Towards sustainable drinking water supply in the Netherlands

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Towards sustainable drinking water supply in the Netherlands

Jolijn van Engelenburg

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Preface

Twenty-five years after finishing my initial studies at Wageningen University, I decided to find out whether I could take my years of experience in drinking water practice at Vitens to a higher, scientific level, by starting PhD research. Vitens agreed to support me in this effort, allowing me to work on my research during office hours and giving me carte blanche in my studies on the topic of sustainable drinking water supply. At the same time, I contacted former colleagues at Wageningen University for an exploratory meeting. The positive responses of both led to the signing of a cooperation agreement in December 2015, and I would like to thank Vitens and Wageningen University for providing me this opportunity.

I also thank family, friends and colleagues for their encouragement and support during my PhD trajectory. Combining my day-to-day work at Vitens with PhD research was demanding. Keeping the research going required all of my project management skills, as the daily work for sustainable development of “my” Veluwe drinking water abstractions, with their multiple stakeholder interests, definitely kept me busy. My transition from stakeholder manager to asset manager in 2019 brought new challenges, but it also enabled me to set aside extra time for my research and to finish this thesis.

This thesis builds on my work experience. My employment at Vitens has provided me in-depth knowledge of current practice in drinking water supply in the Netherlands. Through my job, I have been professionally involved in internal and external discussions and meetings on a large variety of drinking water supply subjects. Nevertheless, bridging the gap between practical knowledge and theoretical science was a challenge. I had to learn to provide a solid scientific foundation for the things I knew from practice. That challenge was a source of personal growth for me, as I am a pragmatic and solution-oriented person by nature, rather than a visionary and theoretical one. Now that this thesis is finished I hope it will be of both scientific and practical value in dealing with the challenges on the road to sustainable drinking water supply.

Jolijn van Engelenburg

Ede, May 2020

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Introduction

1.1 Background and problem outline

Sustainable drinking water supply

Drinking water resources worldwide are threatened by global and local developments such as climate change and growing demand for water. Already climate change, combined with social and economic problems and developments, has caused serious crises in drinking water supply, for instance, in Cape Town, South Africa, (Sorensen, 2017) and São Paolo, Brazil (Cohen, 2016). To deal with these threats, it is imperative to adapt current drinking water supply systems. Here however, uncertainty surrounding the projected impacts of developments presents a challenge, given the urgency of decisions on adaptation measures to secure drinking water supplies. This is true not only on a global and national scale, but also on a local scale.

The World Health Organization (WHO) and the United Nations International Children's Emergency Fund (UNICEF) (2017) estimated that in 2015 nearly 30% of the global population did not have access to a safely managed drinking water supply. Thus, Sustainable Development Goal (SDG) 6 seeks to “ensure availability and sustainable management of water and sanitation for all” by the year 2030. The targets associated with SDG 6 demand access to safe and affordable drinking water for all, water quality protection, sustainable and efficient use and withdrawal of freshwater, and implementation of integrated water resources management (UN, 2015). The SDG targets are set on the global scale, but achievement of these targets builds upon whether they are met on a national and even local scale. The Netherlands offers a case in point. On a national scale, the Netherlands’ drinking water supply currently meets SDG target 6.1, because there is “universal and equitable access to safe and affordable drinking water for all” (UN, 2017), according to the employed indicators. However, sustainability challenges do arise on a local scale within the Netherlands. For instance, there may be local water shortages, water abstraction may impact nearby ecosystems, and water resources may become polluted due to other land and water uses. Moreover, ongoing developments, such as the uncertain growth rate of drinking water demand, combined with the effects of climate change, could as yet put the sustainability of the Dutch drinking water supply under pressure in the future.

Local drinking water supply

A drinking water supply system consists of a heterogeneous network of pipelines which connect drinking water abstraction facilities to customers. These systems have long lifecycles (Bauer and Herder, 2009) and exhibit a diversity of cross-scale feedbacks between socio-economic, technological and environmental factors, as well as between the local, regional and global scales (Dermody et al., 2018). Locally, drinking water supply is the domain of a drinking water production facility, where groundwater or surface water is abstracted from the hydrological system and treated to drinking water quality before being distributed to customers. Although drinking water supply systems are highly technical in character (Bauer and Herder, 2009), their sustainability represents a balance between their socio-economic sustainability, their technological sustainability and their environmental sustainability. This is because on a local scale, a drinking water supply system is intertwined with the environment and society in which it is embedded. Both the nature of the available water resource and its geographical location play a role in these links. These characteristics particularly affect the sustainability of a drinking water supply on a local scale. For example, a water resource may be vulnerable to pollution due to nearby land and water uses, or its abstraction may affect a nearby groundwater-dependent ecosystem.

Drinking water supply in the Netherlands

Various developments challenge Dutch drinking water companies' efforts towards an increasingly resilient and sustainable drinking water supply (Vitens, 2016). Currently, approximately 60% of the drinking water in the Netherlands originates directly from groundwater (Ministry of Infrastructure and Water Management and Ministry of Economic Affairs and Climate Policy, 2018). The country abstracts an average of 1 billion m^3 of groundwater yearly for drinking water and other purposes; this is less than 10% of the annual precipitation excess (Geudens and Van Grootveld, 2017). Despite the apparent abundance of groundwater in the Netherlands, multiple stakeholder interests linked to more intensified soil and subsoil use may affect groundwater quality and limit water availability (Lijzen et al., 2014). The Dutch government cooperates with drinking water companies and other stakeholders to balance the various use interests, while seeking to safeguard the drinking water supply that is so vital for society (Ministry of Infrastructure and Water Management and Ministry of Economic Affairs and Climate Policy, 2018).

Climate change, too, may affect drinking water availability. Broadly, in the Netherlands, climate change is projected to increase winter precipitation and to increase summer drought due to higher temperatures and changes in summer precipitation patterns (Van den Hurk et al., 2014). The extremely dry summer of 2018 may have provided a preview of this effect. In that year, all water users in the Netherlands experienced water shortages, while the hot dry weather led to an extended period of extremely high drinking water demand. This put the Dutch drinking water supply under severe pressure (Van Zanten et al., 2019).

Drinking water abstraction in the Veluwe area in the Netherlands

Because of the large availability and good quality of groundwater, the Veluwe area in the Netherlands has long been an important resource for drinking water, since the early 20th century. Currently, 21 local drinking water facilities abstract groundwater originating from here. The Veluwe area is part of a glacial moraine complex that formed in the Saalien glacial period in the Pleistocene (approximately 100,000 years ago) (Rutten, 1960, Gehrels, 1999).

The Veluwe is a large infiltration area, with an absence of surface water in the higher-elevation central zone (Gehrels, 1999). Land use in the central Veluwe area has remained natural throughout history, being limited to woodland, heather and sand drifts (Witte et al., 2019). The quality of the groundwater in the aquifer has hardly been influenced by anthropogenic contamination and is therefore highly suitable for drinking water supply. Groundwater levels in the central Veluwe zone fluctuate slowly, with an amplitude of several meters. However, around the periphery of the area annual fluctuations have an amplitude of the order of a meter or less (Van Engelenburg et al., 2017). In these areas with shallow groundwater, natural seepage zones are found. This is where people historically settled and developed the first groundwater abstractions for drinking water as well as constructing drainage systems of brooks and springs. However, some of the Veluwe abstractions affect valuable groundwater-dependent ecosystems nearby as well as historical brooks and springs on the Veluwe's periphery. Various measures have been proposed or implemented to compensate for these impacts (Van Engelenburg et al., 2017, Van Engelenburg et al., 2020).

Knowledge gaps and research focus

Providing drinking water for all while sustainably managing drinking water resources is a global sustainability challenge. This central challenge can be broken down into multiple challenges, such as ensuring water safety, countering scarcity and minimising the environmental impacts of drinking water abstraction and weather extremes. These challenges originate in part from the design and current state of drinking water supply systems on a local scale, combined with the impact of climate change, population growth and other developments on different spatial and temporal scales. These developments pressure society to seek ways to adapt drinking water supply systems, not only to global and national challenges, but to these local challenges as well.

Sustainability in water management is a frequently studied topic, focusing for example, on water resources, groundwater or urban water, as done, respectively, by Loucks (2000), Gleeson et al. (2012a) and Behzadian et al. (2014). Sustainability assessments are considered a powerful tool for understanding the sustainability challenges societies now face, as well as for weighing adaptation options regarding different water system components (Ness et al., 2007, Singh et al., 2012). Examples of sustainability assessments are found, for instance, in the Sustainable Society Index (Van der Kerk and Manuel, 2008), the International Water Association Performance Indicator System (Alegre et al., 2006) and the City Blueprint (Van Leeuwen et al., 2012). More specifically related to drinking water supply is the EBC Performance Assessment Model (European Benchmarking Co-operation, 2017), which provides benchmarks for water and wastewater utilities. These examples use criteria relevant to sustainable drinking water supply on various spatial and organisational scales, but they do not account for the various local sustainability challenges caused by the embeddedness of drinking water abstraction in a local hydrological and socio-economic environment.

This thesis takes a first step to overcoming this knowledge gap. It brings into focus on a local scale the sustainability of drinking water supply systems in their local environment. The study follows a two-part approach. The first part investigates hydrological sustainability, because understanding the hydrogeological impact of adaptation strategies is essential. The second part explores local hydrological, technical and socio-economic sustainability characteristics and elaborates these into a sustainability assessment framework. This method recognises the need for an integrated approach to understand local drinking water supply sustainability. The full spectrum of sustainability characteristics and challenges for local drinking water supply must be taken into account. This includes not only local hydrological sustainability challenges, but also the technical and socio-economic challenges posed by, for instance, the long lifecycles and lock-ins characteristic of infrastructures for drinking water supply, and population growth.

1.2 Research objectives and questions

The current research contributes to knowledge on the sustainability of local drinking water supply systems. Specifically, two main objectives were pursued:

- To quantify the impact of measures to improve the hydrological sustainability of local drinking water abstraction in a glacial moraine complex;
- To provide insight into the sustainability of local drinking water supply systems, by means of a sustainability assessment framework.

To achieve the first objective, quantitative hydrological methods were used to analyse the impact of local drinking water abstraction in a glacial moraine complex to the groundwater heads and quality, both historically and in the future. In the Veluwe area, steps have been taken and further measures have been proposed to reduce the hydrological impact of drinking water abstraction and safeguard water resources for future drinking water supply. Two examples of such measures are managed aquifer recharge (MAR) and relocation or redistribution of drinking water abstraction to less vulnerable areas. However, climate change may impact the effectiveness of compensation measures like these. With this in mind, two research questions were posed:

- Q1: What is the impact of managed aquifer recharge (MAR) as compensation for the hydrological impact of local drinking water abstraction in a glacial moraine complex?
- Q2: What is the impact of redistribution of local drinking water abstraction volumes on groundwater levels in a glacial moraine complex, and how does this compare to the projected impact of climate change?

To address the second objective of this thesis, an integrated systems approach was adopted to identify sustainability characteristics of drinking water supply and elaborate these into a sustainability assessment. The aim of such an assessment is to provide knowledge on the sustainability challenges and trade-offs associated with adaptation measures for a local drinking water supply system. This knowledge can support decision-making on local-scale adaptation measures. Here, the following two research questions were posed:

- Q3: What sustainability characteristics are relevant for local drinking water supply systems?
- Q4: How can the identified sustainability characteristics be used to assess the sustainability of a local drinking water supply system?

The analyses presented concern various local drinking water supply systems in the Netherlands, while putting the results into a broader context as well. Thus insight is gained into hydrological and other challenges that societies face on a local scale while working towards sustainable drinking water supply for all in the future.

1.3 Concepts and methods

Local drinking water supply

This thesis focuses on drinking water supply systems on a local scale, in short, local drinking water supply systems. The boundaries of these systems are set by the area in which drinking water abstraction is embedded. Local drinking water supply systems are linked to the hydrological system through abstraction, which occurs through the drinking water supply infrastructure. The socio-economic environment is linked to abstraction through the drinking water supply infrastructure employed to convey drinking water to consumers, and through the hydrological system that connects land uses and local stakeholders to the abstraction.

Sustainability and adaptation

Sustainability is a broad concept which cannot be easily captured. For that reason, preference is often given to use of the concept of “sustainable development”, which means continually seeking “best fits” between a system and its changing environment to come to a new, more sustainable state in the future (Holman and Trawick, 2011). However, there is also a need to assess the results of sustainable development. This requires indicators and indices that express the extent to which goals are met, as the UN (2015) has done in its 2030 Agenda for Sustainable Development. This discourse, however, is complicated by the fact that different stakeholders may have different perspectives on what is sustainable. To resolve this, Baard et al. (2012) suggested close collaboration with local stakeholders during the planning process to link local interests with developed scenarios.

In research, the concept of adaptation is often associated with climate change (Luh et al., 2015, Vijayavenkataraman et al., 2012). However, climate change is only one of the developments that poses sustainability challenges. For instance, in the Netherlands the impact of growing water demand may equal or even exceed the impact of climate change on the sustainability of drinking water supply. As the aim of the current research was to support sustainable development of local drinking water supply, the concept of adaptation was defined as strategies and measures that contribute to sustainable development. To determine what adaptation is required, knowledge of both the current situation and future developments must be available (Meijer, 2007).

Sustainable drinking water supply

Sustainable drinking water supply requires a well-functioning technical infrastructure, embedded in the socio-economic and hydrological/physical system (Sivapalan et al., 2012). The technical system for drinking water supply encompasses the design and functioning of infrastructure for water abstraction, treatment and distribution. In this technical system, the results of past decisions can have legacy effects; in other words, impacts of prior developments can limit the range of possible choices in the future (Liu et al., 2007).

Water resources availability and quality are a product of interactions between the socio-economic, hydrological and technical systems (Liu et al., 2015a). These interactions shape and influence decisions on whether adaptation of a drinking water supply system is desirable in the face of external developments and in view of the various cross-scale feedbacks. Water abstraction, for example, affects water levels, which are part of the hydrological system. The water demand of customers and other water users determines the technical capacity required for drinking water production. The socio-economic system provides the framework of standards, policies, permits and legislation which directs developments in land use and water management. To exploit and maintain the technical system and for water treatment and distribution, investments and energy are needed. These expenditures determine drinking water tariffs.

Knowledge to support sustainable drinking water supply

This research sought to provide knowledge to advance the planning of measures for sustainably adapting local drinking water supply to current and future challenges, in the

Netherlands and worldwide. Planning for a sustainable drinking water supply must consider adaptation to all possible developments (Baard et al., 2012), and include short-term and long-term actions. As noted, drinking water supply infrastructure has a long lifecycle (30-90 years), causing “inter-temporal” path dependence and lock-ins (Bauer and Herder, 2009). This implies that short-term decisions have long-term impact, because of the time lag between developments and the appearance of their full consequences (Liu et al., 2007). Not only climate change, but also other developments, such as economic growth and population increase, may affect the sustainability of a drinking water supply.

Lock-ins in drinking water supply systems limit adaptation options. Moreover, due to the long lifecycles of the involved infrastructure, responses are often needed in the short term to adapt to long-term developments such as climate change – though the outcome of both the development and the response may not yet be fully clear (Bauer and Herder, 2009). As complete an understanding as possible of the local drinking water supply system is thus essential for successful planning. The sustainability assessment developed in this research can provide knowledge on the challenges and trade-offs involved in various local adaptation measures for sustainable drinking water supply systems. As such, its use can help to identify “no-regret” measures that can be implemented in the short term, without affecting or blocking other promising avenues in the future (Loucks et al., 2017).

Models and framework

Table 1.1 presents an overview of the research objectives per chapter and the methods and models used. These are detailed in full in the respective chapters.

Table 1.1 *Research objectives, methods and the models or framework used.*

Chapter	Research objective	Method	Models/framework
2	Determine the hydrological impact of managed aquifer recharge (MAR) near a local drinking water abstraction facility	Quantitative, static modelling	Menyanthes (time series analysis software) PHREEQC (hydrogeochemical model)
3	Compare the hydrological impact of redistribution of local drinking water abstraction volumes with the projected impact of climate change	Quantitative, dynamic modelling	AZURE (hydrological model, MODFLOW) KNMI’14 Climate Scenarios

Chapter	Research objective	Method	Models/framework
4	Establish the sustainability characteristics of local drinking water supply	Qualitative, case analysis	DPSIR framework
5	Present the sustainability assessment framework	Qualitative	Multi-criteria analysis

1.4 Thesis outline

This thesis focuses on the sustainable development of local drinking water supply. Specifically, it investigates the hydrological impact of local drinking water abstraction and develops a sustainability assessment framework for local drinking water supply systems.

Chapter 2 analyses the impact of managed aquifer recharge (MAR) as an adaptation measure to compensate for the effect of local drinking water abstraction in a glacial moraine complex in the Netherlands. The methods used were time series analysis and hydrogeochemical modelling. Chapter 3 compares the impact of redistribution of local drinking water abstraction volumes as adaptation measure with the projected impact of climate change in the same glacial moraine complex as studied in Chapter 2. The findings presented in these chapters can inform decisions on the hydrological suitability and effectiveness of the potential adaptation measures, while taking into account the projected impact of climate change.

A sustainability assessment for a local drinking water supply system must integrate the complexity of interactions between the hydrological system, the technical infrastructure and the socio-economic system. Thus, Chapter 4 identifies sustainability characteristics that describe the state of local drinking water supply systems. Three cases are analysed. One relates to a short-term development, that is, a summer drought, and two concern long-term phenomena, that is, changes in water quality and growth in drinking water demand. Chapter 5 then integrates the sustainability characteristics identified in Chapter 4 with scientific knowledge on sustainability and water management and current practice in planning local drinking water supply. This is elaborated as a sustainability assessment for local drinking water supply, based on a linear adaptation planning approach. The assessment is consequently applied to the two adaptation measures that were analysed in Chapters 2 and 3, and an additional case on riverbank abstraction.

Chapter 6 returns to the research questions, answering them in line with the findings from the previous chapters. It then outlines the main findings and discusses strengths and limitations of the study's methodology and results. This chapter further summarises the scientific contributions of the research. Finally, recommendations are made for sustainable drinking water supply in general and for future research.

Fig. 1.1 presents the relationship between the research questions and study components.

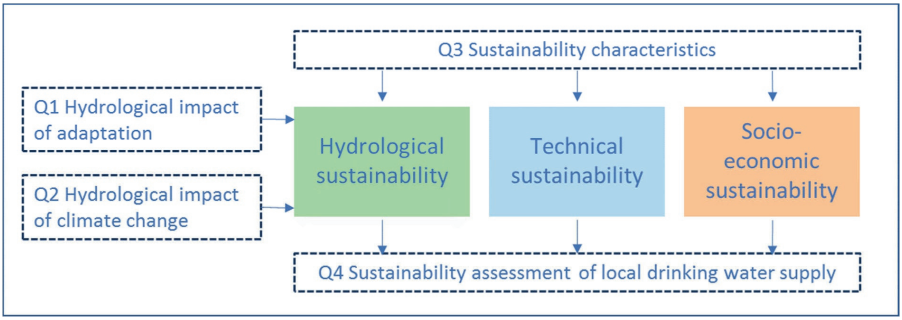

Figure 1.1 *Relationship between the research questions and study components.*

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2

Hydrogeological evaluation of managed aquifer recharge in a glacial moraine complex

Abstract

Managed aquifer recharge (MAR) is a potential adaptation strategy to address dwindling water availability for drinking water supply. In general MAR is used to enable stressed groundwater systems to recharge for recovery or adaptation purposes. In 1998 a MAR project by infiltration of surface water was started to compensate for the impact of a local drinking water abstraction near Epe on the groundwater system in the Veluwe glacial moraine complex in the Netherlands. The thick coarse sand and gravelous aquifers of glacial moraine complexes can retain large groundwater volumes and are often suitable for MAR. The current research evaluated the impact of 20 years of MAR by infiltration to groundwater heads and quality using time-series analysis and water quality modelling. The aim of the research was to enhance understanding of the hydrological processes in a glacial moraine complex and thus support effective MAR design. The results show that MAR has raised nearby groundwater levels in the Veluwe area, but has not contributed significantly to the restoration of the groundwater levels in a nearby groundwater-dependent ecosystem due to local hydrological conditions. Furthermore, 20 years of infiltration did not cause groundwater quality deterioration. These results suggest that MAR in a glacial moraine complex can be an effective adaptation strategy for compensation of groundwater abstraction for drinking water supply, but additionally indicates that the effectiveness for restoration of groundwater-dependent ecosystems strongly depends on the hydrogeological characteristics of the area. A thorough understanding of the hydrology and hydrochemistry of the water system and the used water resource is therefore essential for the design of effective MAR systems. Monitoring and evaluation of groundwater heads and quality will contribute to this understanding.

