other sources.

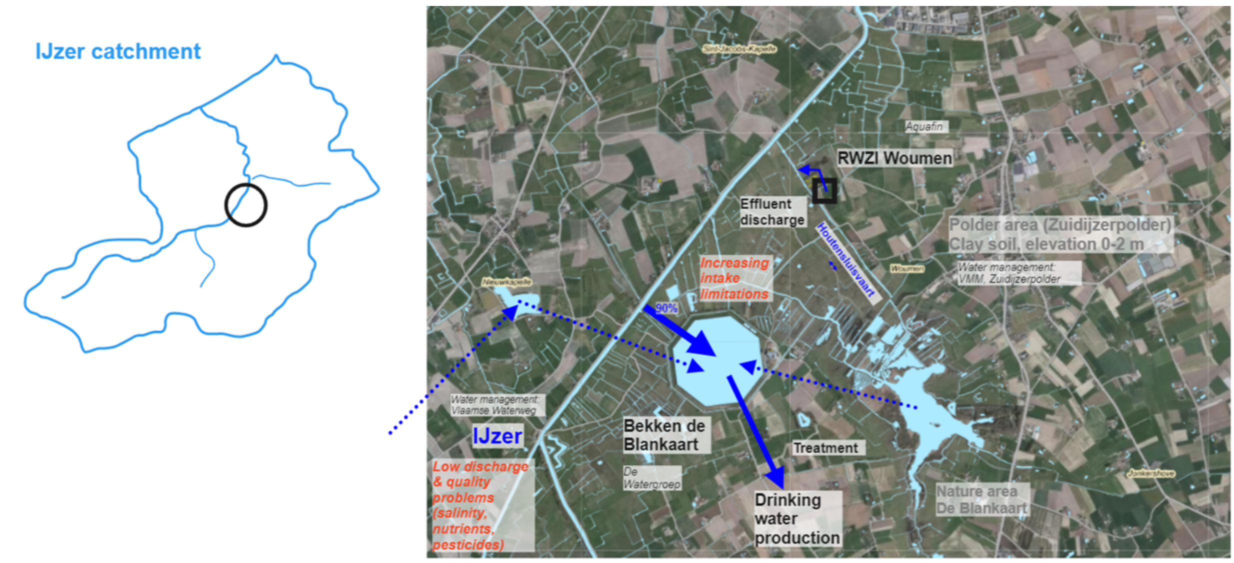


Figure 3-1: Case study overview (RWZI=WWTP) for Woumen.

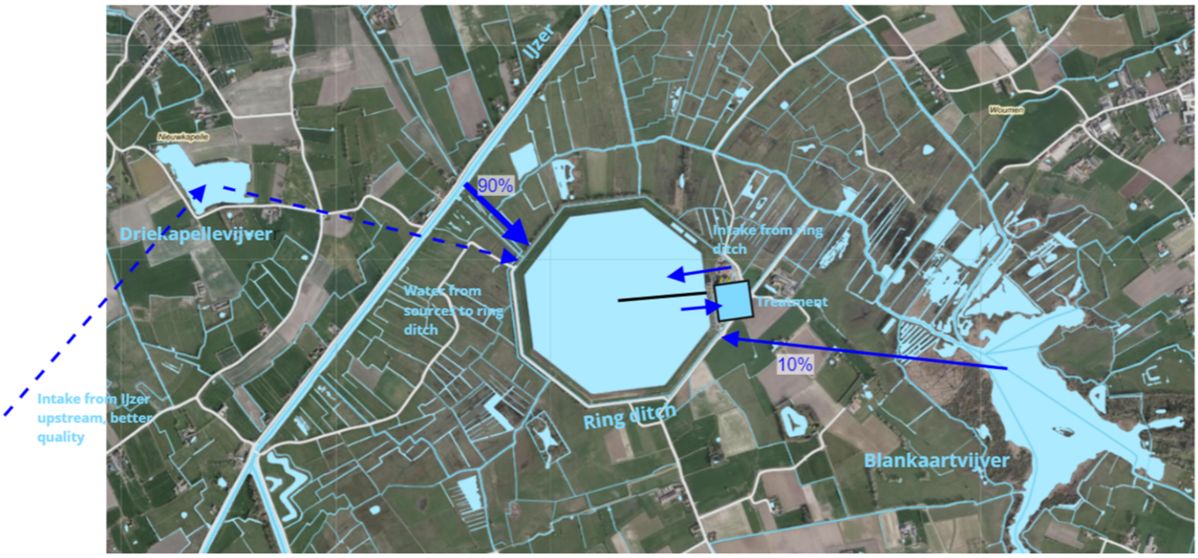


Figure 3-2: Drinking water production system of De Blankaart.

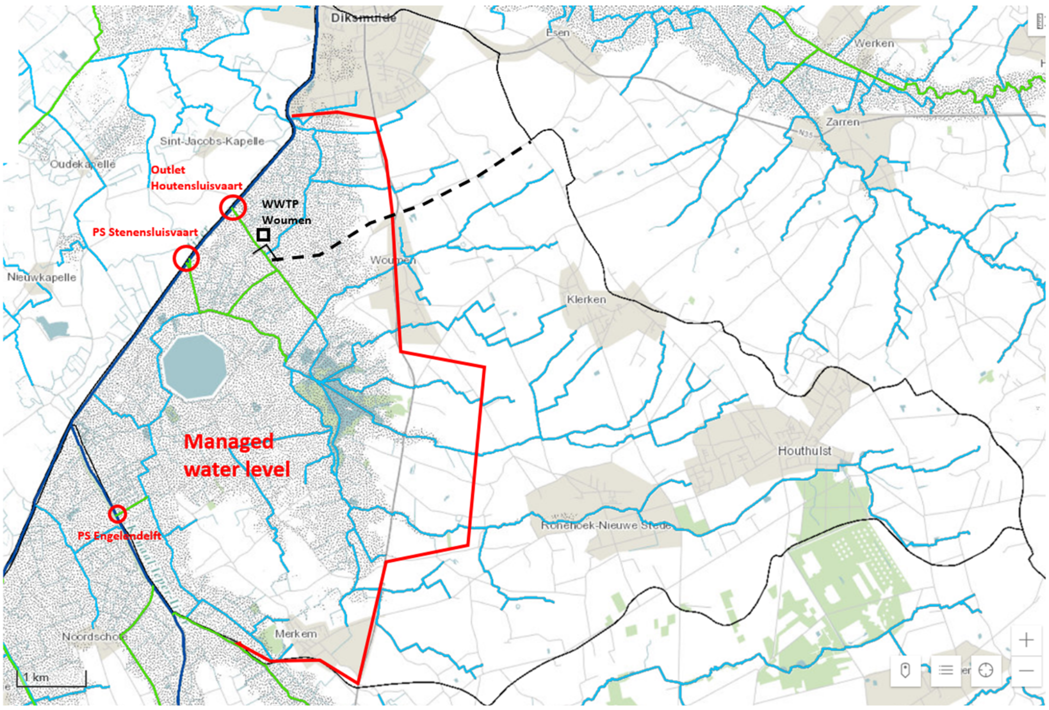


Figure 3-3: The Blankaart basin and polder.

3.1.2 Problem and system criteria

The increasingly frequent periods of low water quality force De Watergroep to interrupt their water intake more frequently and for longer periods of time. This results in dropping water levels in the Blankaart reservoir and reduced raw water availability for drinking water production, which is putting the regional drinking water supplies and manageability of the production centre at risk. Intake limitations result mainly from high salinity, but also nutrients and pesticides can be limiting factors.

On a larger scale, the IJzer river is, and increasingly will be, under pressure both in terms of water quantity and quality, while many users depend on the system. Negative influences of measures to improve water availability for the drinking water supply on the IJzer should therefore be minimised.

The functioning of the Blankaart-Woumen-polder system can be evaluated on the following criteria:

- Amount of water available of sufficient quality for drinking water production.
- Effects of the drinking water production on IJzer discharge.

3.1.3 Proposed solutions

Two potential solutions are proposed to increase the water availability for the drinking water supply:

1) Additional drinking water treatment through Closed Circle Reverse Osmosis (CCRO). De Watergroep is studying the possibilities of adding a CCRO treatment step on all or part of the flow in their treatment process. This would allow them to continue water intake for longer periods of time when the water quality in the IJzer is deteriorating.
2) Wastewater reuse for drinking water production. Aquafin is looking into treatment methods that could make it possible for (part of) their discharge to be reused in the drinking water production.

3.1.4 Research questions

In this study we focused on the following research question:

How do the proposed solutions, additional drinking water treatment and WWTP discharge reuse, affect the regional water system, especially drinking water production and discharge of the IJzer?

3.2 Model setup and scenarios

A system dynamics model was developed for the region. Figure 3-4 shows the model setup for the Woumen case. The model consists of four subsystems: the IJzer (top), the polder system (middle), the drinking water production system (bottom) and the WWTP (right). The model represents the water stocks and flows in the system over time in a simplified way, as well as part of the chloride flows.

Input data for the model are described in Table 3.1. The input data consist of meteorological variables and characteristics of the hydrology in the area. Discharge values of the IJzer are also used as input (Figure 3-5). In Table 3.2 the values for the different parameters in the model are given. Parameter values are based on personal communication with Peter Cauwenberg (De Watergroep).

Table 3.1: Input data for the Woumen model.

Input data	
Precipitation	Measurements from Zarren station (waterinfo.be)
Reference evapotranspiration	Penman-Monteith ET_{ref} from Zarren station (waterinfo.be). Missing values in October 2008, May 2009, April and May 2015, June 2016, and August, September, October, November and December 2023 are replaced with station Waregem.
IJzer discharge upstream	Measured discharge IJzer at Keiem (10km downstream) from DOV, rescaled to discharge at Woumen using modelled mean flows from VMM.
IJzer chloride levels	Measurements from De Watergroep (location B7 upstream of the intake)
IJzer bentazon levels	Measurements from De Watergroep (location B7 upstream of the intake)
IJzer metaldehyde levels	Measurements from De Watergroep (location B7 upstream of the intake)
Inflow brooks to polders	Measured discharge Steenbeek from DOV, rescaled using modelled mean discharges from VMM for other brooks.
Chloride levels polder	Cl measurements from De Watergroep (location B10 upstream of the Stenensluisvaart)
WWTP discharge	Measured discharge from Geoloket VMM
WWTP discharge chloride level	Measured from Geoloket VMM
Validation data	
Polder surface water level	Water level Blankaartvijver from DOV
Polder groundwater level	Groundwater level location DBLP1-3 from DOV

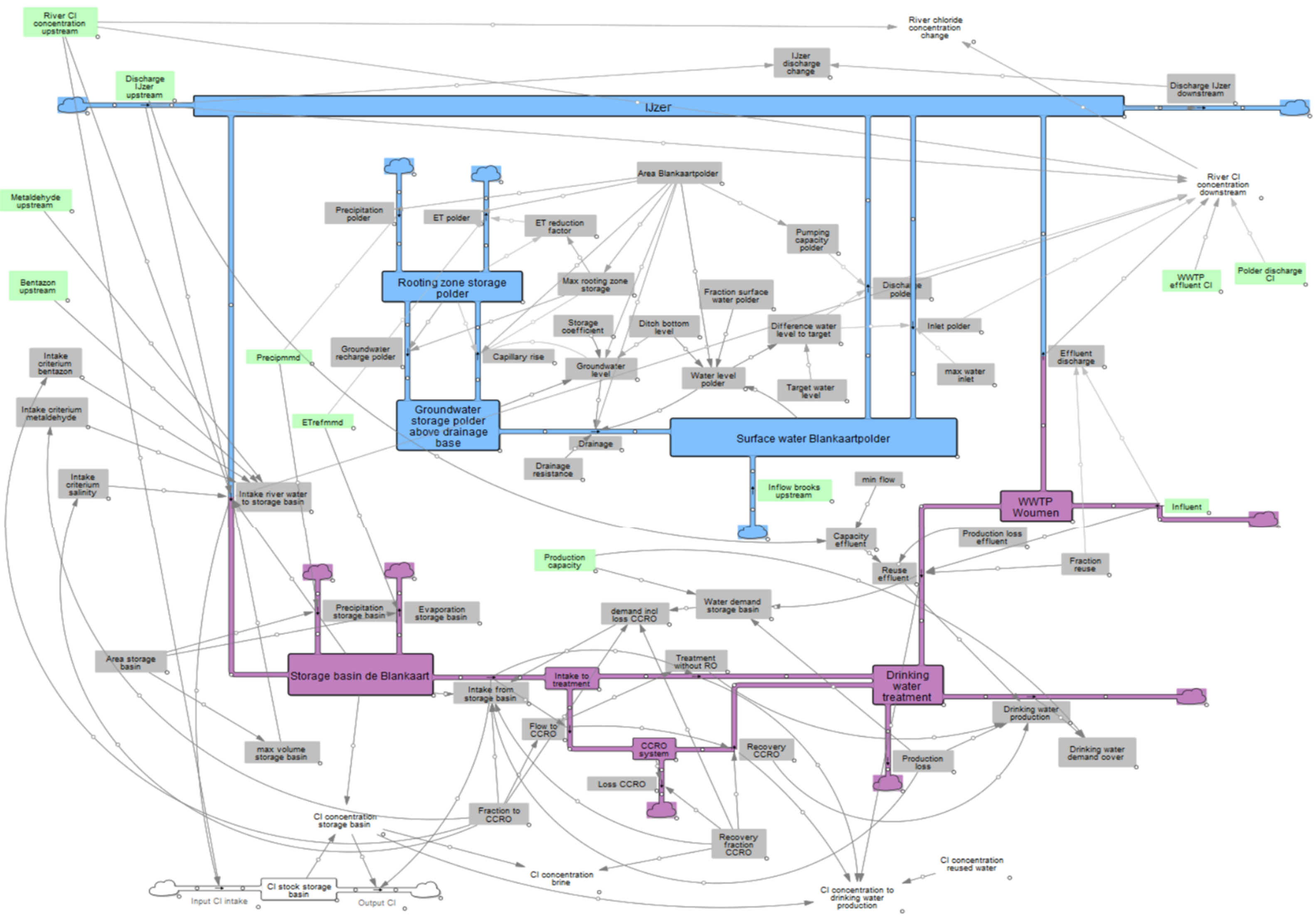


Figure 3-4: Model setup for the Woumen case. Blue: semi-natural water system, purple: anthropogenic water system; boxes are stocks, coloured lines are flows; grey/no boxes: system characteristics, constants and output, green boxes: input.

Table 3.2: Parameters and assumptions for the Woumen model.

Parameters drinking water system		
	Reference scenario	*Scenario's with CCRO*
Intake criterium chloride	180 mg/l	320 mg/l
Intake criterium bentazon	0.6 µg/l	1.07 µg/l
Intake criterium metaldehyde	0.2 µg/l	0.33 µg/l
Discharge IJzer threshold intake	100 000 m^3/d	
Area storage basin	60 ha	
Maximum water depth basin	5 m	
Production capacity	40 000 m^3/d from October 1 till April 30, 15 000 m^3/d from May 1 till September 30	
Production	Intake from storage basin decreases when level in the basin decreases. If volume basin < 1 500 000 m^3, production capacity = 15 000 m^3/d If volume basin < 700 000 m^3, production capacity = 0 m^3/d	
Production loss existing treatment	3%	
CCRO recovery fraction		95%

Parameters polder system	
Area polder (managed water level)	1300 ha
Surface level	3 m TAW
Areal fraction surface water	4%; estimated from topographic maps
Ditch bottom level	1.7 m TAW; assumed 1.3 m below surface level following Van der Gaast (2006)
Maximum water storage root zone	5.4 cm (available water clay soil (Staring B11) between wilting point and field capacity 0.18 cm^3/cm^3 (Heinen et al. 2020); root zone depth grass 30 cm)
Evapotranspiration factor	Reduces when soil water is <80% of field capacity until 0 at wilting point
Capillary rise	Varies between 0 and 4 mm/d depending on root zone water storage and groundwater depth, based on critical z values from Heinen et al. (2020), soil B11
Groundwater storage coefficient	0.1
Drainage resistance	40 days
Target water level	2.7 m TAW (level most of year, overeenkomst peilbeheer 2019)
Pumping capacity polder discharge	1 m^3/s. In reality 2 m^3/s (overeenkomst peilbeheer 2019), adapted to ensure normal model behaviour

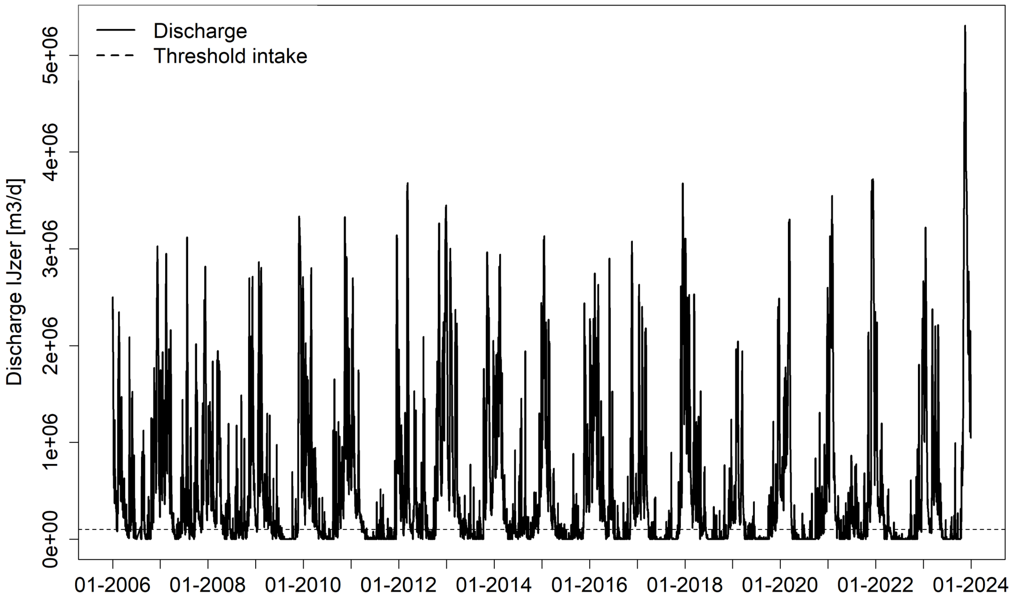


Figure 3-5: Measured discharge of the IJzer. Negative discharge values are converted to zero.

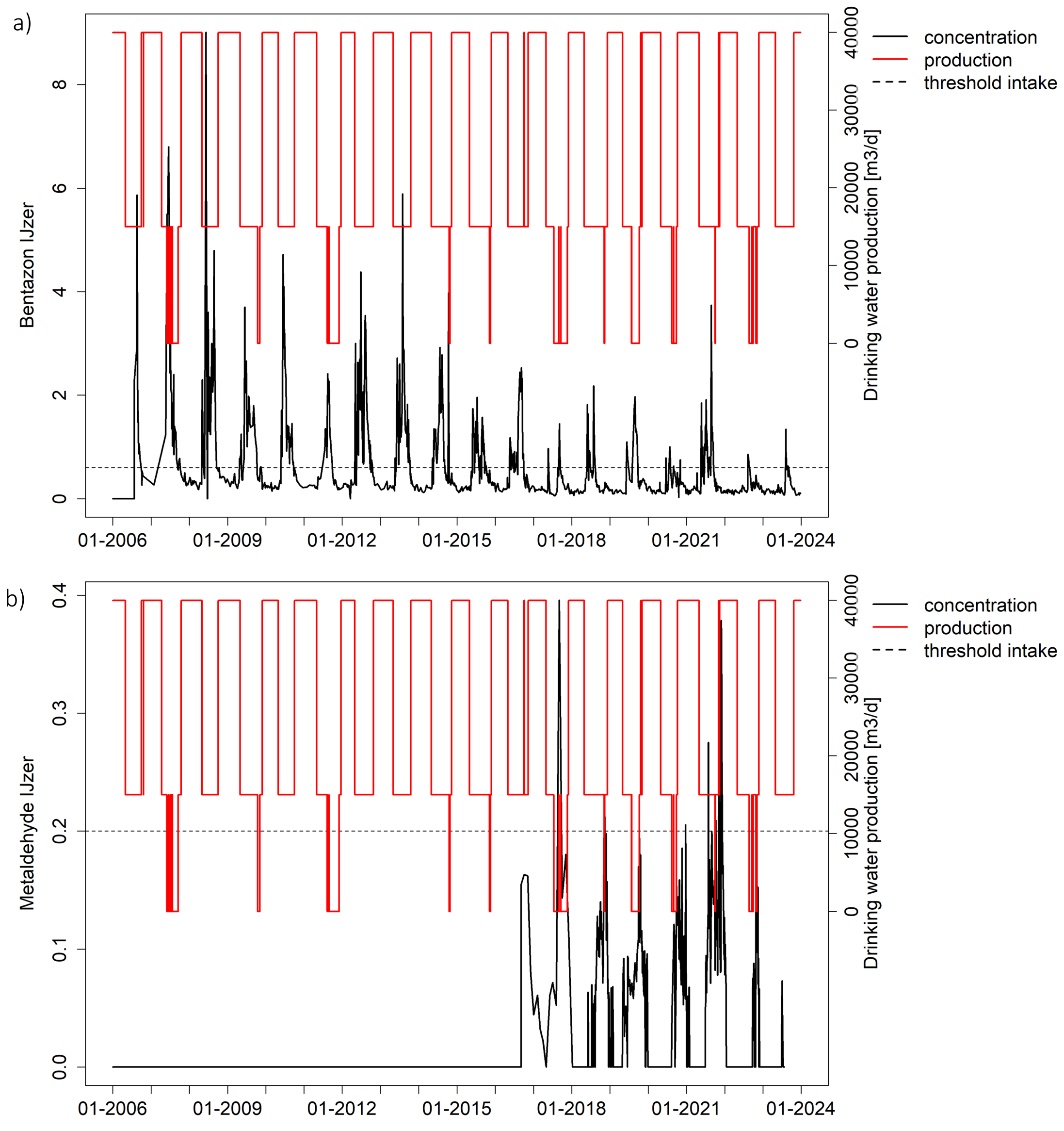
With the system dynamics model the effects of the proposed solutions (CCRO treatment and wastewater reuse for drinking water) on the water system outputs are explored. A reference situation and several scenarios have been defined for the regional analysis. We have assumed that no water intake from the IJzer can take place when the discharge is lower than 100 000 m^3/d. The additional water from other sources than the IJzer (the Blankaartvijver and Driekappellevijver) used for the drinking water production is not included in the regional analyses, because these flows are small compared to the intake from the IJzer. In the reference situation, the IJzer is the only water source and water intake to the storage reservoir is stopped when salinity values are higher than 180 mg/l, bentazon values are higher than 0.6 µg/l or metaldehyde levels are higher than 0.2 µg/l.