2.1 Introduction

Managed aquifer recharge (MAR) is used to recharge stressed groundwater systems (Dillon et al., 2018, Geelen et al., 2017), and can be used as a strategy to reverse a potentially dwindling water availability. Water obtained from aquifers that are recharged via MAR can be used for various purposes, such as drinking water supply, industrial water supply and irrigation. Multiple examples of MAR systems have been developed to reduce the overexploitation of aquifers and restore natural hydrological conditions (Dillon et al., 2018). The potential of MAR is widely acknowledged by water resources specialists and is estimated to contribute to 10% of the global groundwater abstraction (Dillon et al., 2018).

Glacial moraine complexes often contain thick, coarse grained, sandy and gravelous aquifers, and are suitable for MAR because of their high hydraulic conductivity (Brun and Jensen, 2001). However, these complexes are also known for their variation in hydraulic conductivity (Bense et al., 2013), which could limit the recovery efficiency of a MAR system (NRMMC et al., 2009). Good knowledge of site-specific aspects and aquifer properties determine the MAR design (Ringleb et al., 2016). Hydrological models can be used to predict groundwater flow at MAR sites. In areas with geological heterogeneity, such as glacial moraine complexes, detailed hydrogeological mapping is essential to support the hydrological modelling (Brun and Jensen, 2001).

Potential water sources for MAR are rainwater, surface water, groundwater from a different aquifer, reclaimed water, or runoff (Page et al., 2018). The quality of the water source and soil processes such as dispersion, cation exchange, or degradation of contaminants, determine the impact of the MAR to the groundwater quality (Laws et al., 2011). To ensure a hydrologically sustainable MAR design, it is therefore important to have a detailed understanding of the groundwater flow (Maliva et al., 2015) and of the contaminants' transport and fate in the groundwater and soil system (Gurjar et al., 2018).

The Veluwe area in the Netherlands (Fig. 2.1) is a glacial moraine complex with a large unconfined, coarse grained, sandy and gravelous aquifer, containing lateral barriers of glaciotectonic origin (Van Engelenburg et al., 2017, Bense and Kurylyk, 2017). For the last two decades, small-scale MAR has been applied in the north east of the Veluwe area. The research question is: *What is the impact of 20 years of managed aquifer recharge (MAR) as* *compensation for the hydrological impact of the local drinking-water abstraction at Epe in the Veluwe glacial moraine complex in the Netherlands?* To answer this research question the available monitoring data over 20 years of infiltration at Epe have been analysed through time-series analysis and one-dimensional (1D) modelling of groundwater quality. The results will enhance the understanding of hydrological processes in a glacial moraine complex to support effective MAR design.

2.2 Research area

2.2.1 Veluwe, the Netherlands

The Veluwe area is part of a glacial moraine complex originating from the Saalien glacial period in the Pleistocene (approximately 100,000 years B.P) (Rutten, 1960; Gehrels, 1999). The depth of the (freshwater) aquifer reaches up to 200 m, and the unsaturated zone has a maximum depth of approximately 70 m from ground surface. There is an absence of surface water in the elevated part of the system and the Veluwe area forms a large infiltration zone, where groundwater is recharged by infiltration of rainwater (Gehrels, 1999, Kumar et al., 2016). Natural groundwater-level elevation across the area is characterised by fluctuation on the frequency time-scale of decades and with an amplitude of several meters, whereas around the edges of the elevated ridge the groundwater level is much shallower, and groundwater levels show annual fluctuations with an amplitude in the order of 1 m or less (Van Engelenburg et al., 2017). Along these edges with shallow groundwater there are seepage zones and (constructed) brooks and springs that are vulnerable to groundwater level decline. The brooks and springs are mainly discharging groundwater from the Veluwe aquifer, supplemented with local rainwater.

The land use of the central part of the Veluwe has historically been limited to woodland, heath and sand drifts (Witte et al., 2019). The groundwater quality in the aquifer therefore is hardly affected by anthropogenic contamination. Because of the large availability and good natural quality of groundwater in the Veluwe area, it has been used as a drinking water resource for centuries. Currently, Veluwe groundwater is abstracted for drinking water at 21 sites (Fig. 2.1).

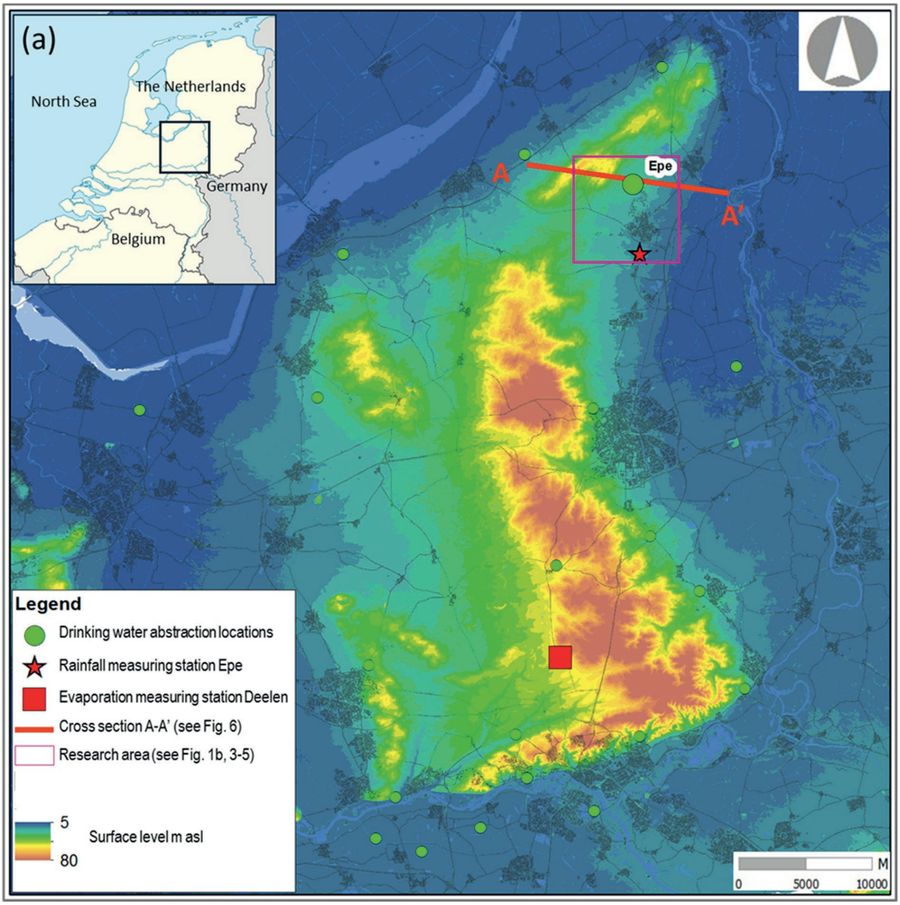

Figure 2.1a *Overview Veluwe area, elevation, drinking water abstractions of Veluwe groundwater, meteorological stations, research area (purple rectangle) and cross-section A-A' (red line, see Fig. 2.4).*

The groundwater flow patterns in the Veluwe area can be erratic, due to the presence of glaciotectonic thrust zones, along which clay layers have been dragged into a sub-vertical position. These imbricated layers were formed when a glacier pushed up the sediment in the area during the Saalien glacial period (Gehrels, 1999, Bakker and Van Der Meer, 2003, Verhagen et al., 2014). The location of these tilted clay layers is barely visible in the landscape, but the impact of some layers on the groundwater flow is noticed through significant jumps in hydraulic heads (Van Engelenburg et al., 2012), similar to those found along tectonic fault zones (Bense et al., 2013). Based on these hydraulic jumps, the location of some apparent tilted clay layers is indicated (Fig. 2.1b), but the depth, length and slope of the tilted clay layers is still uncertain. Due to the origin of the layers, they are expected to descend from west to east, but the actual form has not been determined yet.

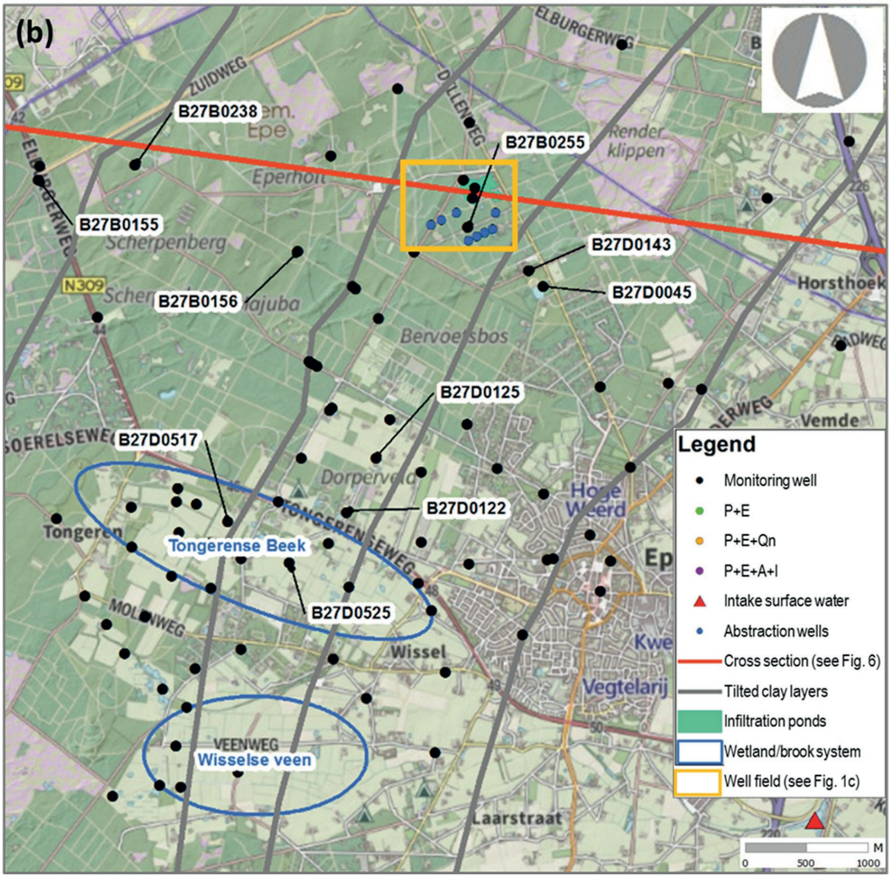

__Figure 2.1b__ Overview research area (purple rectangle in Fig. 2.1a) with used monitoring wells, cross-section A-A' (red line) and well field/infiltration ponds (yellow rectangle).

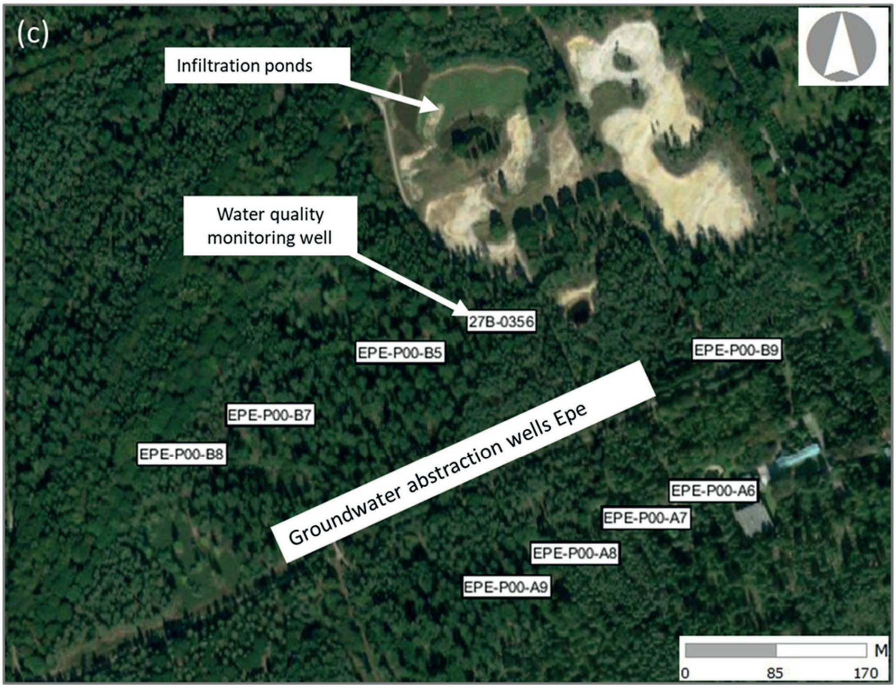

Figure 2.1c *Overview well field with drinking water abstraction wells and infiltration ponds Epe (yellow rectangle in Fig. 2.1b).*

2.2.2 MAR in the Veluwe area

The drinking water abstraction at Epe, near the eastern edge of the Veluwe area (Fig. 2.1), has been abstracting a maximum of 6 million m^3 groundwater per year since 1958 (Fig. 2.2) from a depth of 30-80 m below surface level. The raw water quality is good with low water hardness (mmol/L Ca^{2+}+Mg^{2+}). The abstraction indirectly affects the wetland area Wisselse Veen and the Tongerense Beek brook system (Fig. 2.1b).

Due to the large unconfined coarse-sanded aquifer with a thick unsaturated zone, the Veluwe area is suitable for MAR, enabling spontaneous infiltration of water applied to the surface. Since 1998 untreated surface water has been infiltrated in ponds as part of a local-scale MAR project (Fig. 2.1). The total pond size is approximately 45,000 m^2, and the maximum filling depth in the ponds is approximately 3 m. The intake of surface water takes place from a local brook. This brook mainly discharges groundwater from the Veluwe area towards the nearby river IJssel. By the infiltration, a part of this discharging Veluwe groundwater is infiltrated back into the Veluwe system instead of being discharged to the river. In the first stage of the infiltration scheme (1998–2014), maximum 2 million m^3/yr surplus water was infiltrated (Fig. 2.2). In the second stage, since 2015, the infiltration system was extended to reach a goal of infiltration capacity 6 million m^3/year, to fully mitigate the local drinking water abstraction at Epe. Due to limitations at the intake, this goal has not been met yet (Fig. 2.2). Through adjustments in the water management and technical optimisation of the intake station in 2019 and 2020, it is expected that the goal of zero net abstraction will be met from 2021 onward.

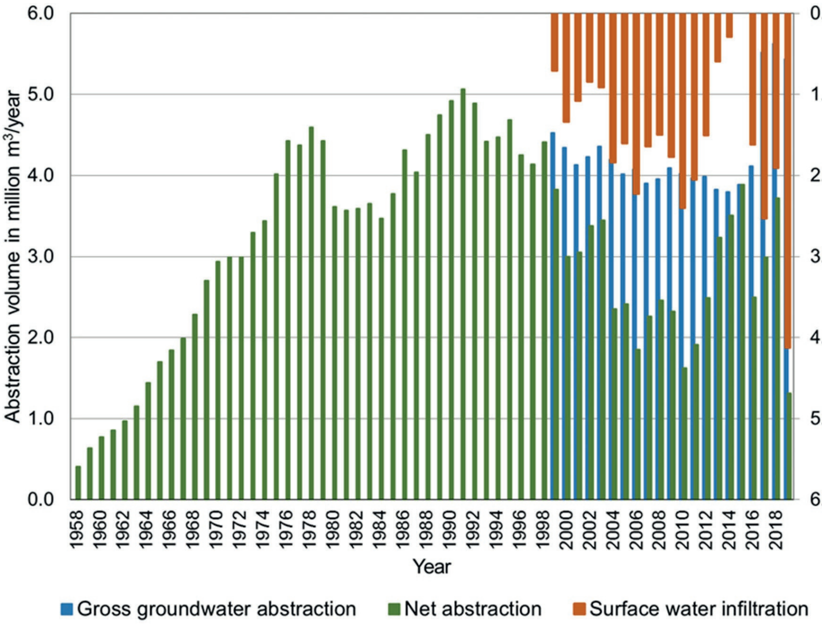

Figure 2.2 *Gross groundwater abstraction (blue), surface water infiltration (orange) and net abstraction (gross groundwater abstraction minus surface water infiltration volume) (green). Actual volumes at the drinking water abstraction and infiltration Epe, the Netherlands from 1958–2019 (data from Vitens, the Netherlands).*

The aim of the infiltration scheme is to restore groundwater levels that are influenced by the Epe drinking water abstraction, and to restore ecological values and seepage flows towards Wisselse Veen (Fig. 2.1b). Because the land use and surface water management was also adapted to restore ecology and seepage in Wisselse Veen, the actual impact from the infiltration on the ecology and seepage cannot be identified. A precondition for the infiltration is that the groundwater quality may not deteriorate. Therefore the impact of the infiltration is measured by analysis of groundwater heads and quality.

2.3 Methodology

In this research the impact of infiltration to the groundwater system is evaluated, to gain knowledge on the hydrogeology of the Veluwe glacial moraine area in the Netherlands. This will support the design of the MAR system for groundwater replenishment in glacial moraine complexes. To achieve the aims of the research, available groundwater head data and water quality data were analysed, using time series analysis and 1D geochemical modelling. Data were collected on groundwater heads, groundwater quality, precipitation, evaporation, groundwater abstraction and surface water infiltration (Table 2.1).

Table 2.1 *Data availability, source, monitoring period and measurement interval for groundwater and weather data, and water quality data.*

Time series	**Source**	**Monitoring period**	**Measurement interval**	**Data used in modelling steps Menyanthes**			**Parameters analysed (this study)**
				Step 1	**Step 2**	**Step 3**	
Groundwater heads	Vitens (this study)	3-61 years	2 weeks/ 3 hours	x	x	x	
Hydrogeological data	REGIS (Dinoloket.nl)	-	-	-	-	-	
Precipitation	Epe KNMI station	1967–2018	Day	x	x	x	
Evaporation	Deelen KNMI station (calculated)	1987–2018	Day	x	x	x	
Groundwater abstraction	Vitens (this study)	1958–2018	Year/Month	-	-	x	
Surface water infiltration	Vitens (this study)	1998–2018	Month	-	-	x	
Net abstraction	Vitens (calculated)	1958–2018	Year/Month	-	x	-	
Water quality:	Vitens			-	-	-	pH, Al^{3+}, Cl^-, HCO_3^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+}, TDS, EC
a. Abstraction wells	(this study)	a. 1973–2018	a. Year				
b. Intake		b. 2006–2018	b. Quarter/ Month				
c. Monitoring well		c. 2005–2018	c. Year				

TDS = Total Dissolved Solids
EC = Electrical Conductivity

To measure groundwater heads on different depths, two or more monitoring wells with various lengths with a screen at the end of the well are situated within one borehole. The measured groundwater heads in each monitoring well represent the groundwater head at the depth of the screen. For water quality analysis, groundwater is abstracted from the monitoring well for a period of time to refresh the water in the well before a sample is taken to ensure the water origins from the screen depth. Because the time series are long, the data collection methodology has developed and changed over time. For instance, the groundwater data used to be collected by hand measurements once every two weeks, and this has been replaced by automated diver measurements. The analytical methods used for water quality parameters have accordingly developed over the years. The groundwater data collection was performed and validated by the authors (Vitens, this study), and groundwater quality analyses were performed and validated by the certified laboratory of the drinking water company that operates the Epe site or external laboratories of equivalent certification.

2.3.1 Groundwater heads

Time series analysis is a statistical modelling method, using time series of measured groundwater heads and different explanatory series to calibrate groundwater-head simulation. In time series analysis, the explanatory series are considered stress models, using a response-function to transform the stress into the contribution to the simulated groundwater heads. The parameters of each explanatory series are optimised, minimising the residuals, which is the difference between the model result and the observations. The analysis was executed using Menyanthes software (von Asmuth et al., 2012). In this research, a time series model is considered valid when the explained variance percentage (EVP) exceeds 70%, the evaporation factor (EVAP) is between 0.5 and 1.5, and the root mean squared error (RMSE) is smaller than 0.15 (Von Asmuth et al., 2011).

The response of the groundwater in the Veluwe system with the thick unsaturated zone is slow, and therefore changes such as abstraction and infiltration result in a long transition period from one state to another. Because this transition period must be omitted from the time series analysis (Von Asmuth et al., 2008), the length of the time series is important for the result of the analysis. Therefore a selection was made from the available groundwater head time series in the area, selecting all monitoring wells that were measured for at least 10 years during the infiltration period. The wetland area Wisselse Veen is a fast responding system on the edge of the Veluwe (Van Engelenburg et al., 2017) and monitoring in this area only started in 2010. Because the aim of the infiltration is to restore seepage flows in this area, and because it is a fast responding system with a short transition period, the researchers chose to include these wells in the research despite the short data period. This led to the selection of 101 time series for 86 monitoring wells (Fig. 2.1b).

The precipitation data time series from the Royal Dutch Meteorological Institute (KNMI) meteorological station at Epe was used. Although there are longer time series of precipitation available, this local station was used because the Veluwe precipitation volume is affected by topography and land use (Ter Maat et al., 2013). For evaporation, the Makkink reference crop evaporation data are used that were calculated by KNMI (Hiemstra and Sluiter, 2011) using the data from the meteorological station at Deelen. Both stations (Epe and Deelen) are located in the Veluwe area and near to the Epe abstraction/infiltration location (Fig. 2.1).

The Menyanthes analysis was executed in three steps with different explanatory series: first only precipitation and evaporation, second with additionally net abstraction, and third with gross abstraction and infiltration instead of net abstraction. When the addition of an explanatory series results in a valid model with an EVP improvement of more than 5% compared to the previous model steps, the impact of the addition is considered a significant improvement. Menyanthes calculates the response of the groundwater head (in meters) to an abstraction of 1 m^3/day (parameter: M0). As the indicator to compare the impact of net abstraction, (gross) groundwater abstraction and surface water infiltration of 1 million m^3/year (approximately 2,800 m^3/day), the stationary impact of 1 million m^3/year was calculated by multiplying the value of M0 with 2,800. A summary of the valid models is given in Appendix I. The electronic supplementary material ESM1 that is supplemented to Van Engelenburg et al. (2020) provides the Menyanthes results for all 101 time series.

2.3.2 Water quality

At the Epe infiltration site, untreated surface water from local brooks is infiltrated. The aim of the water quality analysis is to understand how the infiltration water influences the groundwater quality, by analysing trends in macro parameters. First, a comparison was made of the trends in the infiltration water, the individual abstraction wells of Epe, and a monitoring well positioned between the infiltration ponds and the abstraction wells. Second, the process of cation exchange during infiltration was modelled with PHREEQC, a hydrogeochemical modelling code used to describe the interaction of several hydrogeochemical processes during transport of groundwater through the aquifer (Parkhurst and Appelo, 1999). The aim of the PHREEQC modelling is to simulate the trends of the different anions and cations in the abstracted groundwater after start-up of infiltration, to understand which hydrogeochemical processes take place. The quality of the intake water was used as input. The value for dispersion was calibrated on the trend for sulphate. For calcium and other cations, a 1D PHREEQC transport model was set up to calibrate cation exchange on the breakthrough curves of potassium, calcium and magnesium.

2.4 Groundwater heads

2.4.1 Results for groundwater heads

In the first step of the Menyanthes modelling, all 101 time series were modelled using precipitation (P) and evaporation (E) as explanatory series, resulting in 47 valid models (App. I). The results of this first step confirm that in areas with a fast responding water system, such as the Wisselse Veen area at the edge of the Veluwe, groundwater-head response is explained well by precipitation and evaporation time series (Fig. 2.3). In the second step, the net abstraction (Qn) was added as an explanatory series to all 101 time series. For 11 time series this resulted in significantly improved model results (Fig. 2.4). The results indicate that stress caused by net abstraction is decreasing with the distance between monitoring well and abstraction/infiltration site, but is also influenced by the tilted clay layers: six of the monitoring wells with significantly improved model results are situated just north of the area that has surface water within the same compartment between tilted clay layers as the abstraction/infiltration. The impact of the net abstraction reaches south as far as monitoring well B27D0517, situated at the north side of the fast-responding Wisselse Veen area (Fig. 2.4). The monitoring wells B27D0143 and B27D0045 are close to the abstraction/infiltration, but apparently east of the tilted clay layer: the impact from the net abstraction is comparable to the impact in B27D0125, which is further away but within the same compartment of the abstraction/infiltration (Fig. 2.4). This indicates that there is a limited groundwater flow through the tilted clay layers, causing a preferential flow direction parallel with the clay layers.

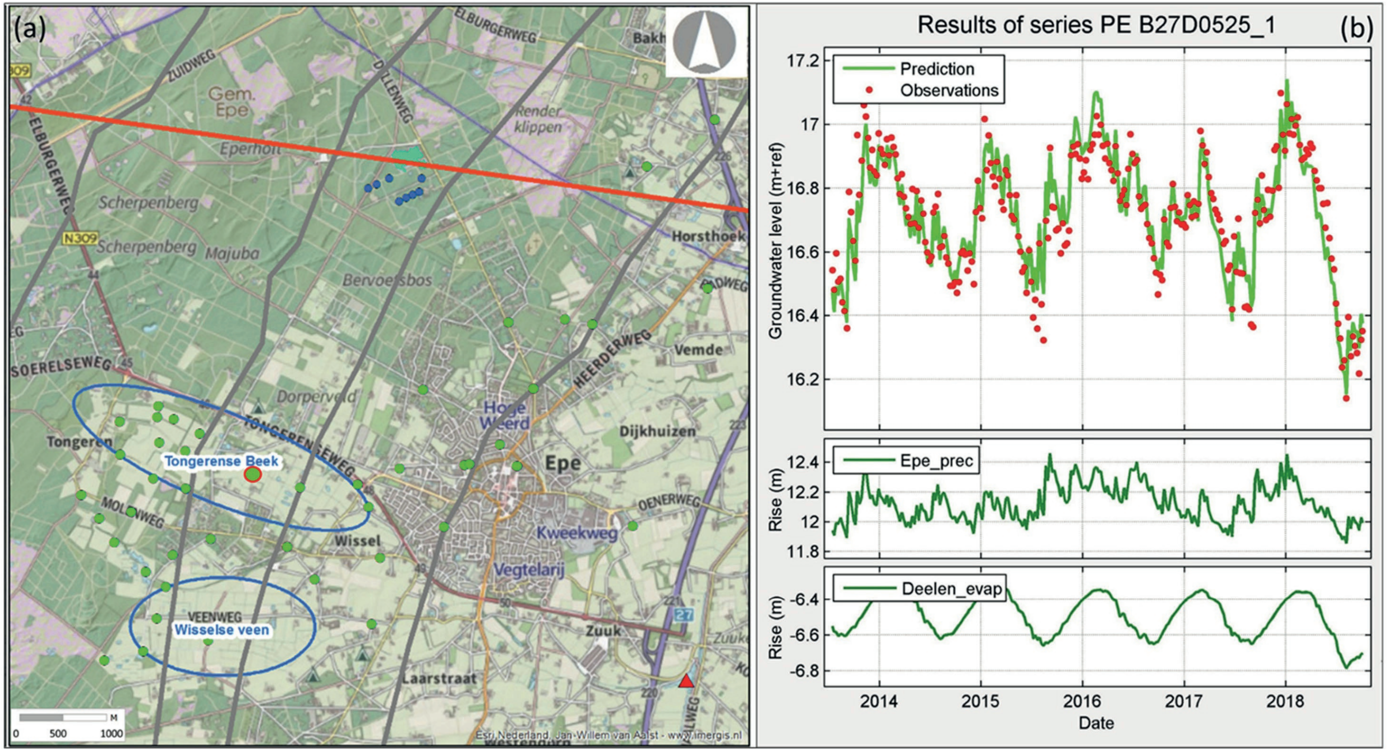

Figure 2.3 *(a) Monitoring wells with valid models with explanatory series P (precipitation) and E (evaporation) in step 1. The red line indicates the cross-section of Fig. 2.6, the grey lines indicate the approximate position of the tilted clay layers; (b) The best Menyanthes model result, with the observed and predicted groundwater level, and the contribution of each explanatory series (well is indicated by red circle).*

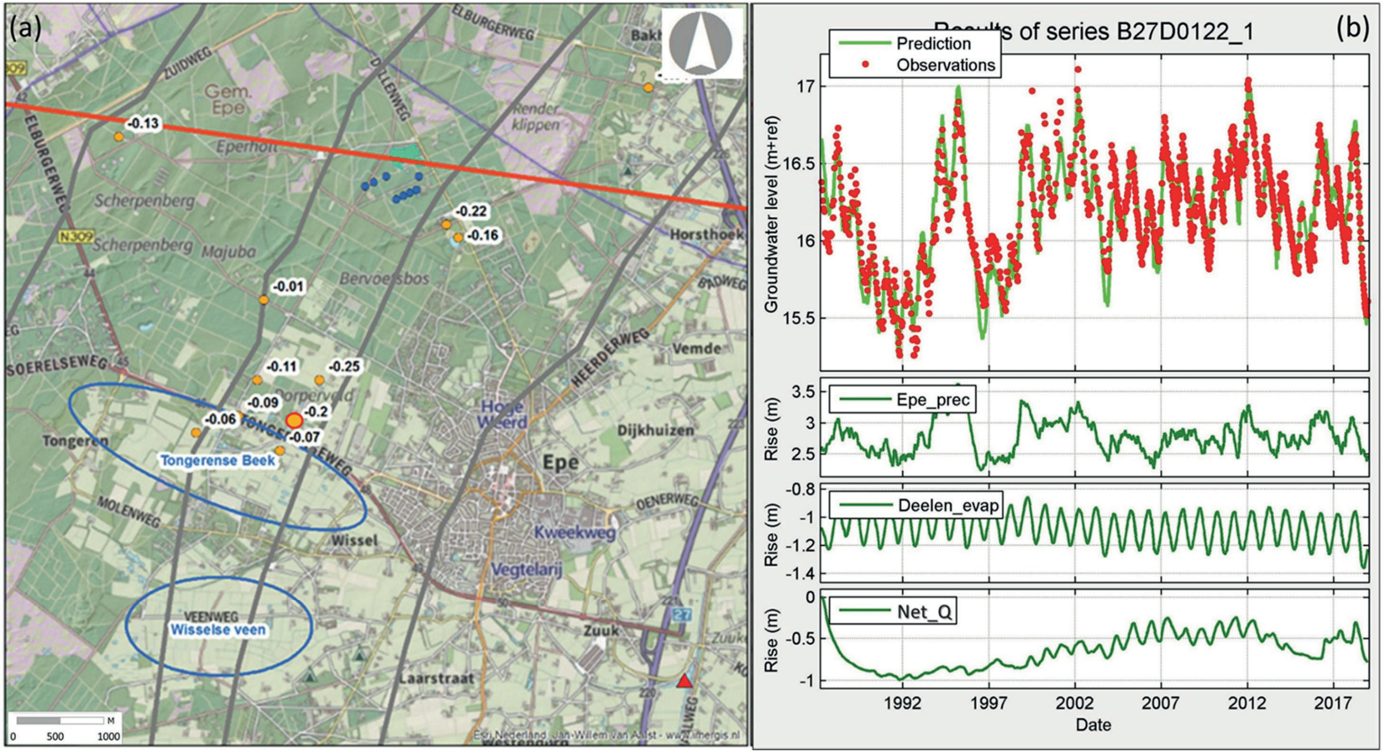

Figure 2.4 *(a) Monitoring wells with valid models with explanatory series P (precipitation) and E (evaporation) and Qn (net abstraction) in step 2. The valid models are labelled with the stationary impact on the groundwater level when 1 million m*^{3}*/year is abstracted or infiltrated. The red line indicates the cross-section of Fig. 2.6, the grey lines indicate the approximate position of the tilted clay layers; (b) The best Menyanthes model result, with the observed and predicted groundwater level, and the contribution of each explanatory series (well is indicated by red circle).*

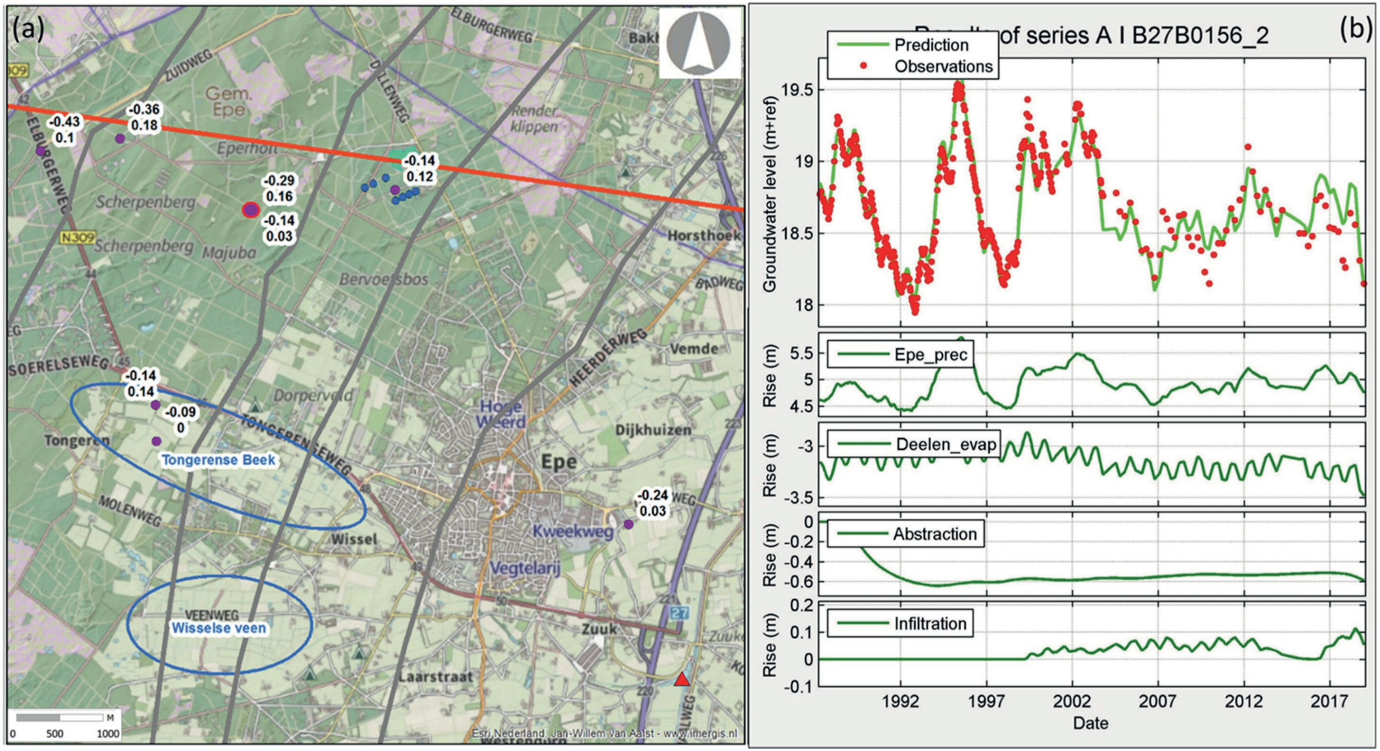

Figure 2.5 *(a) Monitoring wells with valid models with explanatory series P (precipitation) and E (evaporation), A (abstraction) and I (infiltration volume) in step 3. The valid models are labelled with the stationary impact on the groundwater level when 1 million m*^{3}*/year is abstracted or infiltrated. The red line indicates the cross-section of Fig. 2.6, the grey lines indicate the approximate position of the tilted clay layers; (b) The best Menyanthes model result, with the observed and predicted groundwater level, and the contribution of each explanatory series (well is indicated by red circle).*

The results of step 2 also show that the addition of net abstraction as an explanatory factor does not improve the results for the monitoring wells in the fast-responding area (Fig. 2.3, 2.4). The change in groundwater flow resulting from the reduction of the net abstraction volume may cause groundwater to be discharged through the Tongerense Beek surface water system instead of increasing the groundwater levels, which would also prevent seepage flow restoration in the Wisselse Veen area.

In step 3, net abstraction was replaced by (gross) groundwater abstraction and surface water infiltration separately. Eight time series showed a significant improvement compared to the models with net abstraction (Fig. 2.5). These eight time series included data for groundwater heads measured at four deep monitoring screens (sometimes referred to as filters) that are situated in the underlying Maassluis aquifer (Fig. 2.6). These results were unexpected and called for further analysis of this result.

While the Menyanthes analysis did not result in valid models for the shallow screens of these four deep monitoring wells, the groundwater heads time series were analysed visually (Fig. 2.6). The differences in average groundwater heads between the monitoring wells confirm the discontinuity in the groundwater flow in the west-east cross-section caused by the tilted clay layers. Although surface levels decline in the eastward direction, the groundwater heads indicate that both deep and shallow groundwater flow also is partially directed westward. The groundwater head in the shallow screen B27B0155-1 has the lowest average groundwater head of the shallow screens. This may be explained by the location of the monitoring well west of a tilted clay layer system, but also indicates that the groundwater flow is directed westward in this area. B27B0255-1 is situated in the direct proximity of the abstraction and infiltration and therefore shows strong annual groundwater head fluctuations, following the net abstracted volume. The fluctuations due to the abstraction and infiltration volume decrease with the distance to the well field, but additionally there are significant groundwater head jumps between B27B0155-1, B27B0238-1 and B27B0156-1, probably caused by the tilted clay layers (Fig. 2.6).

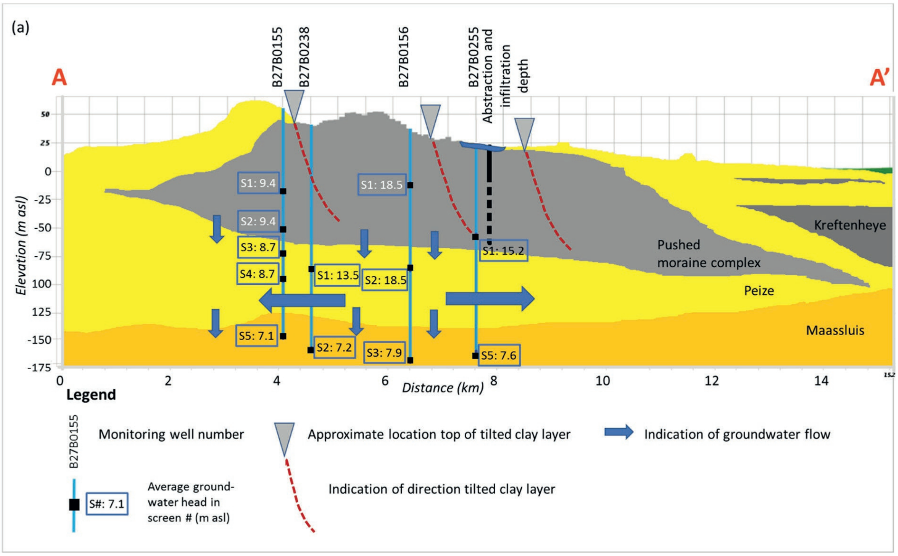

Figure 2.6a *Hydrogeological cross-section of the Veluwe glacial moraine complex; (a) Hydrogeological cross-section A-A' (see Fig. 2.1a), based on REGIS II v2.2 (TNO, 2018) combined with groundwater monitoring data and approximate locations and directions of tilted clay layers.*

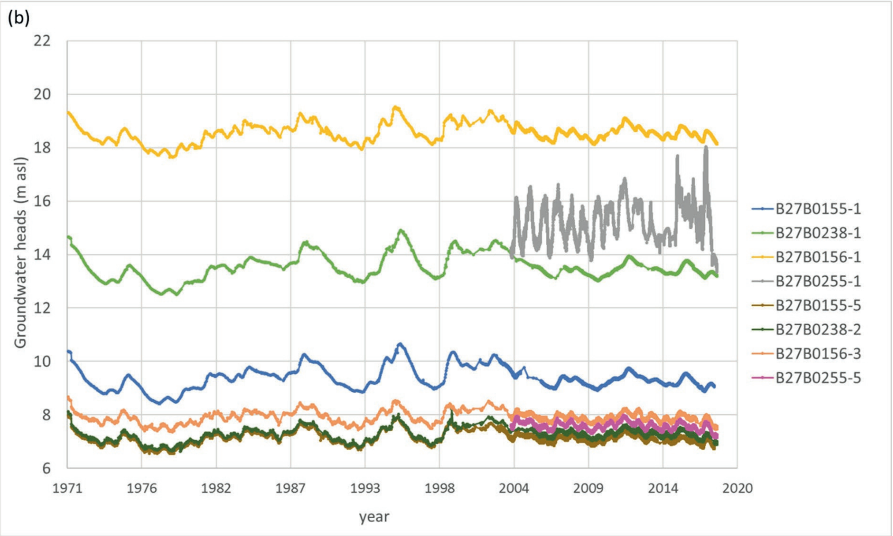

Figure 2.6b *Groundwater-head time series in shallow-screen and deep-screen monitoring wells in cross-section A-A' of the Veluwe (see Fig. 2.1a), source data vitens.lizard.net.*

The deep screens are situated in the Maassluis aquifer, a marine formation below the fluviatile Peize Formation. The average groundwater heads in the deep screens exceed the elevation of the top of the aquifer, which indicates that the Maassluis aquifer is a confined aquifer where the groundwater is under pressure. The groundwater heads in the deep screens differ from the groundwater heads in the screens situated in the overlying Peize aquifer and the pushed moraine complex. and are within a much smaller range compared to the groundwater heads in the shallow screens (Fig. 2.6). This indicates a limited permeability of the interface between the push moraine complex/Peize Formation aquifer, which is confirmed by the presence of a clay layer at an elevation of -123 to -128 m asl (see App. II). However, the Menyanthes model results show that the abstraction and infiltration volume time series partially explain the groundwater fluctuations in the deep aquifer, indicating that there must be some groundwater interaction between this aquifer and the Peize aquifer. The groundwater fluctuation patterns of the four deep screens also reflect the same annual pattern as the shallow screen B27B0156-1 (Fig. 2.6). This could indicate that there is a hydraulic connection between the compartment of the push moraine complex in between the adjacent tilted clay layers where B27B0156 is situated, and the Peize and Maassluis aquifers.