The following scenarios were included:

1. Reuse of effluent. All the water that is available from the WWTP Woumen is used as an additional water source for drinking water with a maximum of 5 000 m^3/d. A production loss of 20% was assumed (personal communication Peter Cauwenberg), so maximum 80% of the effluent per day can be used for drinking water production. Water quality of the effluent was not taken into account and it is assumed effluent is treated (with a 20% loss) before it enters the drinking water production.
2. Implementation of CCRO system. To overcome issues with the water quality in the IJzer a CCRO system is installed parallel to the existing treatment. The fraction of water treated with the CCRO system is 50% of the total production. When the CCRO system is installed, the intake criteria for salinity levels, bentazon and metaldehyde are increased, see Table 3.2.
3. Implementation of both measures. Effluent is used as additional source for drinking water and a CCRO system is installed. The treated effluent is added to the total production and 50% of the total production is treated with the CCRO system. The measures are implemented with the same assumptions as in scenario 1 and 2.
4. Implementation of both measures taking minimum flow of the IJzer into account. Effluent is used as additional source for drinking water and a CCRO system is installed. The measures are implemented with the same assumptions as in scenario 1 and 2. In addition, effluent cannot be reused in case the IJzer discharge is zero.

3.3 Effects of proposed water system solutions

In the reference situation, the salinity, bentazon and methaldehyde levels in the IJzer and/or periods with low flow (< 100 000 m^3/d) frequently led to intake stops from the river to the storage reservoir (Figure 3-5 and Figure 3-6). This does not immediately lead to less drinking water production, but in case of prolonged periods with reduced intake, production decreases (Figure 3-6).
Actual production was regularly lower than the desired production, mainly during the summer periods. Especially in 2007, 2011, 2017 and 2019, intake stops led to lower drinking water production.



c)

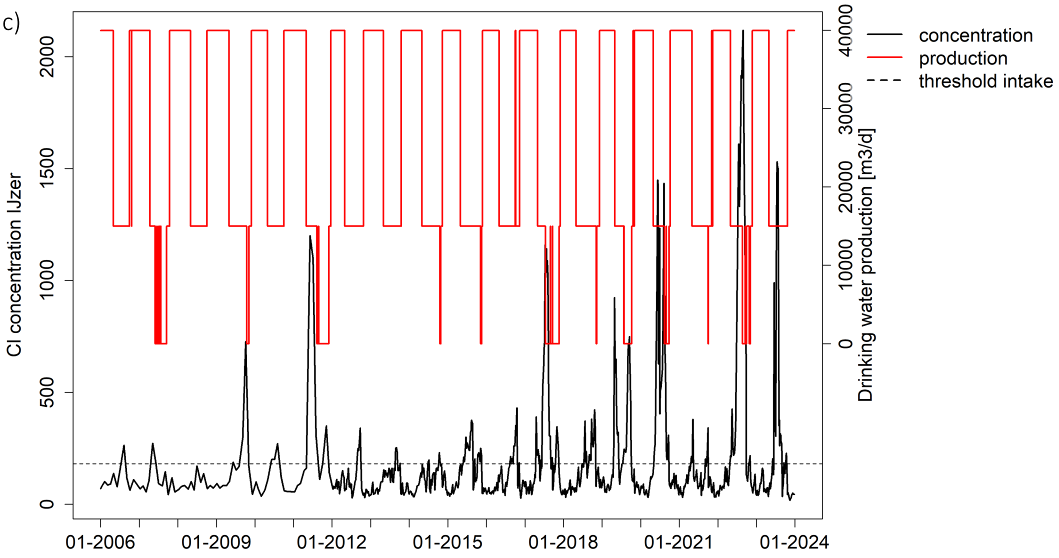


Figure 3-6: Drinking water production in the reference situation (modelled) and a) bentazon levels, b) metaldehyde and c) salinity levels in the IJzer (measured).

The proposed measures to make the drinking water production more robust had different effects. In all scenarios, the total amount of drinking water produced increased when compared to the reference situation (Figure 3-7 and Figure 3-8). However, actual production still could not always reach the desired production (fraction production lower than 1) during the entire period (Figure 3-9).

Figure 3-8 shows the drinking water production in more detail for the last years in the modelled period. As expected, the largest increase in drinking water production was found when both measures were implemented and there were no limitations for effluent reuse (scenario 3). Reuse of effluent only (scenario 1) had the lowest increase in production. During dry periods, the amount of water available from the WWTP decreased while at the same time the water quality of the IJzer deteriorated. That means water availability from both sources decreased in dry periods, leading to less drinking water production. Installation of the CCRO system only (scenario 2) led to higher drinking water production compared to the reference situation and scenario 1, but less production compared to scenario 3. In scenario 2 more water was taken from the IJzer, because there were less intake stops due to water quality issues. However, the discharge of the IJzer was too low to sustain the drinking water production during dry periods. This is also the case in scenario 3, although the production in this scenario was highest, because effluent was available during the dry periods, albeit in smaller quantities. In scenario 4, less effluent is available during these dry periods due to the low discharges in the IJzer and the requirement in the scenario to sustain flow in the IJzer through effluent.

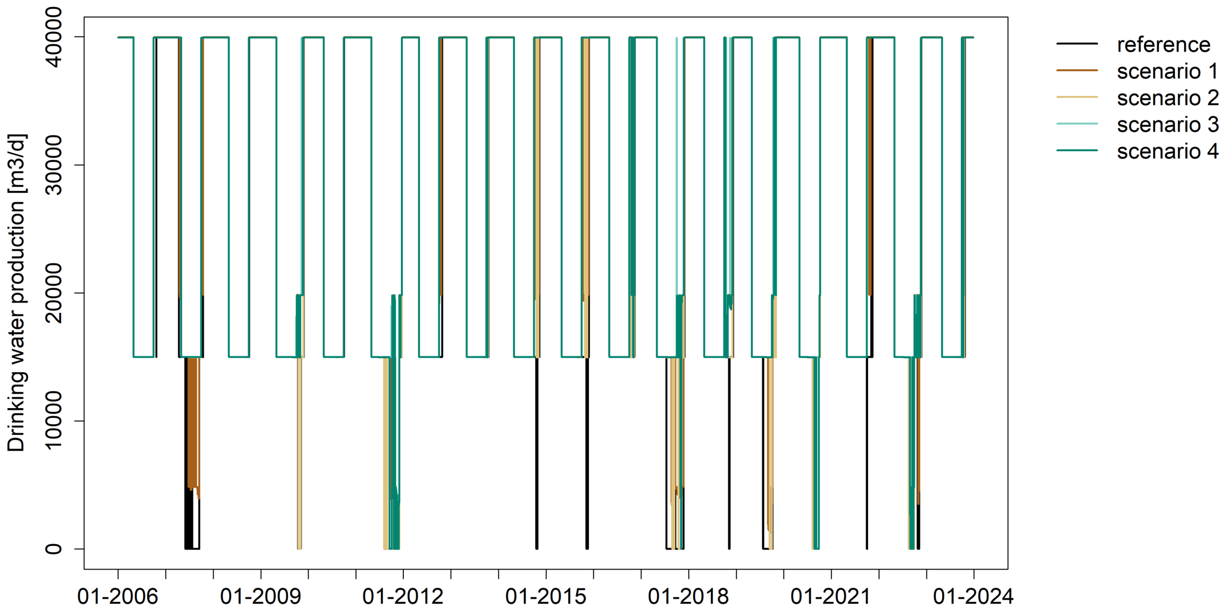


Figure 3-7: Drinking water production for the reference situation and different scenarios for the complete period.

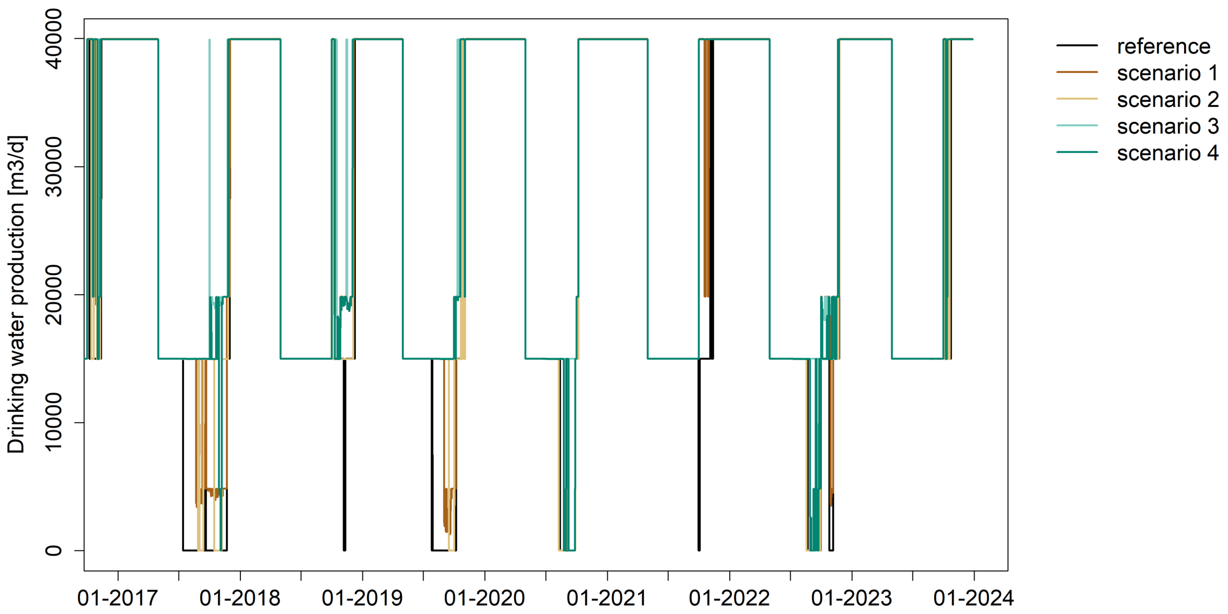


Figure 3-8: Drinking water production for the reference situation and the different scenarios for part of the period.