The infiltration takes place at the surface level in the cone of depression caused by the groundwater abstraction. Due to the limited hydraulic conductivity through the tilted clay layers, the largest impact of the infiltration is found in the compartment between the adjacent clay layers. The groundwater is abstracted at a depth of 30-80 m below the surface, and originates partially from the deep aquifers below the push moraine complex. The abstraction from the aquifer affects the groundwater flow directly; the major part of the infiltration fills the cone of depression and is abstracted within 1-3 years after infiltration. The remaining infiltrated water will only reach the saturated zone after slowly passing through the thick unsaturated zone, causing a slower and smaller response to the infiltration than to the abstraction.

2.4.2 Discussion on groundwater heads

The results of the analysis of the groundwater heads confirm the indicative location of the identified tilted clay layers near the infiltration site. The difference in modelling results between analysis with net abstraction (Qn) and with gross abstraction (A)/infiltration (I) indicate that the location and slope of the clay layers not only influence the phreatic groundwater flow, but could also significantly affect groundwater flow in deep aquifers. This causes an uncertainty in the prediction of the impact of MAR in the Veluwe area.

The results confirmed that the elevated part of the Veluwe is a slow responding groundwater system due to the presence of a thick unsaturated zone, where precipitation and evaporation do not translate directly into the groundwater head (Van Engelenburg et al., 2017). In the slow-responding elevated part of the Veluwe, the simulated models with precipitation and evaporation as explanatory data are not valid, in contrast to the results in the fast-responding system in the Tongerense Beek and the Wisselse Veen area.

The horizontal groundwater exchange in the push moraine complex is limited due to the presence of tilted clay layers, and there is a hydraulic interaction between the push moraine complex and the Peize aquifer, which seems to function as a combined aquifer. The results indicate that although there is a clay barrier between the Peize aquifer and the Maassluis aquifer, there is groundwater interaction between both aquifers. Furthermore the impact of the abstraction and infiltration to the groundwater levels and thus to the seepage flows in the Wisselse Veen wetland area is limited. This can be explained by the assumption that groundwater flow that is restored by the infiltration discharges through the surface water system of the Tongerense Beek before reaching the Wisselse Veen area. These local hydrological characteristics limit the effectiveness of the infiltration towards the Wisselse Veen area.

To further study this interaction, the gained knowledge on tilted clay layers and the interaction between the push moraine complex and the Peize and Maassluis aquifers should be added to the regional hydrological model of the area. An optimisation study could be performed by modelling the impact of the tilted clay layers under different slopes, and the interaction between the deep aquifers and the push moraine complex. This will enhance the understanding of the hydrogeology further, which will support an adequate design of additional MAR in the Veluwe area.

Time series analysis of monitoring data provides historical information on groundwater head trends, which provides knowledge on groundwater dynamics in a hydrogeologically heterogeneous groundwater system, that can help to build or improve a groundwater model

(Van de Vliet and Tiebosch, 2001). The time series analysis did not predict all groundwater-head data series well. Only large changes in the groundwater dynamics, such as abstractions and infiltration, can be explained through this statistical analysis and optimisation. The impact of smaller, or less measurable, influences, such as changes in the surface water systems that affect groundwater recharge or discharge, cannot be predicted with this method. However, because time series models are easy to construct (von Asmuth et al., 2012), they can be used as a quick-scan of an area to gain hydrological knowledge before designing a MAR system, and thus can also contribute to the development of a spatial hydrological model for the area.

2.5 Water quality

2.5.1 Results for water quality analyses

The groundwater quality of the Veluwe area is gradually changing due to acid deposition (Appelo et al., 1982), which is shown by the increase of sulphate in the abstraction wells (Table 2.2). The monitoring well 27B-0356 and the abstraction well B5 are the wells nearest to the infiltration ponds (Fig. 2.1c).

On average, the water quality in both wells after 15 years of infiltration matches the water quality of the infiltration water. This indicates that the original groundwater in these wells was fully replaced by infiltrated surface water in this period of time (Table 2.2). The water quality in other abstraction wells is also affected, but to a lesser extent. This is shown by the differences in the average concentrations of macro parameters, such as pH, HCO_3^-, and the cations Al^{3+}, K^+, Ca^{2+}, and Mg^{2+}, just before the infiltration started (1997–1999), compared to more recent concentrations (2014–2016) (Table 2.2).

Abstraction well B5 and well group A9/B7/B9 are situated near the infiltration. Here the effects of infiltration (dominant) and acidification (minor) are combined, by mixing of native groundwater and infiltration water. The average quality of the infiltration water almost equals the groundwater quality in the monitoring well 27B-0356.2, and the quality of abstracted groundwater in well B5. In the monitoring well only pH shows a slight decline from 7.4 to 7.0, probably due to precipitation of iron during transport and infiltration. Well B5 shows the strongest effect of the infiltration (Table 2.2).

Table 2.2 *Water quality data: Average concentrations of macro parameters just before the infiltration started (1997–1999) and recently (2014–2016) at intake, in monitoring well 27B-356, and in three groups of abstraction wells: highly influenced (B5), mildly influenced (A9, B7, B9) and not influenced (A6, A7, A8, B8). Location of the intake area and wells: see Fig. 2.1c, statistical information: see App. III.*

		Location and period										
		Intake infiltration water	Monitoring well 27B-0356.2	Well B5			Well group A9/B7/B9			Well group A6/A7/A8/B8		
Parameter	**Unit**	2008–2014 (winter)	2008–2014	Before infiltration	After 15 years of infiltration	Difference	Before infiltration	After 15 years of infiltration	Difference	Before infiltration	After 15 years of infiltration	Difference
pH	-	7.4	7.0	6.2	6.8	++	6.3	6.4	+	6.3	6.0	a
Al^{3+}	µg/L	35.5	5.0	203.0	6.0	--	32.0	14.0	-	47.0	33.0	0
Cl^-	mg/L	14	14	14	14	0	13	13	0	12	11	0
HCO_3^-	mg/L	61	59	20	61	++	21	38	+	18	23	a
NO_3^-	mg/L	2	2	5	3	-	2	3	0	4	4	0
SO_4^{2-}	mg/L	25	25	15	23	+/a	10	20	+/a	9	17	a
Na^+	mg/L	10	11	9	10	+	8	10	+	9	9	0
K^+	mg/L	2.8	2.7	1.1	2.7	++	1.0	1.1	+	1.0	1.2	a
Ca^{2+}	mg/L	25	24	10	24	++	9	16	+	7	10	a
Mg^{2+}	mg/L	2.9	2.9	1.9	2.9	++	1.5	2.7	++	1.7	2.2	a
TDS	mg/L	141	141	76	141	++	64	103	+	62	77	a
EC	mS/L	18	18	12	18	++	10	14	+	10	12	a

TDS	Total Dissolved Solids (calculated)
EC	Electrical Conductivity
++/--	Strong effect of infiltration
+/-	Moderate effect of infiltration
0	No effect of infiltration
a	Impact of acidification

Whereas pH rises to an almost neutral value of 6.8, and aluminium concentration declines to a very low level of 6 µg/L, and the concentrations of calcium, bicarbonate and potassium nearly double. The increasing calcium concentration in well B5 from 10 to 24 mg/L is the most notable change in water quality (Fig. 2.7). Well group A9/B7/B9 shows a less pronounced effect. This can be due either to delay by longer travel time, or to a different mixing ratio between infiltration water and native groundwater. In well group A6/A7/A8/B8 the water quality changes only slightly, mainly due to acidification. The decreasing pH in these wells from 6.3 to 6.0 and the increasing SO_4^{2-} concentration show the moderate impact of acidification. Acidification causes an increase of dissolution of lime, here resulting in a small increase of the concentrations of HCO_3^-, Ca^{2+} and Mg^{2+}.

The trend of calcium (Fig. 2.7) illustrates the length of the transition period to a new equilibrium. In well B5 it has taken about three years to reach the calcium concentration of the infiltration water of approximately 25 mg/L (Fig. 2.7). In well group A9/B7/B9 a more gradual transition occurs, where it is unclear if an equilibrium already has been reached in 2017. In well group A6/A76/A8/B8 the calcium concentration is stable around 10 mg/L, confirming the assumption that these wells seem uninfluenced by infiltration water. The modelled trend for sulphate indicates the impact of dispersion, because sulphate can be considered conservative in this aerobic environment. The trend (breakthrough curves) of potassium, calcium and magnesium indicates the impact of cation exchange. The 1D PHREEQC model simulates the quality changes over the period 1993–2018 for cations and sulphate adequately, and shows that the breakthrough of surface water can be described by the main hydrochemical processes dispersion and cation exchange (Fig. 2.8).

2.5.2 Discussion on water quality

The first step in geochemical modelling is to start with basic processes like transport, dispersion and ion exchange. If the simulation is not satisfactory, more complex processes can be added to the model, like (kinetic) solution of minerals or redox processes. In the studied case with an oxic, sandy aquifer containing only low contents of reactive minerals, it can be assumed that dispersion and ion exchange are the dominant processes (Appelo, 1982). This assumption is confirmed by the presented model results, which show a good simulation by only modelling transport, dispersion and ion exchange.

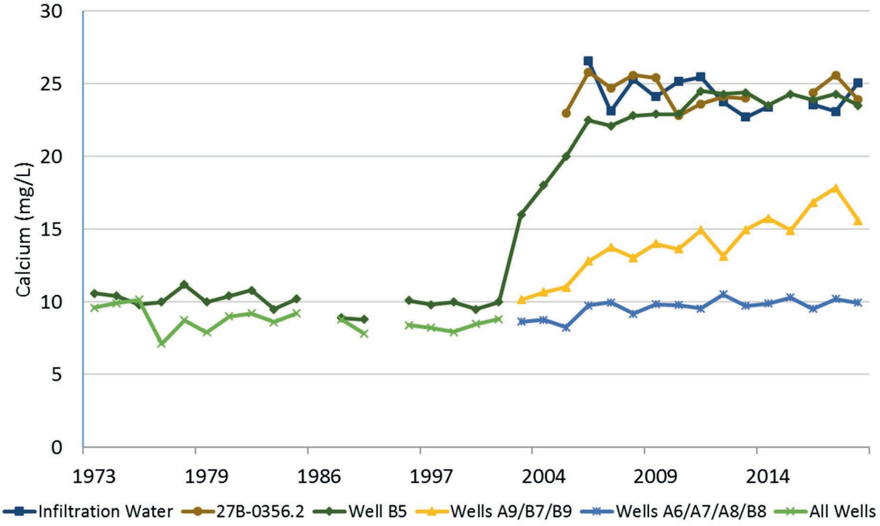

Figure 2.7 *Measured calcium concentrations (in mg/L) in the period 1973–2018 in monitoring well 27B-0356.2, abstraction well B5, well group A9 B7 B9 (average), well group A6 A7 A8 B8 (average), and in all abstraction wells (average). For locations and names of wells see Fig. 2.1.*

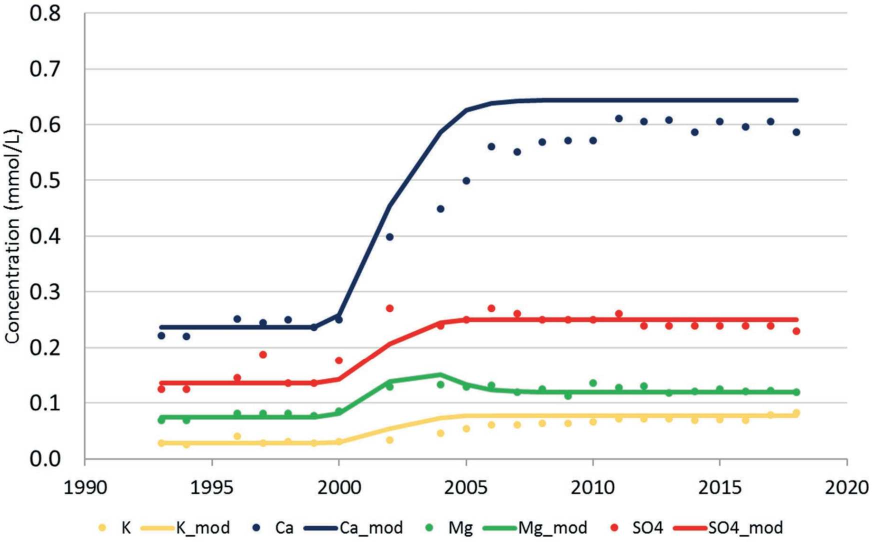

Figure 2.8 *Measured and modelled concentrations of parameters, showing changes in water quality due to infiltration of brook water: Measured (markers) and modelled trends (_mod) of cations K^+, Ca^{2+}, Mg^{2+} and sulphate SO_4^{2-} (in mmol/L) in abstraction well B5. PHREEQC Version 3.5.1 (29 May 2019) was used. For locations and names of wells see Fig. 2.1.*

Based on the modelling results with PHREEQC, the travel time is estimated at approximately 2 years from infiltration pond to abstraction well B5. Therefore it is expected that the effect of the extension of the infiltration volume that started in 2015 will protrude in the abstraction wells gradually from 2017 onwards. The years 2014–2016 are used in the comparison, because they represent the period just before the recent extension of the infiltration volume in 2015.

MAR is frequently used as a treatment step for reclaimed water, because the passage through the unsaturated zone potentially improves the quality of the infiltrated water (Bekele et al., 2011). In this research, the PHREEQC modelling results in an average cation exchange capacity for the aquifer. The water quality analysis shows that the influence of the infiltration to the quality of the abstracted groundwater is relatively small, and the rise of hardness is the most remarkable change in the quality of the abstracted groundwater.

The impact of the infiltration on the water quality in the adjacent area is uncertain, because the available groundwater quality data were limited to the abstraction wells and one nearby monitoring well. To avoid the risk of spreading of infiltration water to the surrounding groundwater system, the net yearly abstraction will be kept positive, by controlling the groundwater abstraction volume as well as the infiltration volume. Although in winter periods the infiltration rate can exceed the abstraction rate, the winter surplus will remain within the cone of depression caused by the groundwater abstraction, due to the slow response of the Veluwe groundwater system. To prove this assumption, more data from monitoring wells combined with non-stationary modelling of the surrounding groundwater system is required.

2.6 Conclusions and recommendations

In this research, monitoring data associated with over 20 years of infiltration at Epe, the Netherlands, was analysed with time series analysis and 1D modelling of groundwater quality. The aim of the research was to evaluate the impact of 20 years of managed aquifer recharge (MAR) as compensation for the hydrological impact of the Epe drinking water abstraction in the Veluwe glacial moraine complex, to enhance the understanding of hydrological processes in a glacial moraine complex to support effective MAR design. The results of the research suggest that MAR in a glacial moraine complex can be an effective strategy for storage of surplus surface water, compensation of groundwater abstraction, or water quality improvement. The results also show that the complexity of the hydrogeology in a glacial moraine complex may affect the possibility to reach a specific goal, and may cause unintended side-effects, such as problems with water quality changes or increased groundwater levels in other areas. A precondition for an effective MAR system is an adequate intake as well as infiltration facility. To design effective MAR systems, a thorough knowledge of the hydrology and hydrochemistry of the groundwater, as well as the surface water system that is used as the water resource for infiltration, is essential.

In the Epe infiltration case, long time series of monitoring data were available. The time series analysis confirmed that the glacial moraine complex of the Veluwe area, with a thick coarse-grained, sandy and gravelous aquifer, is suitable for MAR, but also showed that its hydrogeological heterogeneities may reduce the effectiveness of MAR. The infiltration has provided a positive impact on nearby groundwater levels. However, from the research it can be concluded that the infiltration does not contribute significantly to the restoration of the water system in the Wisselse Veen area, because of the groundwater discharge in the deep aquifers below the glacial moraine complex and the surface water discharge in the Tongerense Beek system. The water quality data and modelling showed that due to the good quality of the infiltrated water, 20 years of infiltration mainly resulted in a change in acidity and hardness of the abstracted groundwater. The 1D geochemical modelling indicated that cation exchange and dispersion are the main geochemical processes in the aquifer between infiltration and abstraction. From the research it is concluded that time series analysis and 1D geochemical modelling may contribute valuable knowledge of the water system, provided that there are sufficient monitoring data available. A well-functioning monitoring system of groundwater heads and quality is essential, preferably starting before the MAR system is designed.

Finally, from this research it is concluded that the Veluwe glacial moraine complex in the Netherlands is fit for MAR by infiltration. To predict the impact of MAR on the local and regional groundwater system of the Veluwe area, a further understanding of the hydrogeology of the area is necessary. The findings of this research can be elaborated to gain additional knowledge on the complex hydrogeology of the push moraine with tilted clay layers.

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3

Impact of redistribution of drinking water abstractions and climate change on groundwater-dependent ecosystems

Abstract

The Veluwe area in the Netherlands is a glacial moraine complex containing a large volume of groundwater of natural quality that is an important source of drinking water. However, some of the groundwater abstractions in the area affect nearby groundwater-dependent ecosystems. This research investigated the impact of redistributing abstraction volumes between four abstraction locations within the Veluwe area as potential adaptation strategy for reducing these impacts. A detailed, well-calibrated hydrological model was used to study the projected impact of this redistribution to the groundwater levels in nearby groundwater-dependent ecosystems. The results showed that redistribution of abstraction volumes can contribute to restore local groundwater levels, but also highlights that the effectiveness varies depending on the hydrological relationship between the abstraction site and the related ecosystem. Additionally the projected impact of climate change scenarios to the groundwater levels was studied. Findings indicate that in a slowly responding large aquifer such as the Veluwe area, climate change will likely cause rising groundwater levels, despite the projected increase in summer dryness. This impact may even exceed the impact of redistribution of abstraction volumes in some parts of the Veluwe area. Improved understanding on how climate change affects the groundwater system will help to provide a solid basis for adaptation strategy development. In addition, the results also highlighted the need for local hydrological knowledge and high-resolution modelling.

3.1 Introduction

Groundwater resources are often the preferred source for drinking water supply. Groundwater is considered less vulnerable to pollution than surface water, and groundwater quality is usually very stable (Broers and Lijzen, 2014). However, groundwater abstractions can have an impact on groundwater levels, potentially affecting other water use, such as by agriculture and groundwater-dependent ecosystems. In areas where groundwater systems are likely to be affected by climate change, sustainable groundwater management is challenging and complex, and tools to support decisions on improving the long-term sustainability of a groundwater abstraction could be of help (Carmona et al., 2013).

Many climate change studies on water resources ignored groundwater and focused on surface water (Gleeson et al., 2012b). Recent studies, however, have shown that groundwater resources are potentially vulnerable to climate change too (Gleeson et al., 2012a, Gleeson et al., 2010, Gleeson and Wada, 2013, Van der Knaap et al., 2014). Climate change may cause a deterioration of valuable groundwater-dependent ecosystems through desiccation, but can also influence groundwater abstractions, e.g. for drinking water supply. Improved understanding on how climate change affects the hydrological system, including groundwater, is necessary to develop adaptation strategies.

Due to the complexity of groundwater systems and limited data availability it is difficult to assess the impact of climate change on groundwater systems. In this research a detailed, well-calibrated (geo)hydrological model is used to study the projected impact of climate change scenarios on a large aquifer in the Netherlands, which can help understand the impact of climate change to similar hydrological systems under similar climatological conditions.

In the Netherlands the projected climate change can be broadly characterised as an increase in precipitation in winter and an increase in summer drought due to higher temperatures and a change in summer precipitation patterns (Van den Hurk et al., 2014). This trend is already visible in the meteorological data (Daniëls, 2016). In the Netherlands the increase of precipitation surplus in winter will partially discharge through the surface water system and therefore only partially recharge the groundwater system. In summer the projected temperature rise and change in precipitation pattern may cause an increase in evapotranspiration and a decrease in phreatic groundwater levels. Climate change in the

Netherlands is therefore expected to cause stronger desiccation of groundwater-dependent ecosystems. Currently many Dutch ecosystems experience desiccation from decreasing summer groundwater levels (Runhaar et al., 1996), so there is concern that climate change will cause a further deterioration of valuable groundwater-dependent ecosystems (Witte et al., 2012, Witte et al., 2014).

Climate change and other future developments, such as land use change and population growth, can influence not only the availability of groundwater resources for drinking water, but also the drinking water demand (Kumar et al., 2016). The uncertainty of the impact interferes with the urgency to decide on adaptation measures concerning drinking water supply. In addition, adequate adaptation of drinking water systems to these kinds of long-term developments is complicated and involves not only technical, but also social, political and economic aspects (Staben et al., 2015, Kloosterman, 2015, Zwolsman et al., 2014). Therefore, it is important to assess the effect of adaptation measures, also regarding climate change, before these measures are implemented.

The goal of this study is to assess the projected impact of climate change on the hydrology of the Veluwe area and to compare this to the impact of redistribution of existing drinking water abstraction volumes in the Veluwe area by using a state-of-the-art hydrological model. The Veluwe area is a slightly elevated area in the central part of the Netherlands (Fig. 3.1). The groundwater in the Veluwe area is an important source of drinking water. However, some drinking water abstractions have negative impacts on groundwater-dependent ecosystems. To reduce impacts, partial redistribution of abstraction volumes between existing abstraction sites within the Veluwe area is considered. Evaluating the effect of such a redistribution on groundwater levels in the hydrological system of the Veluwe area by using a state-of-the-art groundwater model combined with climate change scenarios will help to inform decisions on the suitability and effectiveness of the considered measure. For the Veluwe area the AZURE model is available, which has already been calibrated and validated by De Lange and Borren (2014). The availability of this model offers a unique opportunity for a detailed study of the impacts of different climate change scenarios and adaptation measures. To the best of our knowledge this is one of the first studies that uses a detailed hydrogeological model to compare the projected impact of climate change and adaptation measures on drinking water abstraction.

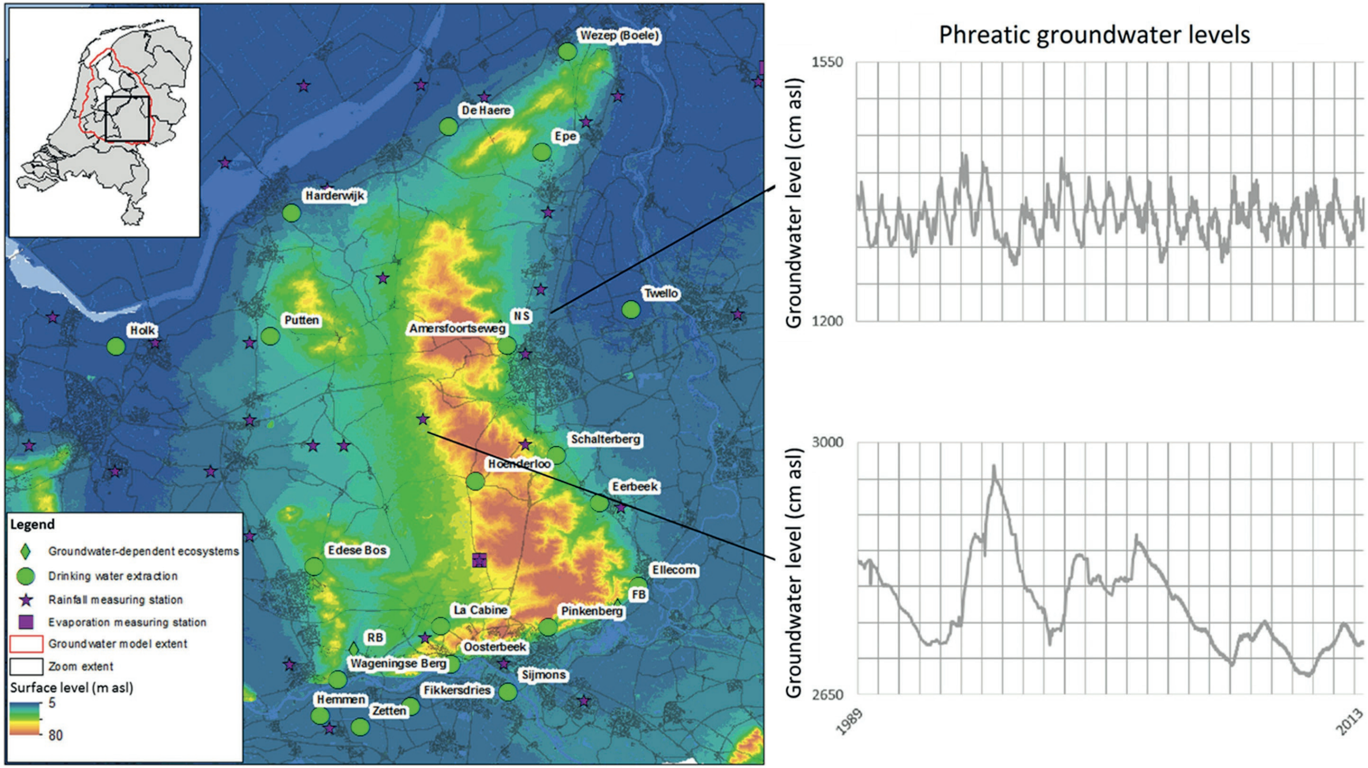

Figure 3.1 *Map of the Veluwe area with the locations of groundwater abstraction sites including Amersfoortseweg (AM), Ellecom (EL), La Cabine (LC) and Hoenderloo (HO), the groundwater-dependent ecosystems NS (Nieuwe Sprengen), FB (Faissantenbos) and RB (Renkum Brooks), the model area and meteorological stations. The insets show the dynamics of the phreatic groundwater levels in two monitoring wells: near Apeldoorn, near the edge of the Veluwe system (upper inset, fast response) and near Radio Kootwijk, in the centre of the Veluwe system (lower inset, slow response).*

3.2 The Veluwe area

The Veluwe area is part of a moraine complex dating back to the Saalien glacial period in the Pleistocene (Rutten, 1960, Gehrels, 1999). The hydrological system can be seen as a large sandy aquifer of up to 200 m depth, with a thick unsaturated zone reaching up to a maximum depth of 60 m. The elevated part of the system forms a large infiltration area that recharges the aquifer.

The groundwater system of the Veluwe is a slow-responding system (Gehrels, 1999), because there is only a limited surface water system in this area, and the groundwater levels are deep below the soil surface. Groundwater level fluctuations in this area are characterised by low frequency fluctuations with a large amplitude (Fig. 3.1, lower inset). Around the edges of the elevated ridge the groundwater level is much shallower. Here seepage zones have developed and groundwater level fluctuations are higher in frequency and have a smaller amplitude (Fig. 3.1, upper inset). The groundwater levels are not continuous due to the presence of tilted clay layers, causing a discontinuous pattern that obstructs groundwater flow (Gehrels, 1999, Verhagen et al., 2014) especially along the steep eastern and southern edges. Although detecting tilted clay layers is difficult, some of them can be located where significant jumps in hydraulic heads are measured on both sides of a tilted clay layer (Person et al., 2007). However, modelling the hydrology of these edges is complicated (Van Engelenburg et al., 2012).

The central part of the Veluwe is rich in nature like woodland, heath and sand drifts. Due to the hydrogeological structure of the system most of these ecosystems are rainwater-dependent (Yousefpour et al., 2015). In contrast to this, the ecosystems at the edges of the area are groundwater dependent. The presence of shallow groundwater and seepage zones along the edges of the Veluwe caused the historical development of a constructed drainage system of brooks and springs, which was traditionally used for economic exploitation by watermills (Menke and Meijer, 2007). These brooks and springs mainly depend on groundwater levels. In the Veluwe area groundwater was abstracted for urban drinking water supply systems, starting from the early 20th century. The first abstractions were located at the edges of the area, where the groundwater was easily reached. Currently drinking water is abstracted from groundwater originating from the Veluwe area at 21 sites (Fig. 3.1).

Verhagen et al. (2014) estimated that on a yearly basis 90×10^6 m^3 of groundwater is abstracted from the Veluwe system for drinking water, nearly 8% of the average annual precipitation on the area. In comparison, the average annual reference evaporation during the period 1981–2010 is roughly 65% of the average annual precipitation (Fig. 3.2). Compared to the annual recharge of the Veluwe groundwater system the impact of the drinking water abstraction to the system as a whole is still relatively small. However, locally the impact can be considerable, because most of the drinking water abstractions are located near the edges of the Veluwe, sometimes near valuable groundwater-dependent ecosystems or historical brooks and springs. Most of the drinking water abstraction sites in the Veluwe area, however, do not affect groundwater-dependent ecosystems, or measures have already been taken to compensate for the effect.

There are three drinking water abstractions where compensation is under consideration: Amersfoortseweg (AM), Ellecom (EL) and La Cabine (LC). These abstractions were included in this research project because of their relation to a nearby groundwater-dependent ecosystem (Fig. 3.1). A fourth abstraction, Hoenderloo (HO), was selected because expansion of the abstraction volume at this site was expected not to affect any groundwater-dependent ecosystem, because it is located near the central part of the Veluwe, where the ecosystems depend on rainwater. Abstraction AM affects nearby groundwater-dependent artificial spring systems. To compensate for the impact of AM on these springs locally abstracted groundwater is supplemented to some of the springs, except the ‘Nieuwe Sprengen’ system (NS). The Faissantenbos (FB) near abstraction EL is a groundwater-dependent woodland ecosystem, which needs calcareous seepage water. The impact of the drinking water abstraction EL amplifies the impact of the agricultural drainage, which caused a decrease of seepage flows towards the ecosystem (Skaggs et al., 1994). The Renkum Brooks system (RB) that is related to abstraction LC consists of constructed brooks. Due to decreasing groundwater levels and deterioration of the brooks, the current discharge of the system is now considered too small to achieve the ecological goals.

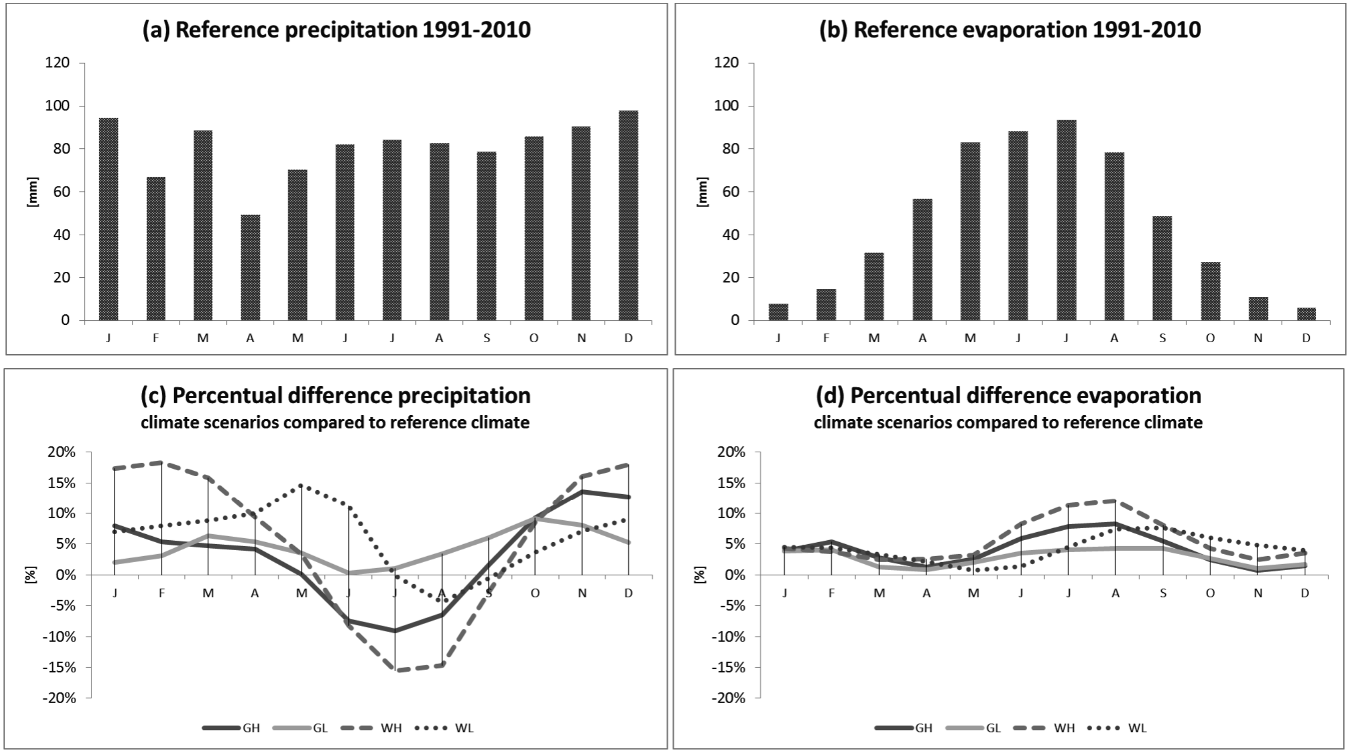

Figure 3.2 *Reference precipitation and evaporation and projected relative change according to the KNMI'14 climate scenarios. Reference precipitation (a) and reference evaporation (b) are the average monthly precipitation and evaporation (mm) in the reference period (1991–2010) for the meteorological station (a) Apeldoorn and (b) Deelen; KNMI'14 climate scenarios percentage of change is the percentage of change (%) according to each KNMI'14 scenario for 2050 relative to the reference precipitation (c) and evaporation (d); for detailed information see https://data.knmi.nl/datasets.*

3.3 Method

3.3.1 Model

To estimate the hydrological impact of climate change and the selected adaptation measures, the existing AZURE-model (De Lange et al., 2014, Hekman et al., 2014) was used, a well-calibrated, high-resolution hydrogeological model. AZURE uses MODFLOW for saturated groundwater flow (Harbaugh et al., 2000) and MetaSWAP for the unsaturated groundwater zone (Van Walsum and Groenendijk, 2008, Van Walsum and Veldhuizen, 2011). The input variables in AZURE are designed to be used at a minimum resolution of 25 m, but the model can be run at a coarser spatial resolution. It can be used for both transient and steady-state calculations. In AZURE the most recent information regarding the geology of the Veluwe area is used (De Lange et al., 2014) and the model has been calibrated using the available time series of data on precipitation, temperature and groundwater levels. In general the results of the AZURE model compare well to the observed groundwater levels (De Lange and Borren, 2014, De Lange et al., 2014).

Comparing the results to the observed values, on average the median (p50) of the modelled 1995 – 2005 groundwater level time-series is slightly lower than observed, especially in the elevated areas. Approximately 20% of the modelled groundwater levels are 0.5 meter lower than the observed levels, again mainly in the elevated areas. Less than 10% is 0.5 m higher than the observed values, spread out over the whole model area. A detailed description of AZURE is available in the full report of (De Lange and Borren, 2014) and to the National Hydrological modelling Instrument NHI (http://www.nhi.nu), which is a Dutch framework of hydrological models including AZURE (De Lange et al., 2014, Delsman et al., 2008).

3.3.2 Climate scenarios in the Netherlands

The Royal Netherlands Meteorological Institute (KNMI) constructed climate scenarios for the Netherlands based on global and regional climate models (Lenderink et al., 2007, Van den Hurk et al., 2007). In 2014 the KNMI scenarios for 2050 and 2085 were updated (Van den Hurk et al., 2014). Both global temperature rise and air circulation change were taken into account as steering parameters and used to create four scenarios. The recent update of the scenarios considered the CMIP5 climate model simulations (Taylor et al., 2012); http://ipcc.ch/report/ar5/) and used additional simulations using KNMI climate models EC-Earth and RACMO2 (Van den Hurk et al., 2014). KNMI distinguishes two important trends: temperature rise (G= moderate or W=warm) and change in air circulation (L=low or H=high), and combines these trends into four climate scenarios (Fig. 3.2). The projected general trend is an increase in both precipitation and evaporation compared to the current climate (Fig. 3.2). Accordingly discharge through surface water and recharge of groundwater are projected to increase during winter. The period with negative recharge will increase and become more negative, which will cause a decrease in groundwater levels.

3.3.3 Research methodology

First, the study area was modelled in a transient manner using current climate variables and the Dutch KNMI’14 climate scenarios as meteorological forcing for AZURE. The used spatial resolution was 250 m. From the results steady-state mean groundwater recharges were derived, representative for the current climate and each of the four climate scenarios. Subsequently, the derived groundwater recharges and the modelled current recharge were used in steady-state calculations for the redistribution scenarios. Since the Veluwe has a thick unsaturated zone, a long spin-up period for the model was required to stabilise the unsaturated zone. Therefore the first 10 years were not included in the calculations of the steady-state recharge. Groundwater recharges of transient calculations were used in the steady-state calculations for the redistribution scenarios. The reference precipitation and evaporation were calculated using the mean values over the period 1991–2010. The datasets of the 2050 KNMI climate scenarios were used.

The reference situation and the scenarios were defined (Table 3.1), based on the current situation in the Veluwe area. The abstractions AM, LC and EL are existing drinking water abstractions, where the possible impact on resp. NS, RB and FB is under discussion. To be able to deliver sufficient drinking water in the area, the drinking water company needs to consider redistributing the abstracted volumes within the Veluwe area, without changing the total abstraction volume. Therefore expansion of HO is considered. Not all theoretically possible scenarios were considered. The scenarios were selected because they are possible without fully relocating drinking water abstraction sites. The scenarios would, however, require a redistribution of abstraction permits and an enlargement of the technical infrastructure of HO (production capacity and distribution capacity).

The impact of the scenarios is assessed by the change in groundwater recharge and groundwater levels in the Veluwe area and for the groundwater-dependent ecosystems nearby the studied abstraction sites. The expected impact of the proposed measures was an increase of groundwater levels in the groundwater-dependent ecosystems and thus improvement of the abiotic conditions in these areas, allowing to restore desiccated ecological values.

To limit the number of calculations of the redistribution scenarios, it was chosen to use the current climate and the GH scenario for 2050 (GH2050). Compared to the other scenarios GH2050 represents the most challenging climate scenario regarding the groundwater-dependent ecosystems (Fig. 3.2, 3.3). The impact of the scenarios on recharge and groundwater levels was studied for the model domain, the Veluwe area and the groundwater-dependent ecosystems NS, FB and RB.

Table 3.1 *Summary of abstraction volumes (million m^3/yr) and maximum groundwater level change (m) in the related groundwater-dependent ecosystems for the reference situation and redistribution scenarios 1–3 under current climate or scenario GH2050, compared to groundwater levels in the reference situation under current climate ("ref").*

Redistribution scenarios	Climate scenario	Abstraction volumes (million m^3/yr)				Groundwater level change (m)		
		AM	EL	LC	HO	NS	FB	RB
Reference situation	Current	7.0	6.0	10.0	3.2	ref	ref	ref
Reference situation	GH2050	7.0	6.0	10.0	3.2	0.10-0.30	0-0.20	0.30-0.45
1	Current	5.5	6.0	10.0	4.7	0.05-0.40	0	0
2	Current	5.5	5.0	8.0	7.7	0.05-0.40	0-0.05	0
3	Current	5.5	3.0	5.0	12.7	0.05-0.40	0.05-0.15	0.05-0.12
1	GH2050	5.5	6.0	10.0	4.7	0.10-0.60	0-0.20	0.30-0.45
2	GH2050	5.5	5.0	8.0	7.7	0.10-0.60	0.10-0.30	0.30-0.45
3	GH2050	5.5	3.0	5.0	12.7	0.10-0.60	0.15-0.35	0.30-0.50

3.4 Results

3.4.1 Climate change scenarios

The current annual total groundwater recharge is ~340 mm in the Veluwe area (Fig. 3.3). The reference recharge is projected to increase by 20 to 40 mm due to the KNMI'14 climate change scenarios (Fig. 3.3). Model calculations confirm that in the Veluwe area the projected climate change will possibly contribute to an increase in the groundwater levels up to 2 meters or more (Fig. 3.4a). A small area west of the Veluwe area shows a comparable impact, albeit to a lesser extent. This area is called the Utrechtse Heuvelrug and has hydrological characteristics similar to those of the Veluwe.