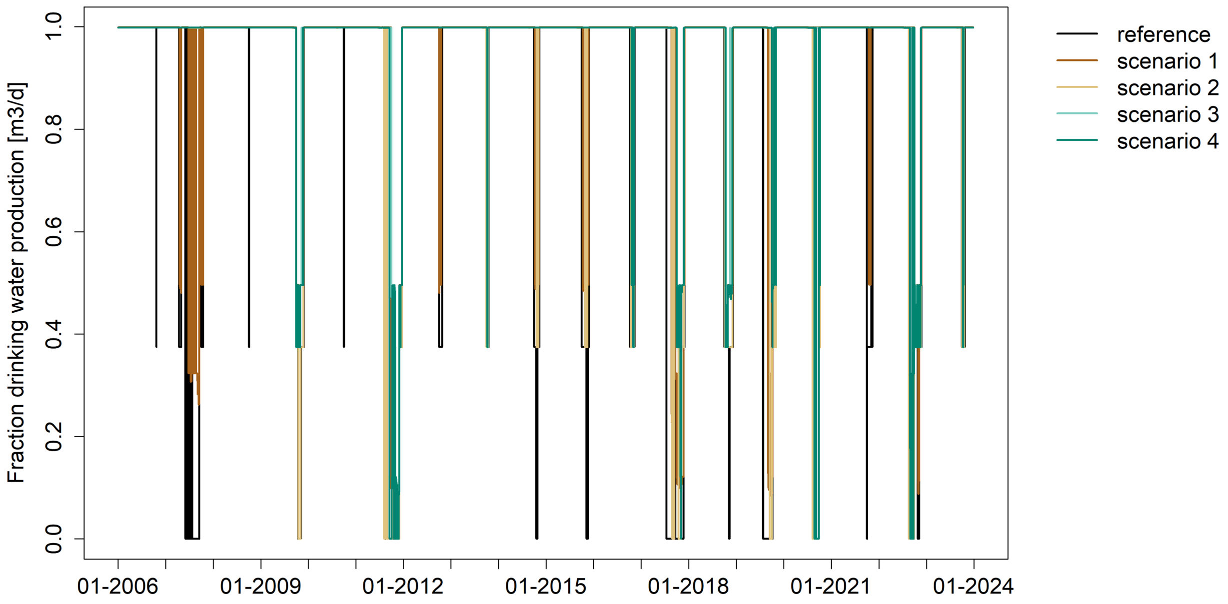


Figure 3-9 Fraction of the desired drinking water production for the reference situation and different scenarios for the complete period.

The implemented measures did not only impact the total drinking water production, but also had effects on the total water intake from the IJzer to the storage basin. The total water intake from the IJzer per year was lower in scenario 1 (water reuse) compared to the reference situation (Figure 3-10). For scenario 2 (CCRO system), the total water intake was higher compared to the reference situation every year, because issues with water quality did not lead to intake stops anymore. When both measures were implemented (scenario 3 and scenario 4), water intake was lower than in the reference situation in most years, because the reuse of effluent replaced the water from the IJzer. However, in years when water quality in the IJzer deteriorated or discharges were low, like 2011 and 2017 (Figure 3-5 and Figure 3-6), total water intake in scenario 3 and scenario 4 was higher than in the reference situation, because water from the IJzer was taken over a much longer period when the CCRO system was available. The water intake is higher in scenario 4 than in scenario 3, because low discharge of the IJzer was not taken into account in scenario 3 and more effluent was reused in scenario 3.

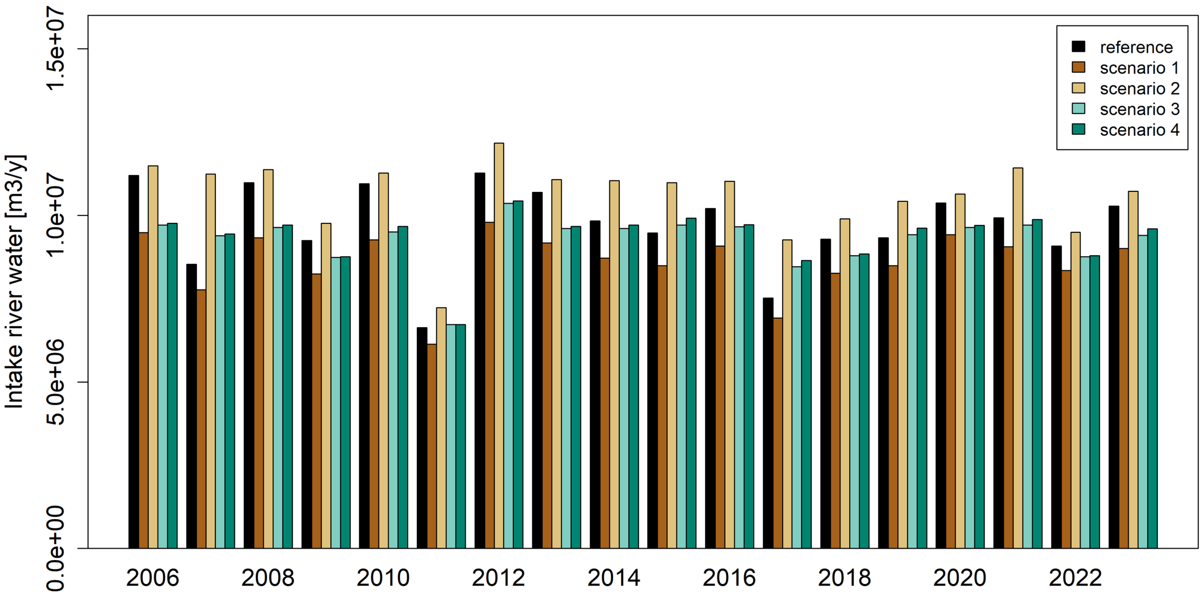


Figure 3-10: Total water intake per year from the IJzer for the reference situation and the different scenarios.

The differences in water intake of course immediately affected the amount of water stored in the storage basin (Figure 3-11 and Figure 3-12). Scenario 3 led to the highest levels in the storage basin, followed by scenario 4. This is in line with the water intake from the IJzer and the available effluent. With both measures implemented the basin storage volume still reached the threshold of 700 000 m^3 when drinking water production was stopped (for example in 2011 and 2020), but less often than in the reference situations and other scenarios. In 2007 and 2021, for example, enough water was available after implementing both measures to sustain the desired production.

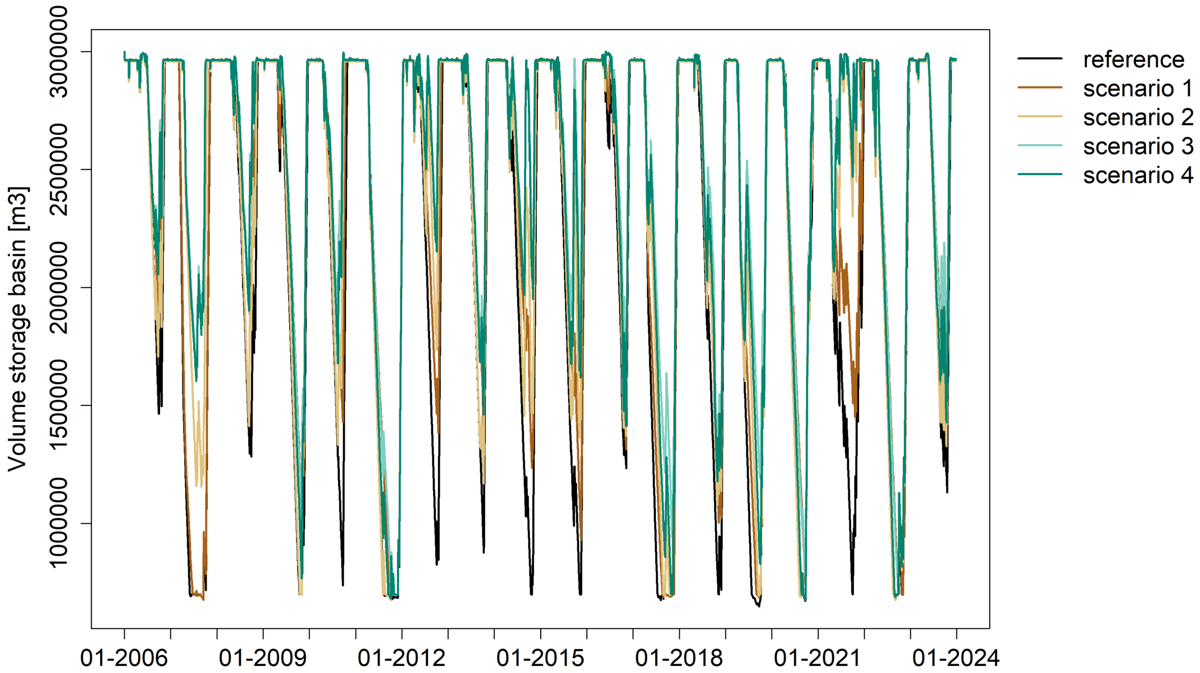


Figure 3-11 Volume of water in the storage basin for the reference situation and the different scenarios for the entire period.

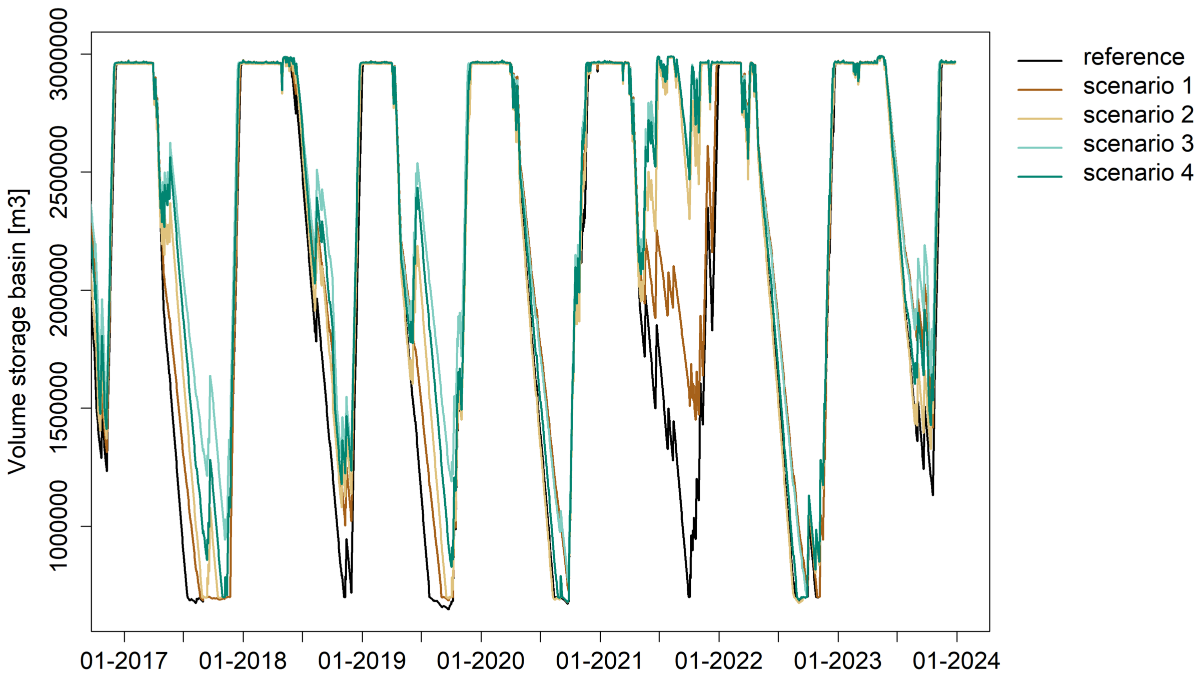


Figure 3-12 Volume of water in the storage basin for the reference situation and the different scenarios for part of the period.

When both measures were implemented, the total drinking water production originated from effluent, water treated in the existing treatment system, and water treated with the CCRO system. The amount of effluent is limited to a maximum of 5 000 m^3/d, so most of the water still came from the IJzer. In scenario 4, water cannot be reused in periods when discharges in the IJzer are low (i.e. discharge is 0 m^3/d). The total amount of effluent reused per year for scenario 3 and for scenario 4 is shown in Figure 3-13. As expected, more effluent was reused in scenario 3 in each year in the modelled period, since periods with zero discharge in the IJzer occurred every summer. In scenario 3, during the entire modelling period on average a total of $1.712*10^6$ m^3/y of effluent was reused. An average of $1.464*10^6$ m^3/y was reused in scenario 4. The largest difference in yearly total between the scenarios was $0.527*10^6$ m^3 in 2022. This difference in reuse was caused by the low discharges in summer as shown by the difference in the daily amount of effluent that was reused (Figure 3-14). Thus, when low discharges of the IJzer were taken into account less water was available for drinking water production during the period when demand for the water was highest (because intake to the storage basin also stops during periods with low discharge). This is not surprising as of course water availability is limited for all users during dry periods.