In contrast to the Veluwe area, the adjacent areas do have a surface water system on top of the groundwater system. In these areas vegetation is usually groundwater-dependent, because the groundwater level is close to the vegetation root zone. Results do not show a change in average groundwater levels in these areas, but do show a substantial impact on the average *lowest* groundwater levels (Fig. 3.4b; yellow and orange areas).

Vulnerable groundwater-dependent vegetation can disappear when the groundwater level falls below a certain level, even if only for a short time period. Therefore, the change in lowest groundwater level provides an indication of the potential risk of desiccation of groundwater-dependent ecosystems. Under GH 2050 the average lowest groundwater level in the Veluwe area and the Utrechtse Heuvelrug is projected to increase (Fig. 3.4b). In the groundwater system of the Veluwe the increase in winter precipitation will cause an increase in groundwater recharge. An increase in summer evaporation will only have a limited impact on the groundwater level, because the vegetation is rainwater dependent; the root zone of the vegetation is not related to the groundwater level, which is between 5 and 50 m or more below the soil surface. This explains that under climate change the groundwater level in the Veluwe area and the Utrechtse Heuvelrug area is projected to increase.

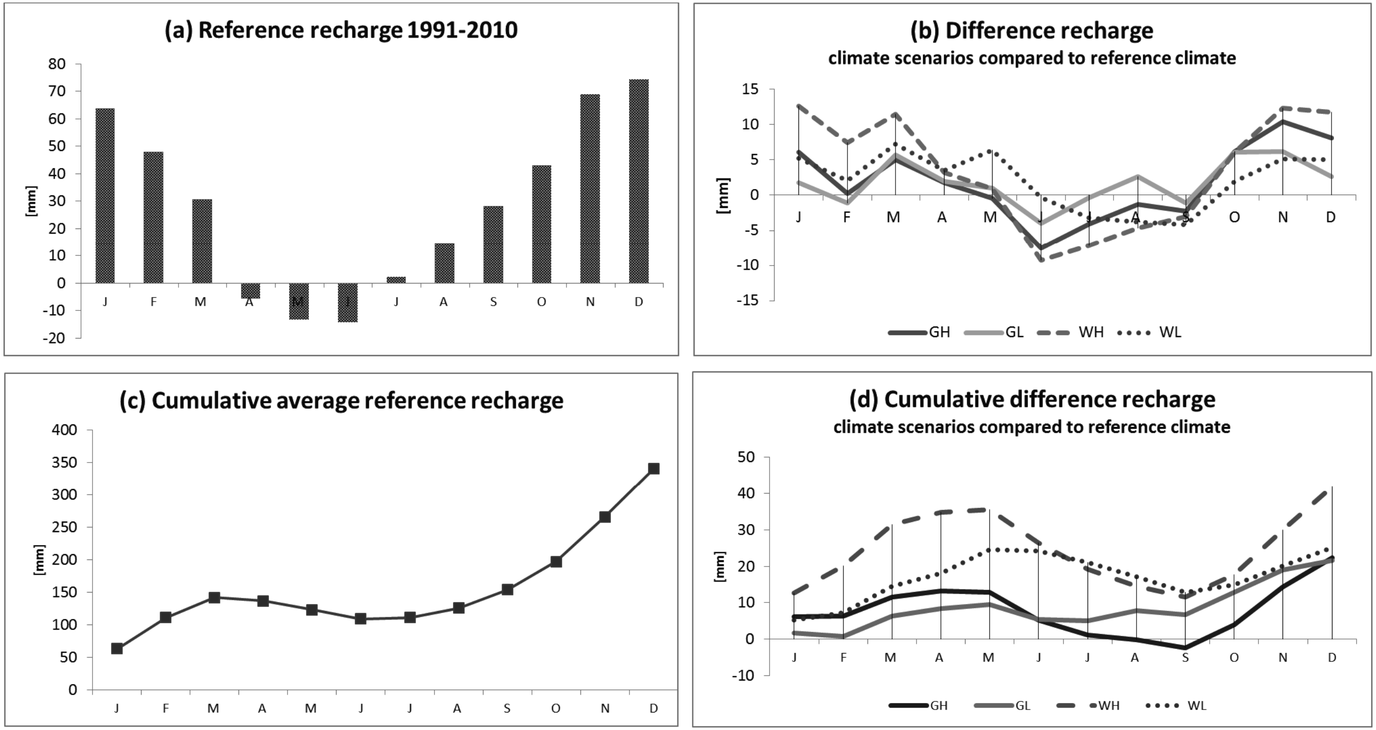

Figure 3.3 *Model results on groundwater recharge in the Veluwe area in mm: (a) average recharge in reference period (1991–2010); (b) net change in recharge in 4 KNMI'14 climate change scenarios 2050 (GL, GH, WL, WH) compared to reference recharge; (c) cumulative average recharge in reference period (1991–2010); (d) cumulative difference recharge according to the KNMI climate scenarios. Note: All results have been calculated in this study using the AZURE model and have been averaged for the Veluwe area.*

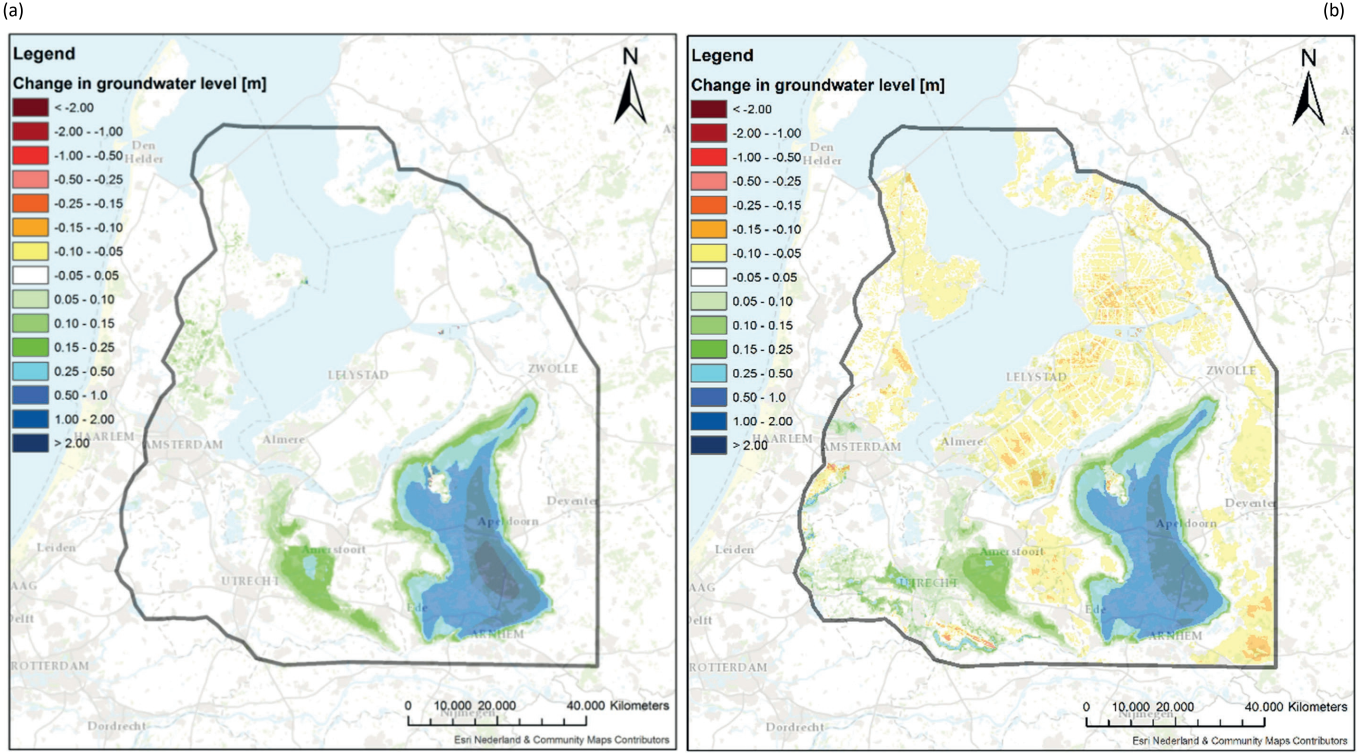

Figure 3.4 *Calculated change in groundwater level (m) for GH2050 in the AZURE model domain: (a) mean average groundwater level and (b) lowest groundwater level. The lowest groundwater levels have been calculated by averaging the three lowest levels for each year of the calculation period over the full calculation period as an indication for the driest situation.*

Although under GH2050 the average groundwater level in the adjacent areas does not change, the average *lowest* groundwater levels are projected to drop 5–15 cm (Fig. 3.4b). This can be explained by two major hydrological differences compared to the Veluwe area. First, the surface water system discharges most of the additional winter precipitation, which limits the groundwater recharge in the area. Second, the groundwater level is close to the soil surface and vegetation is mainly groundwater dependent. The increasing temperature caused by climate change will increase plant transpiration and thus will cause a decrease in groundwater levels in summer, possibly causing desiccation of vegetation (Runhaar et al., 1997, Runhaar et al., 1996). In contrast, the calculated lowest groundwater levels of NS, RB and FB show a projected increase under GH2050 (Table 3.1).

3.4.2 Redistribution scenarios

The results of the steady state model runs show that redistribution of abstraction volumes will affect the groundwater levels (Table 3.1, Fig. 3.5). In all redistribution scenarios the permitted abstraction at AM is reduced by 1.5 million m^3 per year compared to the reference situation. This is projected to cause a 0.4 m increase in groundwater levels. The oval shape of this impact area is caused by the resistance of the tilted clay layers, which force the groundwater to flow parallel to them. The size of the affected area decreases with an increase in the abstraction volume at HO. At HO the expansion of the abstraction volume is estimated to cause a decline in groundwater level between 0.5 m (scenario 1) and 2 m (scenario 3).

Reduction of EL causes an increase in the groundwater level at FB between 0.05 (scenario 2) and 0.15 m (scenario 3). As the area surrounding FB has a surface water system that drains the area, the surface water discharge is likely to increase when the groundwater abstraction is reduced. Therefore the groundwater is only partially recharged and the increase in groundwater level remains limited.

The results imply that a reduction of LC will have no (scenario 2) or only a limited (scenario 3) impact (max. 0.15 m) to RB. This relatively small impact is caused by the distance between LC and RB and the complex hydrogeology of the area – a complicated tangle of tilted clay layers.

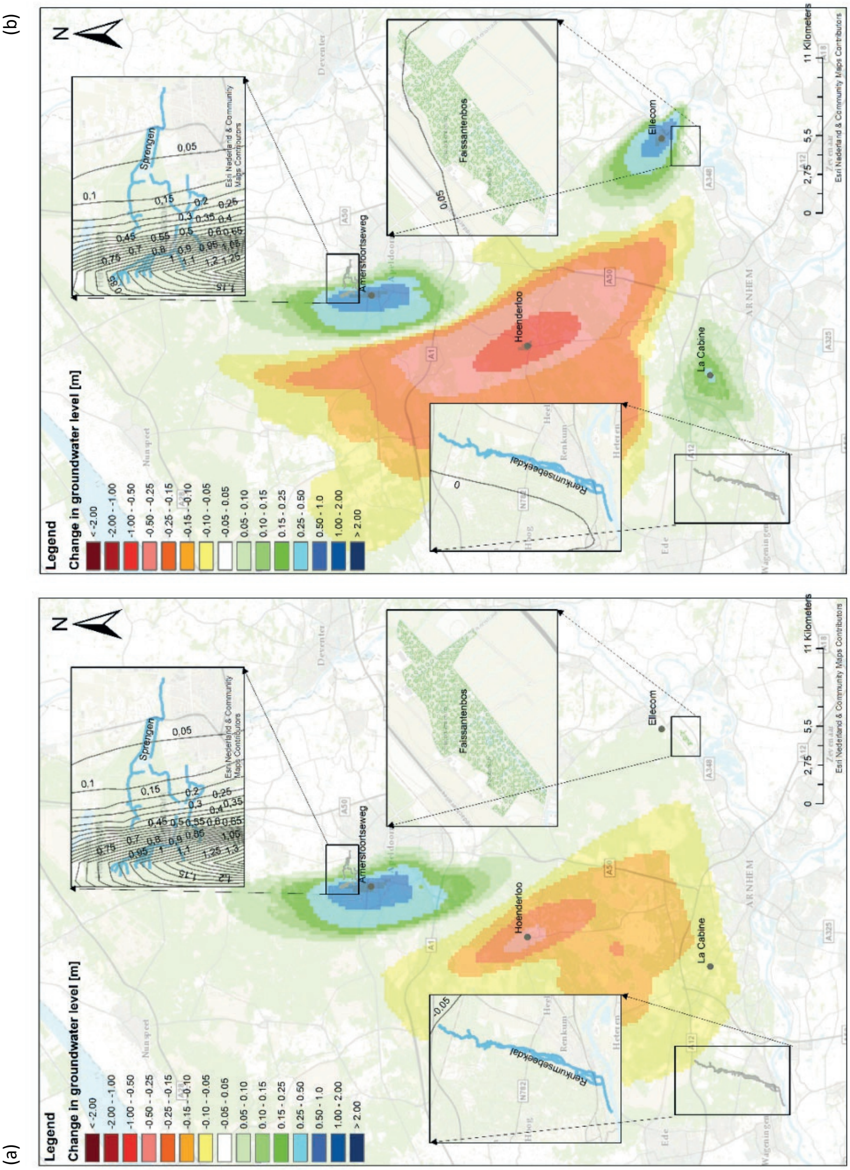

Figure 3.5a, b *Change in groundwater levels in (m) compared to the reference scenario in: (a) redistribution scenario 1 under current climate; (b) redistribution scenario 2 under current climate.*

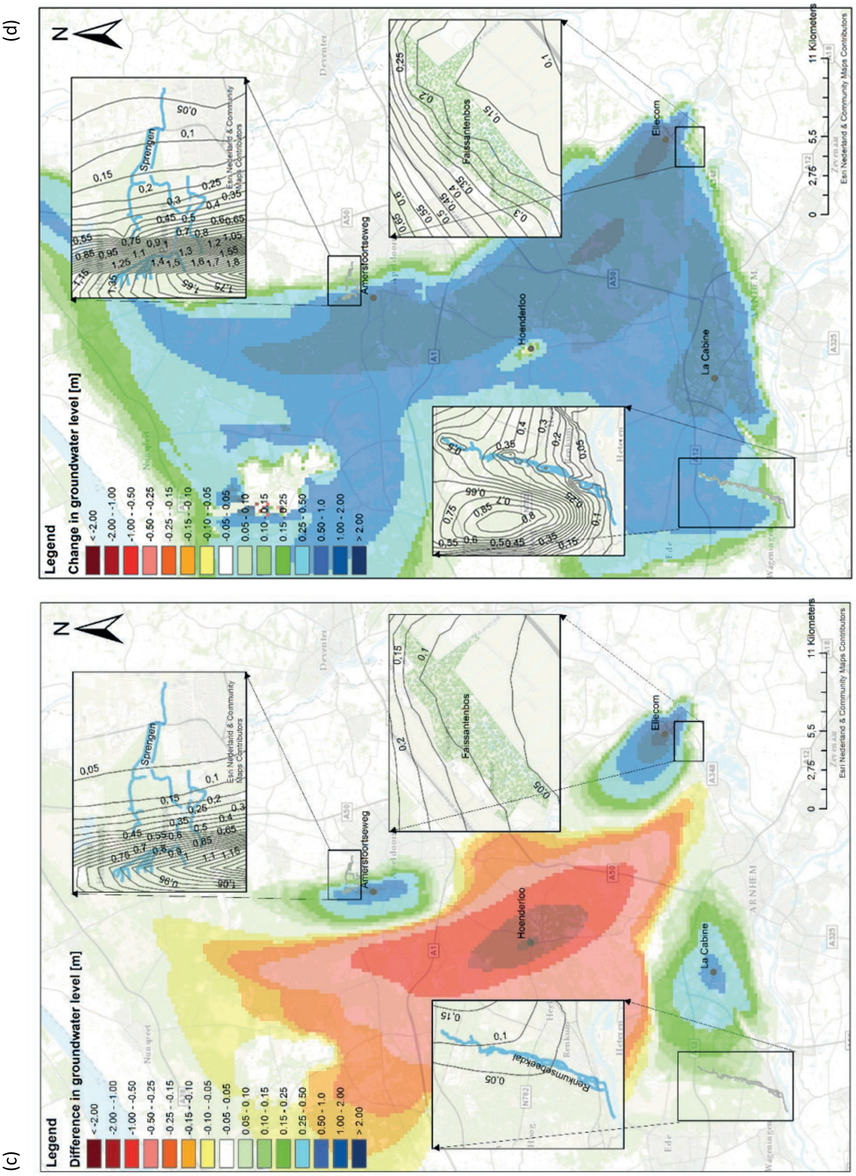

Figure 3.5c, d *Change in groundwater levels in (m) compared to the reference scenario in (c) redistribution scenario 3 under current climate; (d) redistribution scenario 3 combined with climate scenario GH2050. Locally zoomed in on the studied groundwater-dependent ecosystems NS, FB and RB.*

3.4.3 Combined scenarios

The redistribution scenarios in combination with the climate change scenario GH2050 show an overall increase in the groundwater levels in the Veluwe area (Table 3.1, Fig. 3.5d). Simulation results, however, do indicate that the size of the impact of climate change compared to the projected impact of the redistribution scenarios varies for each of the studied ecosystems. The impact of reduction of AM is twice the impact of climate change on the groundwater level at NS, whereas the impact of reduction of EL on FB is only half the impact of climate change. The effect of the reduction of LC is approximately one third of the effect of climate change on the groundwater level in RB. The projected impact of climate change to the groundwater levels compensates more than fully for the decrease in groundwater level as caused by the largest expansion of HO.

3.5 Discussion

The results of this study project a substantial increase of the average groundwater level in the Veluwe area under Dutch climate change scenarios, caused by the slowly responding groundwater system. Even the ecologically more relevant average lowest groundwater level is projected to increase due to climate change. In contrast, the average lowest groundwater level in the adjacent areas, with a combined surface water and groundwater system, is projected to decline because of the fast response of the system: in winter the surface water system will immediately discharge excess precipitation from the area, and therefore there will be limited recharge of the groundwater system. In addition, the groundwater-dependent vegetation will cause an increase in evapotranspiration in summer, resulting in a significant decrease in groundwater levels.

Projected impacts of the redistribution scenarios vary depending on the hydrological relationship between the abstraction site and the related ecosystem. The projected hydrological impact of partial reduction of the abstractions LC and EL to the ecosystems of RB and FB is expected to be limited, especially compared to the impact of climate change. Partial redistribution of AM, however, is expected to clearly have an impact on NS.

Model

Due to the complexity of groundwater systems and limited data availability it is often difficult to assess the impacts of climate change on groundwater systems. However, for this study it was possible to use AZURE, an existing, detailed hydrological model, already calibrated using extensive observational data. Because of the use of these detailed historical data, the model is expected to remain reliable in terms of near-future projections (De Lange et al., 2014). On the other hand, the Veluwe area is considered a complex hydrological system, with steep hydraulic gradients, tilted clay layers and a thick unsaturated zone. Refinement of the model might improve the results, but is hard to accomplish (Verhagen et al., 2014, Wegehenkel, 2009). The results of the model approximate the measured groundwater levels relatively well (De Lange et al., 2014), although on average the simulated groundwater levels in the elevated areas are too low compared to the observed values, partially caused by the limited accuracy regarding the tilted clay layers. Nevertheless, the results of the model calculations are supported by expert knowledge of the hydrological characteristics of the system (Van Engelenburg et al., 2012, De Lange and Borren, 2014). Taking these uncertainties into account, it is still reasonable to assume that groundwater levels in the Veluwe area will increase due to climate change.