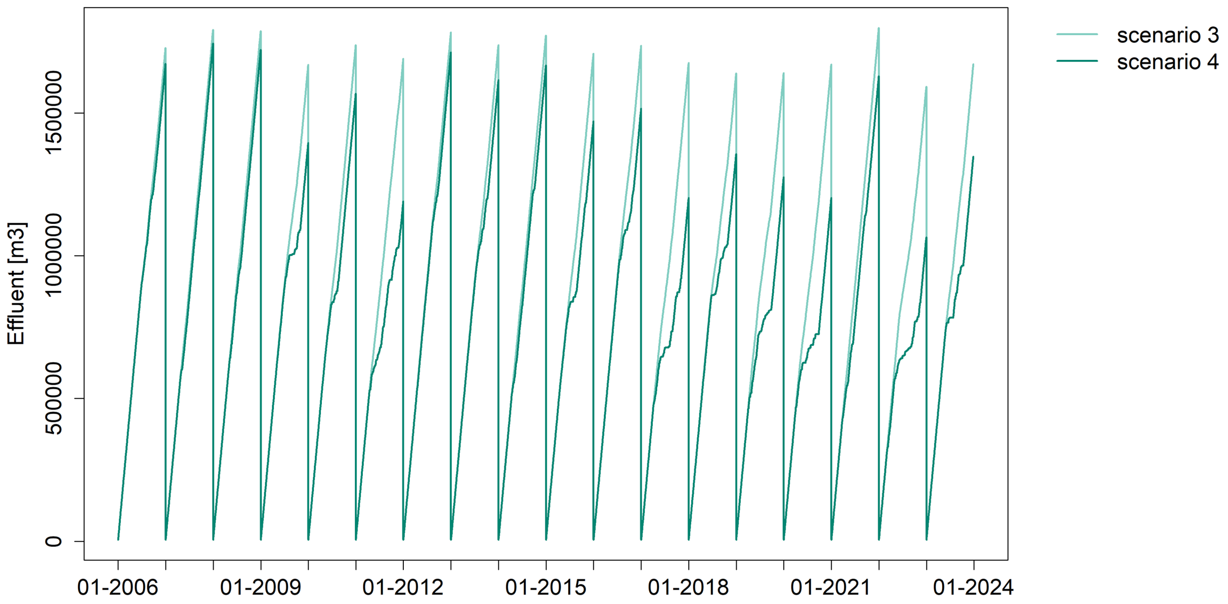


Figure 3-13 Yearly cumulative values of total effluent used for drinking water production.

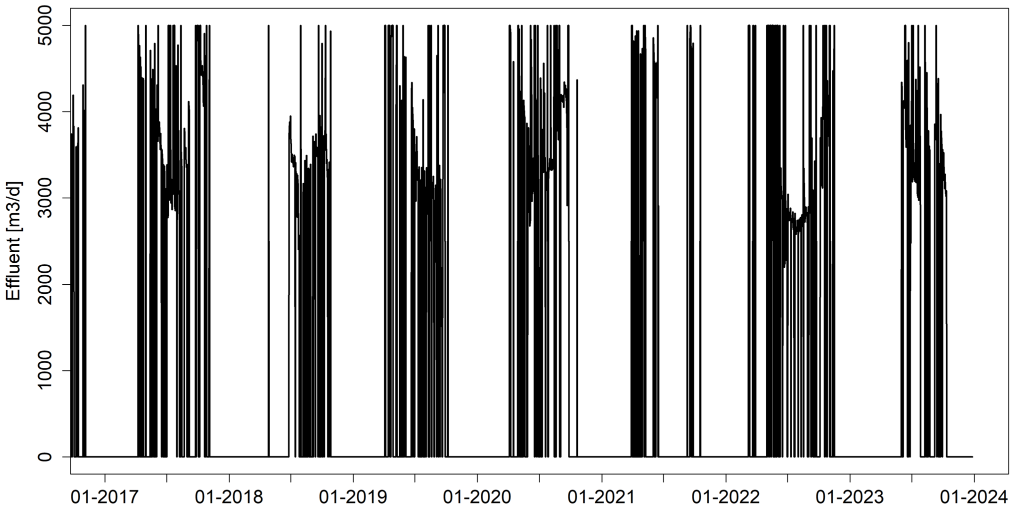


Figure 3-14 Difference between amount of effluent reused per day between scenario 3 and scenario 4.

3.4 Conclusions

- Implementation of the measures increased the total drinking water production and combining the two measures resulted in the highest production. In all scenarios, however, desired drinking water production could not always be reached during dry periods, because not enough water was available in the IJzer and through effluent.
- Reuse of the WWTP effluent led to less water intake from the IJzer. When the possibility of water reuse was limited during periods without discharge in the IJzer to consider the environmental flow in the IJzer, less water was available for drinking water production during dry periods.
- Installation of the CCRO system on the other hand led to increased water intake from the IJzer, which meant less water was available downstream especially during drier periods. This extra water abstraction during a period when water quality is already deteriorating, might lead to more salt water intrusion upstream. It was not possible to include this effect in the regional analysis, because a more detailed surface water model is needed to assess the salt water intrusion.

4 Mechelen

4.1 Case study description

4.1.1 Overview

This case study focuses on an area at the outskirts of Hombeek at the edge of the city of Mechelen in central Flanders. Here, built-up areas along streets have been growing in the past years, increasingly with separated sewage systems. It is a flat, loamy area with a mix of residential areas and agriculture, consisting of grasslands and (vegetable) crops. The area has to deal with consequences of wet conditions, as the capacity to discharge heavy rainfall is limited, but also with drought, as groundwater levels have been declining strongly after several dry years. The area is drained by the Dorpsloop (Figure 4-1). The Dorpsloop is partly fed by rainwater sewage systems from the urban areas. This case study deals with one of these, the system that drains the Zepstraat/Bankstraat area (red dotted lines in Figure 4-2), and discharges to the Oude Tantelaerloop (OTL), a piped water stream that crosses the railway from the south to feed into the Dorpsloop.

Figure 4-1: Water system around the study area (Staes & Coorevits, 2021), blue=wet/accumulating, red= expected ditches, brown=drier, infiltrating.

4.1.2 Problem and system criteria

The increase in paved area has created a need to buffer the urban runoff, as the expanding rainwater sewage system will be increasingly unable to discharge peak rainfall events, which will intensify with climate change. In addition, dry summers and groundwater use for irrigation are increasing the pressure on the groundwater and call for a more efficient use of the available water sources.

The functioning of the Hombeek water system can be assessed by the following criteria:

- Prevention of flooding damage;
- Sufficient water for agriculture;
- Increased recharge and/or reduced net pressure on groundwater stores.

4.1.3 Proposed solution

To reduce problems in the area, a multi-purpose rainwater reservoir has been designed. The reservoir will be used for:

- Stormwater buffering. The rainwater reservoir will be built next to the OTL (Figure 4-2), which will store the rainwater sewage discharge before discharging it under the railway to the Dorpsloop stream. The southern streets (Kattestraat and further south) do not have a separated system yet, whereas the Zepstraat and Bankstraat do. Therefore, initially, two reservoirs (772 m^3 and 1416 m^3) are built to separate the rainwater from the mixed water (Figure 4-3). In the next years, the sewage system will be converted to a fully separated system in the whole region. After this conversion the two reservoirs will act as one reservoir (2188 m^3) and all water can be reused. The reservoir will have watertight edges, but, for practical reasons, is permeable at the bottom (Figure 4-2). Part of the water will thus infiltrate directly from the reservoir.
- Water reuse for agriculture through subirrigation. The stored rainwater in the reservoir will be used to supply water to surrounding farm fields through subirrigation (Figure 4-2 and Figure 4-3). Except for supplying additional water to farmers, the subirrigation could have the added advantage of stimulating groundwater recharge, as part of the subirrigation water will infiltrate to the groundwater. Before the water enters the subirrigation system, it is treated with a sand filter.

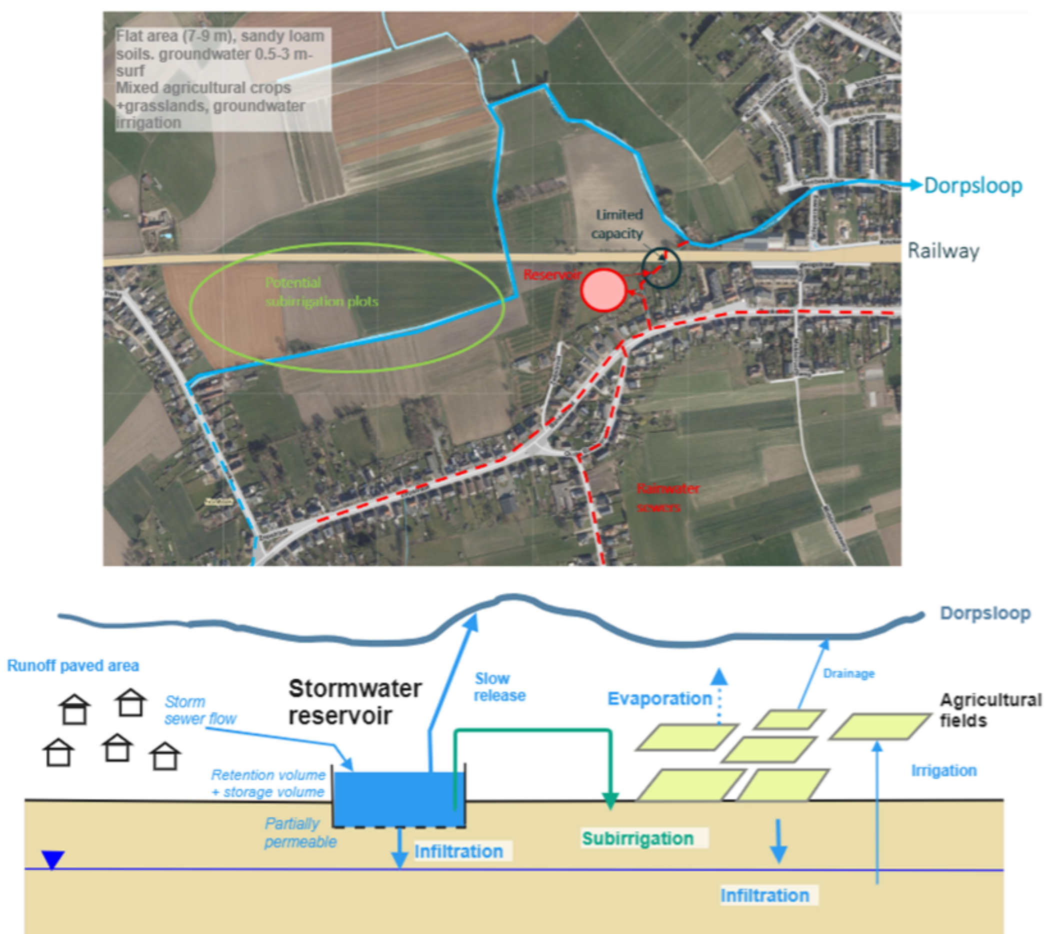


Figure 4-2: Overview of the Mechelen case study and sketch of the implemented measure to store and reuse water.