The groundwater level was used as indicator of the impact on related groundwater-dependent ecosystems, because of the uncertainties associated with direct and indirect effects caused by climate change. Climate change can potentially change the vegetation in response to increasing temperatures and shifts in precipitation (Kruijt et al., 2008). To which extent the vegetation will change also depends on soil moisture-climate interactions (Seneviratne et al., 2010). The projected increase of groundwater levels will influence the soil-water balance and could potentially change the vegetation. In case of increased rooting depth and/or a vegetation with higher transpiration rates, this could potentially result in lower groundwater levels. Due to this complexity of interactions of changes in temperature, precipitation and groundwater level, the dynamics of vegetation as a result of redistribution of groundwater abstractions is hard to predict and thus hard to model.

Besides that, large parts of the Veluwe are considered to be dry areas, covered with vegetation that does not depend on groundwater. The vegetation in these areas is unlikely to be affected by a decrease in groundwater level, although the vegetation in this dry centre area is likely to change due to increasing temperature and shifts in precipitation. For these reasons the groundwater level changes are considered to be a strong indicator for the impact of climate change and partial redistribution of abstractions on the Veluwe area.

Climate change scenarios

The projected general trend in climate change in the Netherlands is an increase in precipitation and evaporation compared to the current climate. Already over the last century precipitation has increased in the Netherlands, especially since 1980 (Buishand et al., 2013). The increase is probably caused by higher sea surface temperatures and changes in circulation, but could also be influenced by land use change and urbanisation (Daniëls, 2016). Global climate models especially indicate an increase in winter precipitation in the Netherlands related to the global mean temperature change; the projected change in mean summer precipitation is less conclusive (Lenderink et al., 2007). The model results indicate that the increases in winter precipitation are the main cause of the increased groundwater levels in the Veluwe area. As discussed above, most of the recent research on climate change in the Netherlands points in the same direction, i.e. an increase of winter precipitation. Therefore an increase in groundwater levels in the Veluwe area as a result of climate change is likely.

Redistribution

Relocation of a drinking water abstraction plant requires a large societal investment in the drinking water supply system and can take up to 10 years of preparation before becoming operational. Redistribution of drinking water abstraction volumes between existing sites is a less far-reaching measure, although this also requires considerable changes in the drinking water supply system. This study focusses on redistribution between existing sites. It is necessary to determine the necessity and impact before deciding on relocation or redistribution, and future developments such as climate change need to be taken into account. Based on the results of this study it can be concluded that at one location (AM) redistribution will have a strong positive impact on the related groundwater-dependent ecosystem (NS). Redistribution of LC and EL seems less urgent, because the impact of climate change largely exceeds the effect of a partial redistribution of the abstraction volumes. Recently, scenarios have been developed regarding future drinking water demand (Van der Aa et al., 2015b). These scenarios were not taken into account, because the aim of this study was to assess the impact of redistribution with regard to the hydrological characteristics of the area within the currently permitted amount of groundwater within the Veluwe area.

3.6 Conclusion

The goal of this study was to assess the projected hydrological impact of climate change in the Veluwe area around the middle of the 21st century and to compare this to the impact of redistribution of existing drinking water abstraction volumes in the Veluwe area by using a state-of-the-art hydrological model. Therefore detailed climate change scenarios were combined with a detailed hydrological model. The results show that the hydrological characteristics of an area determine the impact of climate change: increasing groundwater levels in a slowly responding large aquifer without surface water system, as opposed to decreasing groundwater levels in fast responding combined groundwater-surface water systems. The results emphasise that a thorough understanding of the complex hydro(geo)logical system of a glacial moraine is essential to assess the potential impact of climate change and local drinking water abstractions, preferably combined with the use of a state-of-the-art hydrological model. This is a valuable contribution to the scientific knowledge on the impact of climate change to groundwater resources.

After comparing the impact of climate change to the effect of redistribution of drinking water abstractions, it can be concluded that for one of the abstraction sites redistribution would have a strong positive impact even compared to the projected climate change impact. For the two other abstraction sites redistribution seems less urgent because the projected impact of climate change will exceed the impact of redistribution in the future.

However, not only hydrological facts and figures determine this necessity. Also stakeholder opinions need to be taken into account (Van den Brink et al., 2008), as well as environmental and socio-economic aspects, such as energy use and societal costs. A decision support method that combines the outcome of a hydrological study with the stakeholders’ viewpoints could help to decide on adaptation measures.

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4

Sustainability characteristics of drinking water supply

Abstract

Developments such as climate change and growing demand for drinking water threaten the sustainability of drinking water supply worldwide. To deal with this threat, adaptation of drinking water supply systems is imperative, not only on a global and national scale, but particularly on a local scale. This investigation sought to establish characteristics that describe the sustainability of local drinking water supply. We use an integrated systems approach, describing the local drinking water supply system in terms of hydrological, technical and socio-economic characteristics that determine the sustainability of a local drinking water supply system. Three cases on drinking water supply in the Netherlands are analysed. One case relates to a short-term development, that is the 2018 summer drought, and two concern long-term phenomena, that is, changes in water quality and growth in drinking water demand. The approach taken recognises that next to extreme weather events, socio-economic developments will be among the main drivers of changes in drinking water supply. Effects of pressures associated with, for example, population growth, industrial developments and land use changes, could result in limited water resource availability, deteriorated groundwater quality and growing water demand. To gain a perspective on the case study findings broader than the Dutch context, the sustainability issues identified were paired with global issues concerning sustainable drinking water supply. This resulted in a proposed set of generally applicable sustainability characteristics, each divided into five criteria describing the hydrological, technical and socio-economic sustainability of a local drinking water supply system. Elaboration of these sustainability characteristics and criteria into a sustainability assessment can provide information on the challenges and trade-offs inherent in the sustainable development and management of a local drinking water supply system.

4.1 Introduction

Climate change combined with a growing drinking water demand threatens the sustainability of drinking water supply worldwide. The goal set for drinking water supply in Sustainable Development Goal (SDG) 6.1 (UN, 2015) is “to achieve universal and equitable access to safe and affordable drinking water for all by 2030”. Reaching this goal is complicated by changing climate variability combined with socio-economic problems and developments. Worldwide drinking water supply crises are visible, resulting from a combination of limited water resource availability, lacking or failing drinking water infrastructure and/or increased drinking water demand, due to short-term events or long-term developments. Still, nearly 10 percent of the world population is fully deprived of improved drinking water resources (Ekins et al., 2019), and, additionally, existing drinking water supply systems often are under pressure. For instance, two recent examples of water crises were reported in Cape Town, South Africa and São Paolo, Brasil. In Cape Town, Sorensen (2017) found that at the end of each summer water use is restricted, pending the winter rains to set in. In São Paolo, drinking water supplies are at a historic low, and on a daily base water pressures are lowered to reduce the water use, which especially affects the poor (Cohen, 2016). To deal with such challenges and threats to safe and affordable drinking water, adaptation of the current drinking water supply system is imperative, not only on a global and national level, but also on a local scale.

Typically, the spatial or temporal scale determines whether drinking water supply is considered sustainable, given the set goals. In the Netherlands, for instance, the national drinking water supply currently meets the indicator from SDG 6 (UN, 2018) on safely managed drinking water services and safely treated waste water. At the same time the more specific goals on (local) water quantity, quality, and ecology as set by the European Water Framework Directive (WFD), are not met yet (European Environment Agency, 2018). Consequently, there still are sustainability issues for drinking water supply in the Netherlands, for instance due to water shortage (Ministry of Infrastructure and Environment and Ministry of Economic Affairs and Climate Policy, 2019), impact on water-related ecosystems (Van Engelenburg et al., 2017) or water pollution (Kools et al., 2019, Van den Brink and Wuijts, 2016). Additionally, future developments such as the uncertain drinking water demand growth rate (Van der Aa et al., 2015b) and the changing climate variability (Teuling, 2018), may put the sustainability of the Dutch drinking water supply under pressure in the future.

The interaction with its local environment affects the sustainability of local drinking water supply. The abstraction of groundwater or surface water from the hydrological system, and subsequent treatment to drinking water quality before being distributed to customers, requires a local infrastructure (typically a drinking water production facility, embedded in a distribution network of pipelines). Although the daily routine of drinking water supply has a highly technical character (Bauer and Herder, 2009), the sustainability in the long-term depends on the balance between technical, socio-economic and environmental factors. This balance is especially complex for local drinking water supply, which is intertwined with the local hydrological system and local stakeholders through its geographical location. Local hydrology for instance determines the physical vulnerability to pollution from e.g. land use, and to reduced water resource availability during drought. It also determines the impact of the abstraction to groundwater levels, and to land use and local stakeholders, and thus affects the sustainability of local drinking water supply.

Because of the interconnections between physical, technical, and socio-economic factors as well as across space, organisational levels and time, adaptation of the local drinking water supply to current and future sustainability challenges calls for an integrated planning approach (Liu et al., 2015b). Integrated models have been developed to understand the complex interactions between the physical, technical and socio-economic components in various water systems (Loucks et al., 2017). Systems integration, considering all system characteristics, will help to identify the sustainability challenges in a system (Liu et al., 2015b). However, a systems analysis to assess local drinking water supply and to identify sustainability challenges on a local scale has not yet been developed.

This chapter aims to propose a set of sustainability characteristics that describe the drinking water supply system on a local scale. To reach this aim, cases on drinking water supply are analysed using a conceptual framework. The selected cases represent a short-term event and long-term developments that affect water quality and water resource availability, the technical drinking water supply infrastructure and/or the drinking water demand. The system boundaries are set to drinking water supply on the local scale. While the drinking water supply on a local scale is also affected by outside influences from different organisational and spatial scales, the analysis accounts for these external influences too.

4.2 Method

The adopted approach consists of four steps. The first step is the analysis of three drinking water practice cases, aiming to identify the sustainability issues in these cases. In step 2 these issues are categorised, and used to propose a set of characteristics that describe the sustainability of the local drinking water supply system. In step 3 the sustainability issues from the case studies are cross-checked with global drinking water supply issues, which in step 4 leads to a set of criteria that describe the sustainability characteristics of the local drinking water supply system. The research method outline is presented in Fig. 4.1.

Three Dutch cases were selected based on their potential to negatively affect the sustainability of drinking water supply. The aim was to identify sustainability issues in a short-term event such as extreme summer drought or other disturbances, and the issues resulting from long-term ongoing developments on water quality, water resource availability, or drinking water demand. Because the first author of this article is employed at a drinking water supplier (Vitens, the Netherlands), this provided the researchers with in-depth knowledge of current practice in the Netherlands, obtained through professional involvement in internal and external discussions and meetings on the topics of the cases. The results of the case studies were cross-checked with internal colleagues within Vitens, and combined with Dutch governmental reports on these events and developments (e.g. Ministry of Infrastructure and Environment and Ministry of Economic Affairs and Climate Policy (2019), Vitens (2016)). In Section 4.3 the cases are described, and illustrated with Vitens data, summarising the sustainability issues resulting from the case studies.

The sustainability issues as identified in the cases are subdivided into hydrological, technical and socio-economic issues. To cross-check and broaden the perspective from the drinking water supply in the Netherlands to a more general perspective, these issues are related to the targets set for Sustainable Development Goal 6 (see App. V), and reports on the global situation on drinking water supply (UNICEF and WHO, 2015, WHO and UNICEF, 2017, UN, 2018). This results in a proposal for sustainability characteristics and criteria of local drinking water supply systems that can be applied in various contexts (Section 4.4).

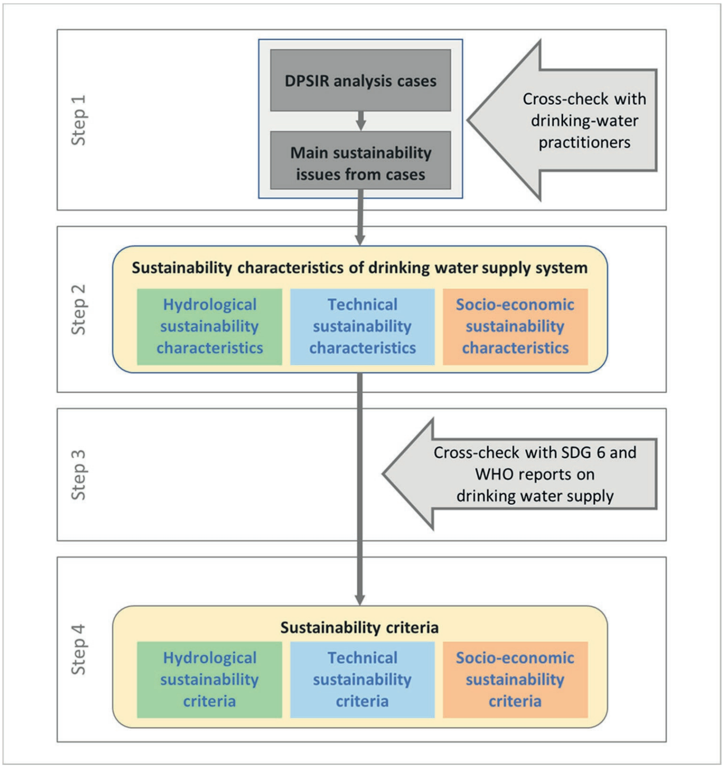

Figure 4.1 *Outline research method.*

4.2.1 An integrated systems approach to sustainable drinking water supply

This study focuses on drinking water supply systems on a local scale, in short, local drinking water supply systems. The boundaries of these systems are set by the area in which drinking water abstraction is embedded. Local drinking water supply systems are linked to the hydrological system through abstraction, which occurs through the drinking water supply infrastructure. The socio-economic environment is linked to abstraction through that same drinking water supply infrastructure, which is employed to convey drinking water to consumers, and through the hydrological system that connects various forms of land and water use and local stakeholders to the abstraction.

A systems analysis of this local drinking water supply system with the focus on sustainability must integrate the complex interactions between the hydrological system, the technical infrastructure, and the socio-economic system. Sustainable water systems can be defined as water systems that are designed and managed to contribute to the current and future objectives of society, maintaining their ecological, environmental, and hydrological integrity (Loucks, 2000). Drinking water supply can be looked at from a socio-ecological perspective as well as from a socio-technical perspective. Socio-ecological systems research considers the interaction between a resource dependent society and nature, to enlarge the ability to adapt to future developments such as climate change and other stresses (Pant et al., 2015). The socio-technical systems approach focusses on the interactions between science and society, in order to effectively move towards more sustainable technologies and behaviour as a response to the impact of socio-economic developments (Pant et al., 2015). As the drinking water supply uses local water resources it is strongly embedded in the local hydrological system, which calls for a socio-ecological approach. Because technology is central but also strongly connected to the public values and their societal relevance, drinking water supply systems can also be considered socio-technical systems (Bauer and Herder, 2009).

The socio-ecological approach observes relations between the socio-economic and environmental system, whereas the socio-technical approach observes the socio-economic and technical system. In this study we combine both approaches by describing the local drinking water supply system in terms of hydrological, technical and socio-economic characteristics that determine the sustainability of a local drinking water supply system.

4.2.2 Case analysis method

The use of a conceptual framework for a consistent analysis of water management cases is a common method to study water management cases. For instance Smith (2009) used a conceptual framework to review cases that improved the sustainability of water management, while Allan et al. (2013) used a conceptualisation to describe the transition from conventional towards adaptive water governance and management. Here, DPSIR (Eurostat, 1999) is used for the analysis of the three selected drinking water supply cases to obtain an overview of the impact (I) of drivers (D), pressures (P) and responses (R) to the state of the drinking water supply system (S) (Fig. 4.2). DPSIR was originally developed to describe causal relations between human actions and the environment. It has also frequently been used for relations and interactions between technical infrastructure and the socio-economic and physical domain (Pahl-Wostl, 2015, Hellegers and Leflaive, 2015, Binder et al., 2013). *Drivers* describe future developments such as climate change and population growth. *Pressures* are developments (in emissions or environmental resources) as a result from the drivers. The *state* describes the system state that results from the pressures. In this research the aim is to describe the system state of the drinking water supply system in terms of local hydrological, technical and socio-economic sustainability characteristics (see Section 4.2.1). The changes in system state cause *impacts* to system functions, which will lead to societal *responses*. Although the framework has been applied on different spatial scales, Carr et al. (2009) recommend using the framework place-specific, to ensure that local stakeholder perspectives are assessed as well. With the research focus at the local drinking water supply system, these local perspectives are implicitly included. The drivers, pressures and responses can be on local as well as higher organisational and/or spatial scales, thus ensuring that - where essential - relevant higher scales are accounted for too.

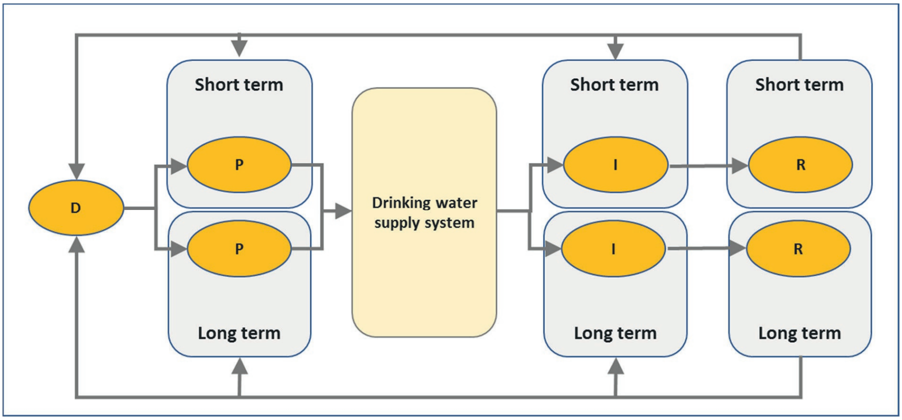

Figure 4.2 *Analysis of the local drinking water supply system, using DPSIR, considering short-term and long-term pressures (P), responses (R) and impact (I), to identify the sustainability issues affecting the state of the system.*

The impact of developments on different temporal scales to the drinking water supply system must be taken into account as well. The long lived, interdependent drinking water supply infrastructure is rigid to change due to design decisions in the past, which is causing path-dependencies and lock-ins (Melese et al., 2015). In addition, consumer behaviour, governance and engineering, and the interaction between these processes cause lock-in situations that limit the ability to change towards more sustainable water resources management (Pahl-

Wostl, 2002). For this reason the case analysis is performed considering both short- and long-term pressures, impacts and responses (Fig. 4.2).

4.2.3 Case selection

Sustainability challenges faced by drinking water supply worldwide are (1) how to respond to short-term events such as extreme drought or other disturbances, and (2) how to adapt to long-term developments that limit the water resource availability, or cause a strong drinking water demand growth. The challenges for drinking water supply in the Netherlands are in nature comparable to these global challenges. Drinking water supply in the Netherlands is of a high standard compared to many other countries. The SDG 6 targets on safe and affordable drinking water (SDG 6.1/6.2) and sanitation and waste water treatment (SDG 6.3) are basically met. But the Dutch government and drinking water suppliers are also challenged to achieve the other goals set in SDG 6, such as improvement of water quality (SDG 6.3), increase of water-use efficiency (SDG 6.4), integrated water resources management (SDG 6.5), protection and restoration of water-related ecosystems (SDG 6.6), and the more specific standards on water quantity, quality, and ecology as set by the European Water Framework Directive (WFD) (European Environment Agency, 2018).

For the first step of this research three drinking water supply cases in the Netherlands have been selected. Case studies using DPSIR were performed to find sustainability issues caused by the identified pressures and short- and/or long-term responses in each case. The cases focus on short-term as well as long-term developments, because short-term shocks have different impacts and call for other responses than long-term stresses (Smith and Stirling, 2010). The first case “2018 Summer drought” deals with the impact of an extreme drought period in the summer of 2018 in the Netherlands, not only affecting drinking water demand and availability, but also limiting water resources for other uses than drinking water, as well as water-related ecosystems (Ministry of Infrastructure and Environment and Ministry of Economic Affairs and Climate Policy, 2019). Cases 2 and 3 deal with long-term developments in the Netherlands on groundwater quality (Kools et al., 2019), and drinking water demand (Baggelaar and Geudens, 2017, Van der Aa et al., 2015b), respectively. All three cases relate to SDG 6 (UN, 2015).

4.3 Case studies

In this section the three cases on drinking water supply are introduced, and the identified impacts, responses and sustainability issues are summarised (research step 1). The complete results of the case studies are presented in App. IV.