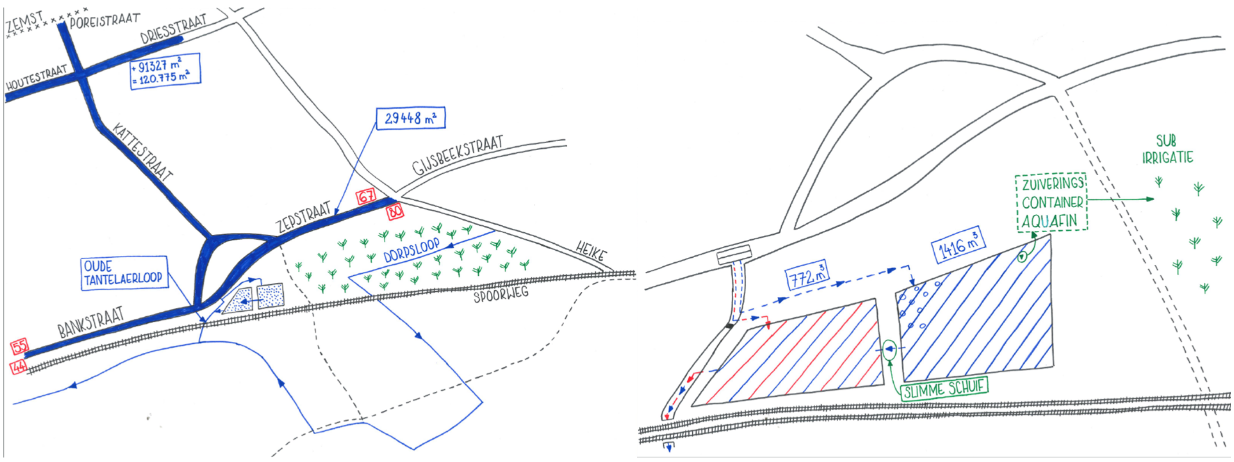


Figure 4-3: Detailed sketch of the situation with the reservoirs and reuse of water.

4.1.4 Research questions

The question we aim to address with the system dynamics model for the Mechelen case is:

> What are the potential effects of the proposed system of rainwater storage and reuse on water supply to farmers and groundwater tables?

4.2 Model setup and scenarios

The setup of the system dynamics model is visualised in Figure 4-4. Input data for the model are described in Table 4.1. In this case only meteorological variables are used as input, because discharge data for the Dorpsloop are not available. Parameter values of the model are given in Table 4.2.

With the model the effects of the reservoir and reuse of the water on the water system were investigated. A reference situation and three scenarios have been explored for the regional analysis. In the reference situation it is assumed that precipitation from the region led to runoff to the Oude Tantelaerloop. We considered a runoff coefficient of 0.8, meaning 20% of the precipitation is lost, for example due to evaporation, before reaching the stream. In the regional analysis a spatial component is not included, this means all precipitation reached the stream in the same timestep (daily). The stormwater retention basin is simplified to a rectangular basin with straight edges instead of sloping edges. We explored three scenarios with the proposed measures:

1. Implementation of a stormwater retention basin (1416 m^3). Precipitation is stored in a retention reservoir. The reservoir loses water through evaporation and infiltration to the groundwater. Operational rules to optimize the available storage in the system were not taken into account.
2. Implementation of a stormwater retention basin (1416 m^3) in combination with subirrigation for agriculture. We have assumed that water is pumped into the subirrigation system throughout the year with a capacity of 240 m^3/d to supply an area of 40 000 m^2. Again optimal management of the reservoir and the subirrigation system was not taken into account.
3. Similar to scenario two, but with the retention basin volume that will be reached in the future: 2188 m^3.

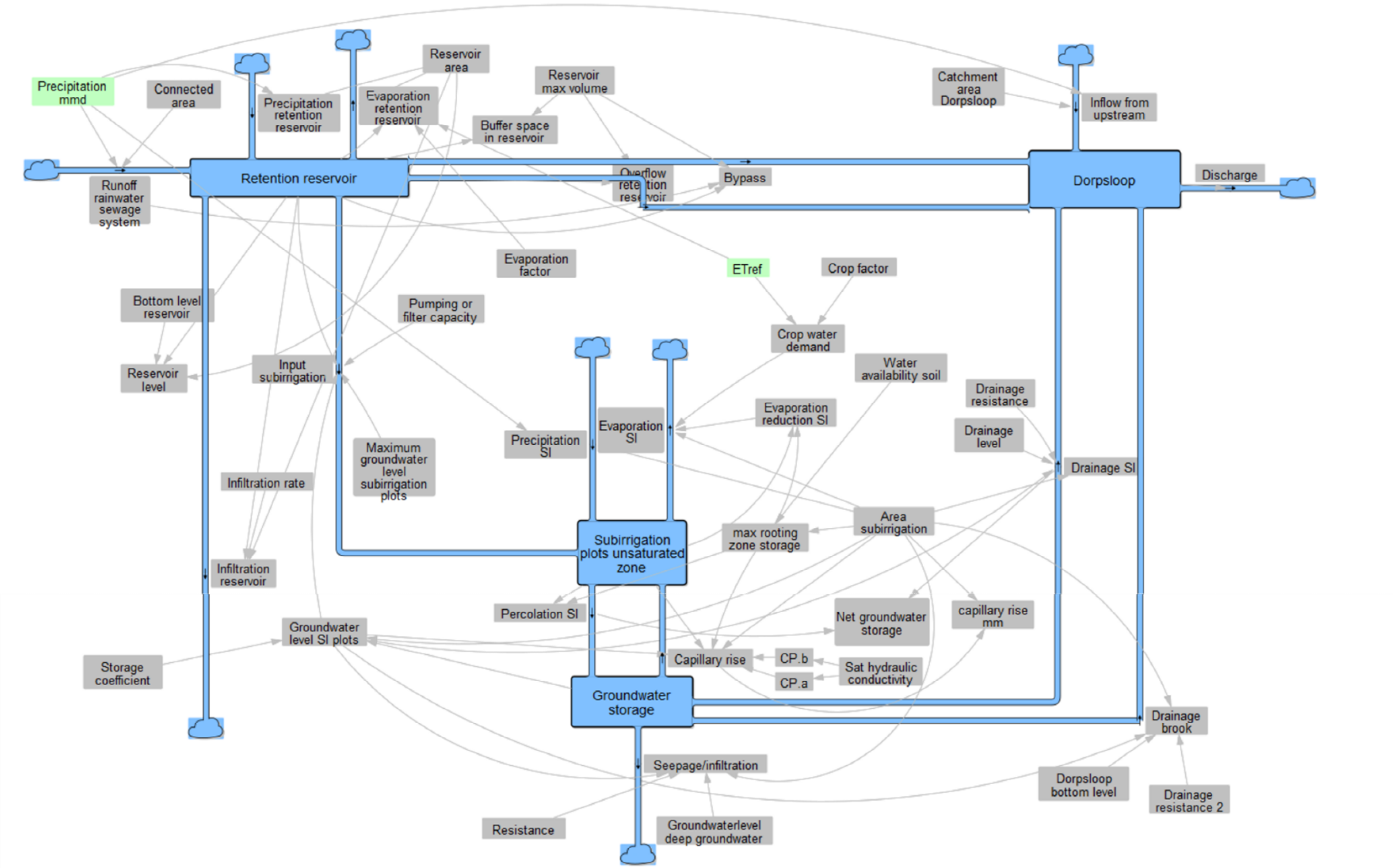


Figure 4-4: Model setup for the Mechelen case. Blue: semi-natural water system; boxes are stocks, coloured lines are flows; grey boxes: system characteristics, constants and output, green boxes: input.

Table 4.1: Input data for the Mechelen model.

Input data	
Precipitation	Measurements from Bonheiden station (waterinfo.be) missing values April 2014, September 2016, October and November 2018 filled with data from Boortmeerbeek station
Reference evapotranspiration	Penman-Monteith ET_{ref} from Herentals station (waterinfo.be) missing values 2010 and 2015 filled with data from Liedekerke station
Validation data	
Groundwater level	Groundwater level location 705/21/11, location 1-0706, location 705/21/1 (DOV)

Table 4.2: Used parameters and assumptions for the Mechelen model.

Parameters stormwater reservoir	
Area storage basin	1416 m^2 (2188 m^2 in scenario 3)
Maximum water depth basin	1 m
Area connected	121000 m^2
Bottom level reservoir	7.5 m TAW
Infiltration reservoir	20 mm/d
Parameters subirrigation system	
Pumping capacity	240 m^3/d
Maximum groundwater level	9.1 m TAW (-0.5m below surface level)
Parameters agricultural area	
Area subirrigation	40 000 m^2
Surface level	9.6 m TAW
Groundwater storage coefficient	0.1
Ditch bottom level	8.3 m TAW; assumed 1.3 m below surface level following van der Gaast (2006)
Drainage level	8.6 m TAW; assumed 1 m below surface level
Maximum water storage root zone	6.57 cm (Available water loam sandy soil (Staring B13, Heinen et al. 2020) between wilting point and field capacity 0.22 cm^3/cm^3, assuming a rooting zone depth of 30 cm, gives 6.57 cm of water storage capacity in root zone)
Evapotranspiration factor	Reduces when soil water is <80% of field capacity until 0 at wilting point
Drainage resistance drainage system	5 days
Drainage resistance brook	40 days
Groundwater level deep groundwater	6.5 m TAW
Resistance deep groundwater	500 d

4.3 Effects of proposed water system solutions

The aim of the stormwater retention basin is to prevent problems with flooding in urban areas and to increase the water availability for agriculture in the region. The implementation of a stormwater basin led to a strong reduction in runoff to the Oude Tantelaerloop, especially when combined with subirrigation (Figure 4-5). For the complete period the average runoff to the stream was 71 582 m^3/y for the situation without retention basin, 62 872 m^3/y for scenario 1, 20 985 m^3/y for scenario 2 and 13 373 m^3/y for scenario 3.
Peaks in daily runoff were also reduced in the scenarios. For the reference situation the peak runoff during the entire period was 6 091 m^3/d, this was reduced to 6 065 m^3/d in scenario 1, to 5523 m^3/d in scenario 2 and to 5477 m^3/d in scenario 3. The reduction in peak values was limited in scenario 1, because the basin was filled to capacity most of the time due to the lack of management rules in the regional analysis (Figure 4-6). The basin was only emptied during very dry periods (e.g., 2018). When the water is used for subirrigation (scenario 2 and 3), more

storage was available in the basin and thus peak values and total runoff to the stream could be reduced further. This indicates that proper management of the retention basin and/or use of the stored water is needed to prevent flooding. When operational rules of the basin are optimized, for example, by emptying the basin based on the weather forecast, the peak values can be reduced more efficiently.

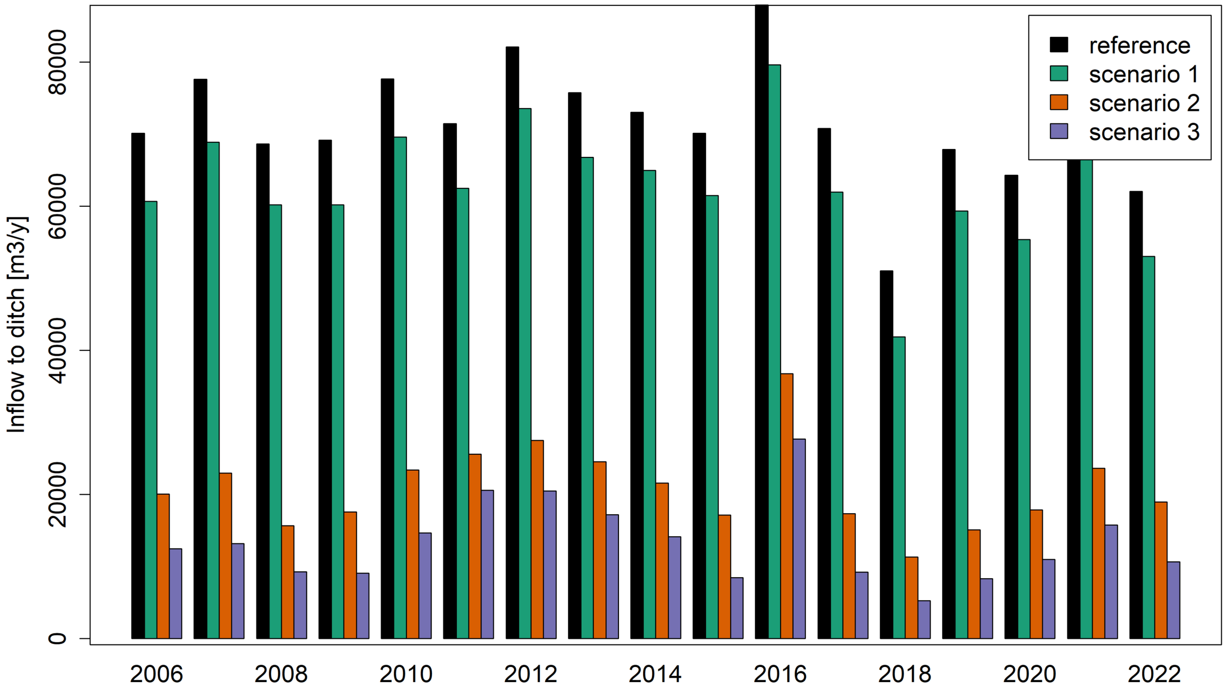


Figure 4-5: Inflow to the Oude Tantelaerloop from runoff of precipitation for the reference situation and after implementation of the retention basin (scenario 1, 2 and 3).

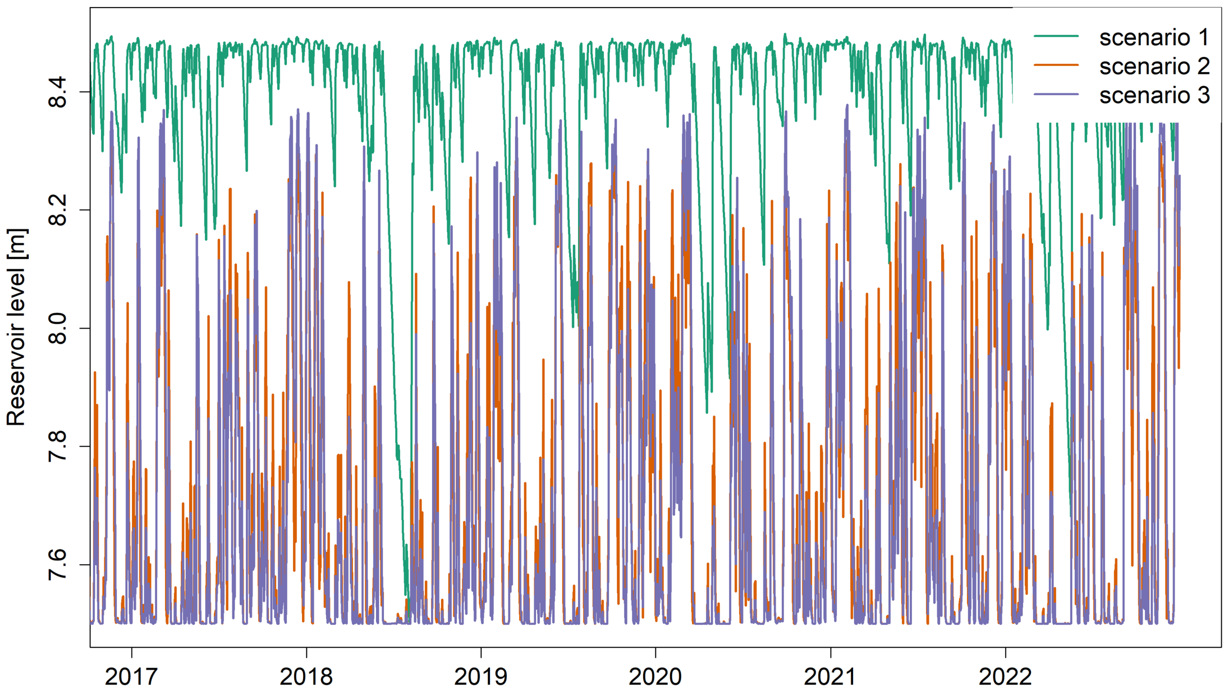
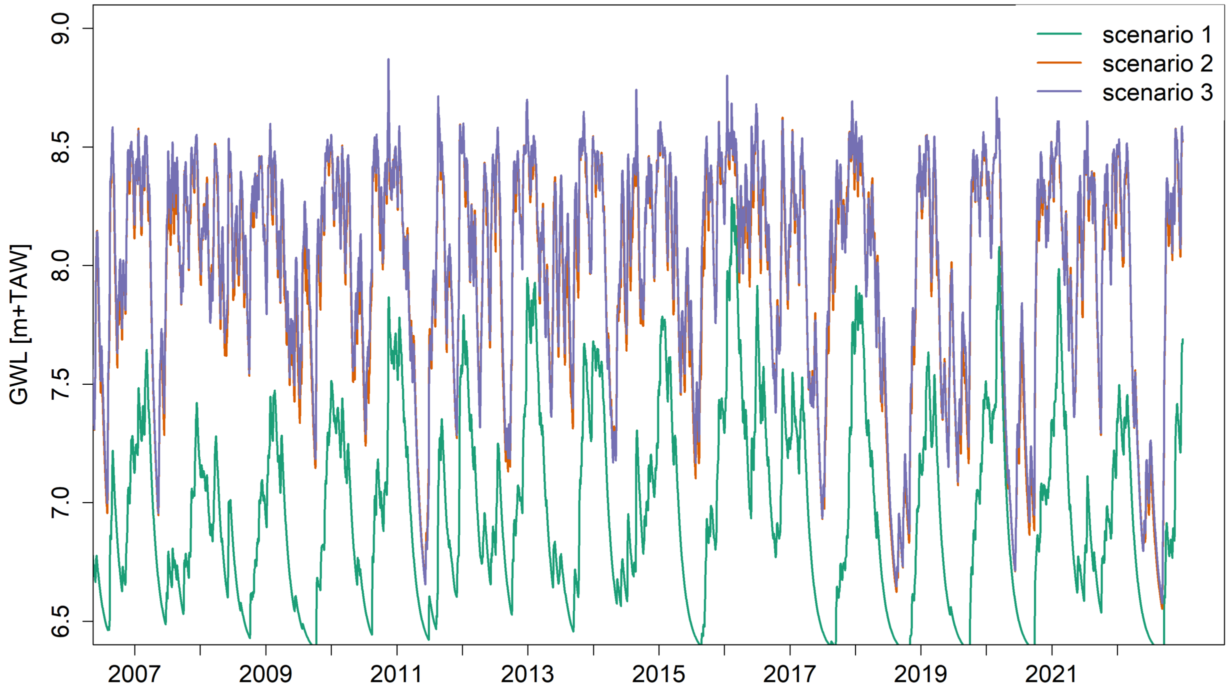


Figure 4-6: Water level in the stormwater retention basin for the three scenarios.

Water from the stormwater retention basin was used to irrigate nearby agricultural fields through subirrigation in scenario 2 and 3. This increased the water availability for agriculture and affected more components of the water system than implementing a retention basin only (scenario 1). When the water from the retention basin was used for subirrigation, groundwater levels below the fields increased during the entire period (Figure 4-7). Groundwater levels showed the largest increase in 2017 with a maximum increase of 1.80 m in scenario 2 and 1.86 m in scenario 3 (Figure 4-8). The increase in groundwater levels varied between the years and throughout the year within a range of approximately 0.12 m to 1.8 m in both scenarios. In drier years, like 2018, the increase was smaller than in wetter years. In scenario 2 the groundwater levels were slightly lower than in scenario 3, because there was less water available from the smaller retention basin.



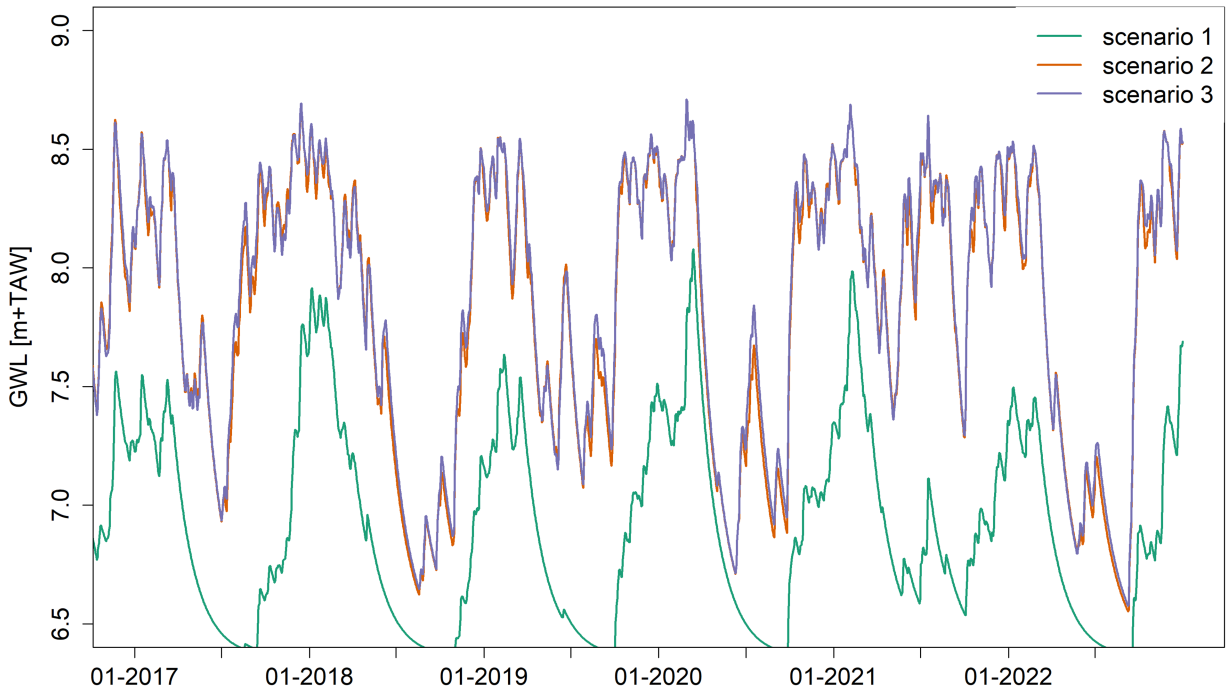


Figure 4-7: Groundwater levels in the situation without subirrigation (scenario 1, equal to reference situation) and for the situation with subirrigation (scenario 2 and 3) for the entire timeseries (top) and last 5 years (bottom).

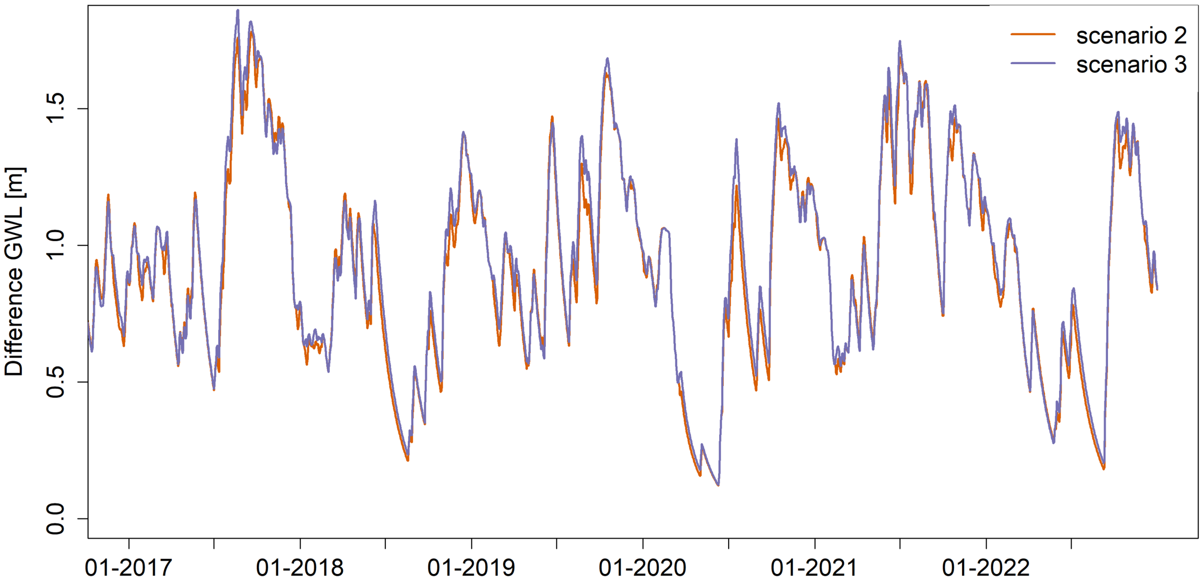


Figure 4-8 Difference in groundwater levels between the scenarios with subirrigation (2 and 3) and the scenario without subirrigation (1).

The increase in groundwater levels had a positive effect on the crops. We have used the actual evapotranspiration to illustrate the effect on crops, because more evapotranspiration indicates better crop growth and thus higher yields. Subirrigation led to a higher actual evapotranspiration during the entire period (Figure 4-9). The average yearly evapotranspiration increased from 400 mm/y in scenario 1 to 461 mm/y in scenario 2 and 463 mm/y in scenario 3. In all scenarios, the average potential evapotranspiration of 496 mm/y was not reached due to water limitations. There was a clear difference in the effect of subirrigation between the years. Yearly average precipitation in the region is 738 mm/y. In a wet year, like 2016 (precipitation 905 mm), actual evapotranspiration was equal to potential evapotranspiration for all scenarios, because there is no water shortage that needs to be compensated. In a dry year, like 2018 (precipitation 527 mm), the actual evapotranspiration in scenario 2 and 3 was much higher than in scenario 1, respectively 430 mm (2) and 433 mm (3) compared to 329 mm (1).

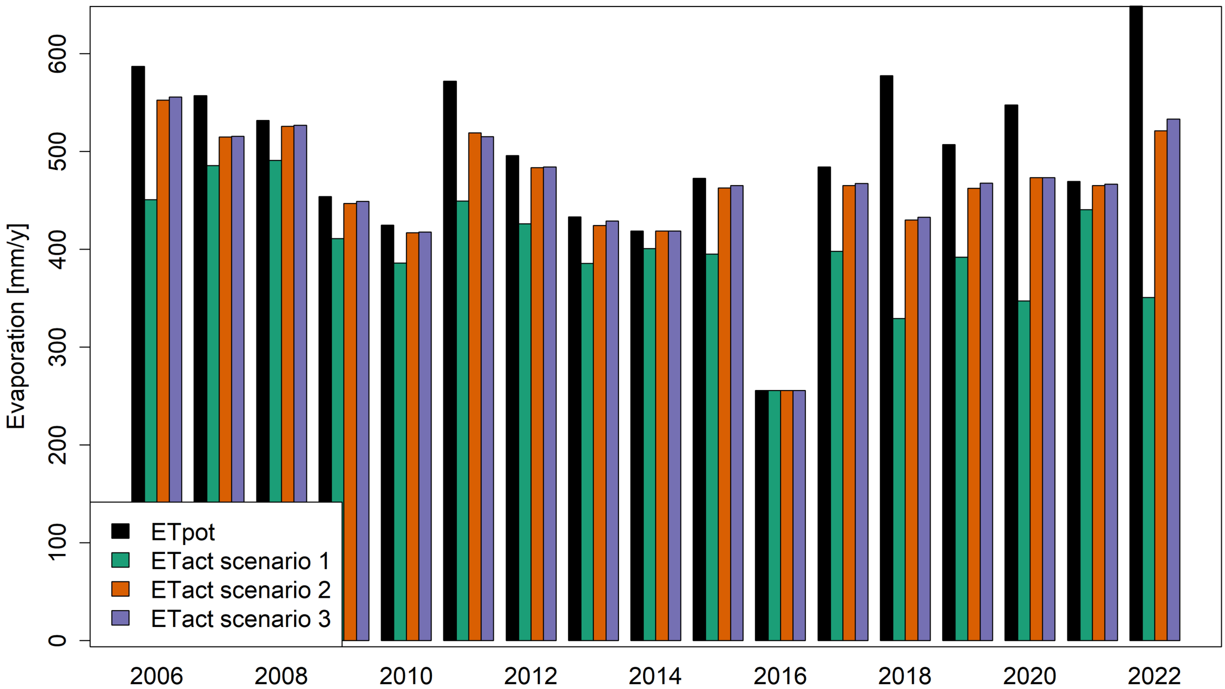


Figure 4-9: Yearly potential evapotranspiration based on observations (input) and yearly actual evapotranspiration for the different scenarios (scenario 1 is equal to reference situation).

The increased groundwater levels also impacted the drainage to streams. The extra drainage to streams caused by the subirrigation in scenario 2 and 3 was limited (Figure 4-10), because groundwater levels were still relatively deep (in wet periods still about 1 m below surface level). In scenario 3 the total amount of drainage was slightly larger than in scenario 2, but differences were small. It was also assumed that the groundwater drained towards the Dorpsloop and not to urban areas. That would mean the extra drainage does not increase the risk of urban flooding.

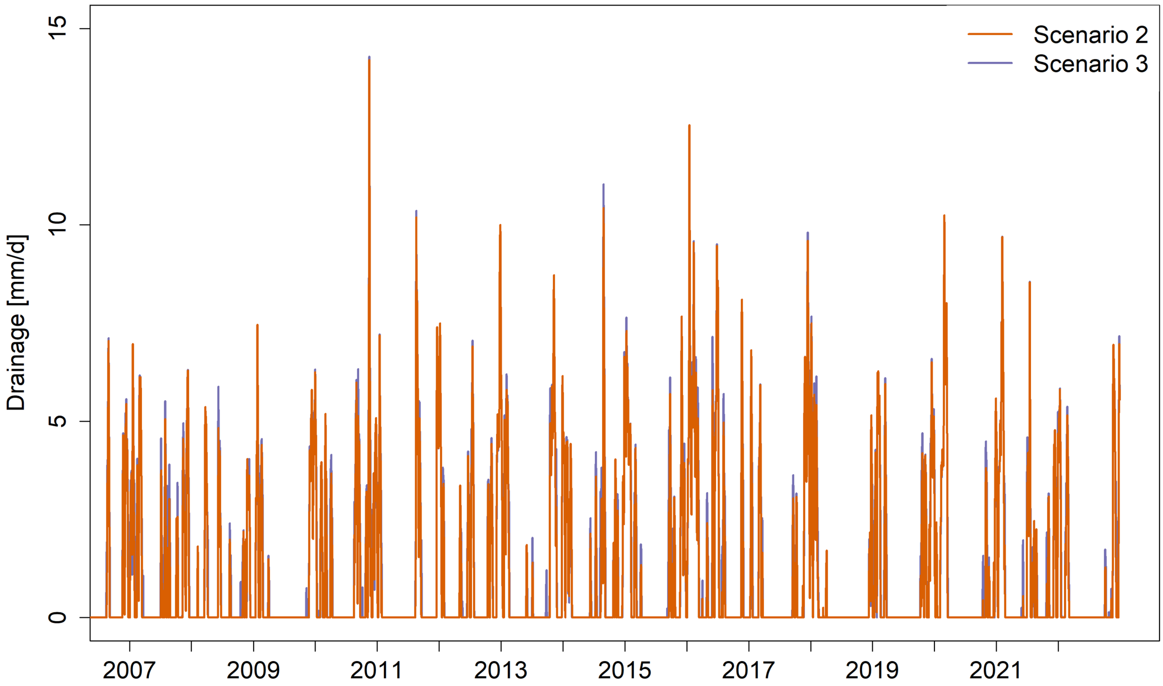


Figure 4-10 Drainage from the groundwater to the stream in the scenarios with subirrigation.

4.4 Conclusions

- The stormwater retention basin was able to reduce the total runoff and peak runoff in the Oude Tantelaersloop, especially when the water was used for subirrigation. When operational rules of the basin are optimized, peak values can be reduced even more.
- Water supplied through subirrigation to the agricultural fields led to higher groundwater levels and higher evapotranspiration values (and thus crop yields increased).
- Excess water from the subirrigation partly left the system through drainage to surface water. However, this water left the system towards the Dorpsloop and therefore did not increase the risk of flooding in the urban areas near the Oude Tantelaersloop. When implementing the system in a different area, the extra drainage caused by higher groundwater levels should be considered to make sure the risk of flooding is not impacted.

5 Reflection

In this report we have shown the results of system dynamics models for two case studies in Flanders, Belgium. These models were used to estimate the regional effect of measures in subsystems of the water system aimed at improving the water availability. Although both case studies involved very different systems and measures, we were able to show the feedbacks and interactions in the systems with this approach, which gave valuable insights.

However, there are some things that should be taken into account when applying system dynamics models. The models give a coarse overview of the system and do not include any spatial differences. For Mechelen, for example, this means that only one groundwater level is determined for the entire area where subirrigation is applied. In reality, there will be differences in groundwater levels across the fields due to elevation differences and influences of surface water. As in all models, the hydrological processes are simplified, albeit some more than others. The percolation, for example, in the Mechelen case contains less detail than other processes. For the exact estimation of the effect of subirrigation on the groundwater level, a more detailed analysis with other types of models is needed. With the system dynamics model, however, we were able to get a coarse estimation of the fluxes in the systems.

System dynamics models have been applied in other regions as well (Stofberg et al. 2024). In general, this approach is valuable to simplify the complex hydrological systems and give coarse estimations of effects of measures. The approach offers the opportunity to combine different types of subsystems, like the natural hydrological system and the anthropogenic water system, in one model and to study feedbacks between these systems. The advantage of the simplifications and coarse estimates is the limited calculation time that is needed. This makes it easy to quickly simulate many scenarios and combinations of measures to get first insights. These first insights can facilitate discussions between all stakeholders and can help with the communication of complex hydrological processes.

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