4.3.1 Case 1 - "2018 Summer drought"

Summer 2018 in the Netherlands was extremely warm and dry, causing water shortages in the water system, and a long period of extreme daily drinking water demand, resulting in a record monthly water demand in July 2018 (see Illustration case 1). The driver in this case is the extreme weather condition, which caused several pressures, such as high temperatures, high evaporation and lack of precipitation. These pressures did not only cause drought damage to nature, agriculture and gardens and parks, as well as limited water availability in the surface water and groundwater systems, they also resulted in an extremely high drinking water demand (Ministry of Infrastructure and Environment and Ministry of Economic Affairs and Climate Policy, 2019). The extreme drinking water demand during summer 2018 put the drinking water supply system under high pressure, resulting in daily and monthly drinking water supply volumes that exceeded all previously supplied volumes (see Illustration case 1). The capacity of the system was fully exploited, but faced limitations in abstraction, treatment and distribution capacity. The high drinking water abstraction volumes added up to the water shortages in both the groundwater and the surface water system caused by the lack of precipitation and high evaporation during the summer. To ensure an acceptable surface water quality for the drinking water supply, measures were taken to limit or reduce salinization.

To reduce the drinking water use, a call for drinking water saving was made, and locally pressures in the drinking water distribution system were intentionally lowered to reduce the delivered drinking water volumes. The problems caused by the summer drought raised a discourse on (drinking) water use and saving, including discussions on controversial measures such as progressive drinking water tariffs, with tariffs dependent on the consumed drinking water volume, and differentiation between high-grade and low-grade use of (drinking) water. Table 4.1 summarises the impacts, responses and sustainability issues of this case.

Illustration case 1: 2018 Summer drought

Within the Vitens supply area the average daily supply volume during the summer period June-August over the years 2012-2017 was approximately 965,000 m^3/day. During the period 27 June-4 August 2018 the daily supply volume exceeded this average summer volume with approximately 28%, with an average volume of nearly 1,240,000 m^3/day (Fig. 4.3a). On 25 July 2019 the maximum daily water supply reached nearly 1,390,000 m^3/day, which was 42% above the baseline daily supply (Fig. 4.3a). The monthly drinking water supply volume in July 2018 of 38 million m^3/month was an increase of 18% compared to the previous maximum monthly supply volumes (Fig. 4.3b). Although the drinking water supply infrastructure was designed with an overcapacity to meet the regular demand peaks, the flexibility to more extreme peaks, or to long periods of peak demand is limited.

Figure 4.3 *Daily (a) and monthly (b) drinking water supply volume by Dutch drinking water supplier Vitens during summer 2017 (average), 2018 (extreme), 2019 (high).*

Table 4.1 *Summary of impact, short-term and long-term response and sustainability issues in case 1 "2018 summer drought" (for complete results of the case study see App. IV).*

Impact	**Short-term response**	**Long-term response**	**Sustainability issues**
Extreme drinking water use, high drinking water demand.	Drinking water suppliers increased abstraction volume.	Development of water saving strategies.	Drinking water use, drinking water demand, drinking water suppliers, abstraction volumes, water saving.
Drought, falling water discharges and groundwater levels, damage to groundwater-dependent ecosystems and agriculture.	Water use limitations, water authorities applied existing drought water policy, risk for water quality.	Development of additional water shortage policy for water management and water governance.	Drought, water discharge, groundwater levels, groundwater-dependent ecosystems, agriculture, water use, water authorities, water policy, water management, water governance, water availability.
Customers worried about drinking water availability.	Drinking water suppliers called upon customers for drinking water saving.	Societal support for drinking water saving strategies.	Customers, drinking water availability, drinking water suppliers, water saving.
Declining surface water discharge and quality.	Drinking water suppliers took measures to safeguard raw water quality.	Development of additional policies on water quality protection.	Surface water discharge, surface water quality, drinking water suppliers, raw water quality, water management policies, water use.
Groundwater quality deterioration.	No response possible due to lack of water.	Development of additional policies on water quality protection.	Groundwater quality, surface water quality, water shortage, surface water discharge, water management policies.
Drinking water quality at risk due to rising water temperature in pipelines.	Sufficient refreshment due to high demand.	Changing the design standard of distribution pipelines to limit risk of temperature rise.	Drinking water quality, treatment method, distribution infrastructure.
Increasing abstraction volume, resulting in increasing impact on land use.	Stakeholder complaints by agriculture and nature.	Increased societal pressure on reduction of impact of drinking water abstraction.	Drinking water demand, abstraction volume, impact of abstraction, land use, stakeholders, agriculture, nature, drinking water suppliers.
Exceedance of abstraction permits, limiting the resilience of the technical infrastructure.	Enforcement procedures by legal authorities.	Extension of drinking water abstraction permits and water saving strategies.	Drinking water demand, abstraction volume, abstraction capacity, abstraction permit, resilience of abstraction, legal authorities, water regulations, water legislation, drinking water saving.
Shortage of drinking water during peak demand due to insufficient resilience of treatment infrastructure.	Reduced drinking water supply volume.	Adjustment of resilience and reliability of treatment infrastructure.	Treatment volume, treatment capacity, drinking water shortage, reliability of the treatment, resilience of the treatment, drinking water standards, drinking water demand, drinking water suppliers.

Impact	Short-term response	Long-term response	Sustainability issues
Insufficient distribution capacity.	Lowering drinking water pressure to reduce drinking water volume.	Adjustment of resilience and reliability of distribution infrastructure.	Distribution capacity, resilience and reliability of distribution, drinking water suppliers, drinking water volume, drinking water standards.
Major disturbances could cause a serious disruption of the supply.	Maximum personnel deployment by drinking water suppliers.	Investments to improve resilience and reliability of technical infrastructure by drinking water suppliers.	Drinking water demand, reliability of technical infrastructure, drinking water suppliers.
High energy use and environmental impact of extreme drinking water production.	-	Incorporating impact on energy use and environmental impact in design of measures to improve resilience and reliability of technical infrastructure.	Drinking water demand, energy use, environmental impact, drinking water suppliers.

4.3.2 Case 2 - “Groundwater quality development”

In the Netherlands 55% of the drinking water supply is provided by groundwater resources (Baggelaar and Geudens, 2017). Analysis of the state of the drinking water resources in the Netherlands in 2014 points out that, although the drinking water quality meets the Dutch legal standards, all water resources are under threat by known and new pollutants (Kools et al., 2019). Long-term analysis of water quality records of Dutch drinking water supply fields shows that the vulnerability of groundwater resources to external influences such as land use strongly depends on hydrochemical characteristics (Mendizabal et al., 2012). Monitoring results show that currently groundwater quality is mainly under pressure due to nitrate, pesticides, historical contamination and salinization (Kools et al., 2019). Nearly half of the groundwater abstractions for drinking water are affected, and it is expected that in the future the groundwater quality at more abstractions will exceed the groundwater standards set in the European Water Framework Directive (European Union, 2000). In addition, traces of pollutants such as recent industrial contaminants, medicine residues and other emerging substances are found, indicating that the groundwater quality will likely further deteriorate (Kools et al., 2019).

Illustration case 2: Groundwater quality development

In the 1980's the Dutch government installed regulations to protect water quality by limiting the growing nitrate and phosphate surplus due to overuse of livestock manure. This resulted in a decrease of the nitrate surplus from 1985 on. However, due to the long travel times in groundwater it took years before the impact of these regulations became visible in the groundwater quality. Fig. 4.4 illustrates the period of time in which the nitrate concentration in an abstraction well still increased despite the 1985 regulations on reduction of the nitrate surplus at surface level: the nitrate concentration in this well has increased until 2005 before the nitrate level started to decrease. Only since 2014 the concentration has dropped below the nitrate standard for groundwater of 50 mg/L.

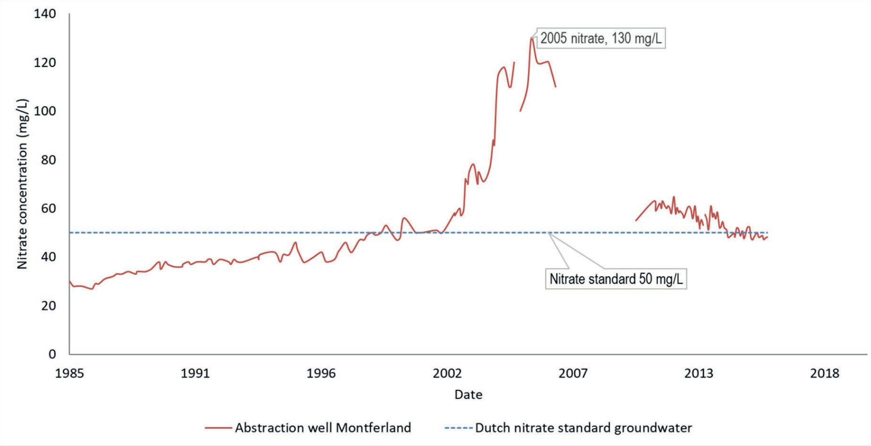

***Figure 4.4** Development of nitrate in an abstraction well in Montferland (HEE-P07-07.0, coordinates X213.540-Y434.761) in the province of Gelderland, the Netherlands (data source Vitens) compared to the Dutch standard for nitrate concentration in groundwater (50 mg/L).*

Groundwater protection regulations regarding land and water use by legal authorities will help to slow down groundwater deterioration (Van den Brink and Wuijts, 2016). However, strategies to restore groundwater quality often will not be effective in the short term, because already existing contaminations may remain present for a long period of time, depending on the local hydrological characteristics (Jørgensen and Stockmarr, 2009) (see Illustration case 2). The impact of contamination cannot be undone, unless soil processes help to (partially) break down contaminants. Thorough monitoring for pollution therefore is essential to follow groundwater quality trends and to respond adequately to these trends (Janža, 2015). Due to the expected deterioration of the raw water quality, different and more complex treatment methods are necessary to continuously meet the drinking water standards (Kools et al., 2019). In general a more complex treatment method leads to higher energy use, use of additional excipients, water loss and production of waste materials, which will lead to a higher water tariff, and to a higher environmental impact (Napoli and Garcia-Tellez, 2016). Table 4.2 summarises the impacts, responses and sustainability issues of this case.

Table 4.2 *Summary of impact, short-term and long-term response and sustainability issues in case 2, "Groundwater quality development" (for complete results of the case study see App. IV).*

Impact	**Short-term response**	**Long-term response**	**Sustainability issues**
Surface water quality deteriorates due to limited surface water discharge.	Monitoring and evaluation of water quality development.	Water legislation on water quality and quantity protection, drinking water savings strategies.	Surface water quality, surface water discharge, monitoring and evaluation, water legislation, water quality and quantity, drinking water saving.
Groundwater quality deteriorates due to deteriorating surface water quality.	Monitoring and evaluation of water quality development.	Improvement of sewage and waste water treatment, and water saving strategies.	Groundwater quality, surface water quality, monitoring and evaluation, water saving.
Soil energy systems may affect groundwater quality.	Monitoring and evaluation of water quality development, research.	Groundwater protection regulations.	Groundwater quality, groundwater pollution, research, monitoring and evaluation, regulations, groundwater quality protection.
Local and upstream land and water use affects the surface water quality.	Monitoring and evaluation of water quality development.	Policy and measures to meet water legislation to protect and improve water quality and quantity.	Surface water quality, land and water use, contaminants, monitoring and evaluation, water legislation, water quantity.
Diffuse and point sources of pollution affect surface water and groundwater quality.	Monitoring and evaluation of water quality development.	Measures to remove historical sources of pollution and to prevent new sources of pollution.	Groundwater quality, nutrients, organic micro-pollutants, other contaminants, surface water quality, monitoring and evaluation, water legislation, water quality protection.
Emerging contaminants in surface and groundwater require new drinking water treatment methods.	Enforcement of groundwater protection regulations on pollution incidents and monitoring and evaluation.	Development of treatment methods to remove emerging contaminants from sewage, industrial waste water and/or drinking water.	Emerging contaminants, groundwater quality, surface water quality, resilience and reliability of the drinking water treatment, groundwater protection, land and water use, water legislation, sources of pollution, drinking water treatment methods, energy use, environmental impact, drinking water tariff.

Impact	Short-term response	Long-term response	Sustainability issues
Land use (change) may cause groundwater quality deterioration.	Enforcement of groundwater protection regulations on land use change and monitoring and evaluation.	Combination of extensive land use functions with drinking water abstraction.	Land use change, groundwater quality, sources of pollution, groundwater protection regulations, water use, enforcement of regulations, monitoring and evaluation, drinking water abstraction, extensive land use, nature, agriculture, water system.
Surface water and groundwater quality deterioration determine the required drinking water treatment.	Monitoring of drinking water quality, in case of emergencies measures are taken to safeguard the drinking water quality.	Adjustment of treatment methods to be able to continue to meet the drinking water standards.	Raw water quality, drinking water standards, water quality, vulnerability of the water system for contamination, treatment methods, reliability and resilience of treatment, drinking water quality, emergencies, energy use, environmental impact, drinking water tariffs.
Variations in raw water quality can only be handled if treatment method is resilient to these variations.	Monitoring and evaluation of water quality development.	Increase of resilience and reliability of drinking water treatment.	Surface water quality, groundwater quality, resilience and reliability of the treatment, monitoring and evaluation, raw water quality, energy use, environmental impact, drinking water tariffs.

4.3.3 Case 3 - “Drinking water demand growth”

Due to drinking water saving strategies the drinking water use in the Netherlands per person has decreased from 137 litre per person per day in 1992 to 119 litre per person per day in 2016 (Van Thiel, 2017). This development resulted in a decreasing total yearly drinking water demand volume in that same period, despite the population growth in the Netherlands (Baggelaar and Geudens, 2017). However, 2013 was a turning point, when the total yearly drinking water demand volume in the Netherlands started to grow again (Baggelaar and Geudens, 2017). The trend in the period 2013–2019 shows a strong increase in drinking water demand (see Illustration case 3). Delta scenarios have been developed for the Netherlands, projecting a drinking water demand development varying between a decrease of 10% to an increase of 35% in 2050 compared to 2015 (Wolters et al., 2018).

The drinking water demand growth rate of the period 2013–2019 as is seen within the Vitens supply area compares to the growth rate in the maximum delta scenario of 35% growth from 2015 to 2050 (see Illustration case 3). If this strong growth rate continues, this will put serious pressure on the drinking water supply. This will partially be due to limitations in the technical infrastructure, but also partially due to limitations in the water resource availability, caused by insufficient abstraction permits, or a possibly negative impact on the hydrological system and stakeholders.

Illustration case 3: Drinking water demand growth

The increase in normalised drinking water supply volume as supplied by Vitens between 2015 and 2019 is 4.5% (Fig. 4.5). Due to this recent demand growth the reserve capacity within the existing drinking water supply infrastructure is already limited. The drinking water demand growth rate of the period 2015–2019 compares to the growth rate in the maximum delta scenario of 35% growth from 2015 to 2050 (Fig. 4.5). If this growth rate is not tempered through a significant reduction of the drinking water use, this would require a large extension of the drinking water supply infrastructure.

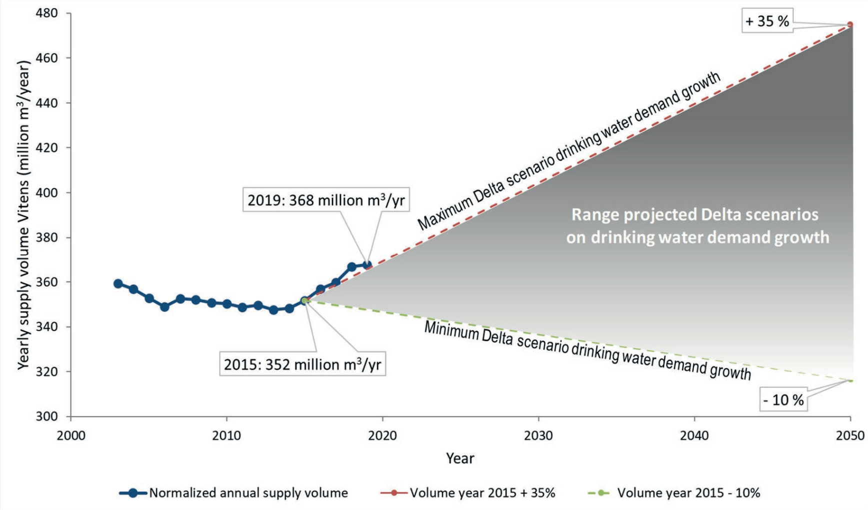

Figure 4.5 *Development of the normalised annual drinking water volume supplied by Vitens (drinking water supplier), the Netherlands 2003–2019, compared to the projected Delta scenarios on drinking water demand growth (Wolters et al., 2018), ranging between a decrease of 10% to an increase of 35% in 2050 compared to 2015. The normalised annual drinking water supply volume excludes the impact of extreme weather conditions on the actual supplied annual volumes of drinking water.*

Given the inflexibility of drinking water supply infrastructure to change, an integrated strategy is necessary to meet this uncertain development of the drinking water demand. To find sustainable solutions for the future not only the technical infrastructure issues must be solved. It also requires strategies on water saving, expansion of permits, development of new abstraction concepts using other water resources, as well as stakeholder processes in the design and use of the local drinking water supply system. This case is basically an extension to the first two cases: the growing water demand amplifies the issues caused by the drought in 2018 and the groundwater quality development. Table 4.3 therefore only summarises the additional sustainability issues with respect to the first two cases.

Table 4.3 *Summary of impact, short-term and long-term response and sustainability issues in case 3, "Drinking water demand growth" (for complete results of the case study see App. IV).*

Impact	**Short-term response**	**Long-term response**	**Sustainability issues**
A limited water resource availability will affect the drinking water availability.	See Table 4.1.	See Table 4.1.	Water resource availability, drinking water availability, resilience of drinking water supply, drinking water demand, water legislation.
A water quality deterioration affects the resilience and reliability of the drinking water treatment.	See Table 4.2.	See Table 4.2.	Water quality, drinking water treatment, reliability of treatment, drinking water standards.
A growing drinking water demand will put the reliability and resilience of the technical infrastructure under pressure.	See Table 4.1.	Drinking water suppliers must adapt the technical infrastructure to the growing water demand. Water saving strategies may reduce the growth rate, which will limit the required extension of the technical infrastructure.	Drinking water demand, reliability of technical infrastructure, drinking water suppliers, drinking water availability, treatment, energy use, environmental impact, drinking water tariff.
A declining drinking water demand may also put the resilience of the technical infrastructure under pressure.	Research on potential risks of a decline in drinking water demand.	Adaptation strategies that increase the resilience of the infrastructure to growth as well as a decline of the drinking water demand.	Drinking water demand, reliability and resilience of technical infrastructure.

4.4 Sustainability characteristics of drinking water supply

The first research step (see Fig. 4.1) resulted in a summary of the sustainability issues for the local drinking water supply system found in the selected cases. In this section the results from research step 1 are combined with the results from research steps 2 to 4 (see Fig. 4.1). In step 2 the sustainability issues from the case studies are categorised into nine hydrological, technical and socio-economic sustainability characteristics. In research step 3, these issues were cross-checked with the targets and indicators in Sustainable Development Goal 6 (further referred to as "SDG 6", see App. V) (UN, 2015) and the 2017 update of the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (further referred to as "JMP") (WHO and UNICEF, 2017). In the final step of the study each sustainability characteristic is elaborated further into five sustainability criteria.

4.4.1 Hydrological sustainability characteristics

Three hydrological sustainability characteristics are proposed that summarise the hydrological issues affecting the drinking water supply as found in the case studies: *water quality*, *water resource availability* and *impact of drinking water abstraction*. Table 4.4 provides a summary of the results of the subsequent research steps (see Fig. 4.1).

Water quality includes the monitoring and evaluation of current water quality, and the trends and expected future development of the water quality and emerging contaminants, as described in the case "Groundwater quality development". In the JMP additionally the importance of microbial aspects as a global water quality issue with a health impact is monitored, such as bacteriological contamination due to untreated waste water or emergencies (WHO and UNICEF, 2017). The JMP also monitors water quality aspects without health impact, such as salinization, water hardness, and colour, which affect the acceptability of the drinking water (WHO and UNICEF, 2017).

Water resource availability for drinking water supply can be differentiated into surface water and groundwater availability, as illustrated in Case 1 "2018 Summer drought". Other sustainability issues are the vulnerability of the surface and/or groundwater system to the water quality being affected permanently by land use, as illustrated in the case "Groundwater quality development". These issues are also relevant when considering a shift to other resources, for instance from groundwater resources to surface water resources for drinking water supply. The water resource availability can also be limited due to small- or large-scale emergencies caused by natural hazards, such as droughts, floods, earth quakes or forest fires (WHO and UNICEF, 2017), that will put the sustainability of the local drinking water supply under pressure.

The *impact of the drinking water abstraction* to the hydrological system entails the impact on both the surface water system and the groundwater system, but also the balance between the annual drinking water abstraction volume and the annual recharge of the (local) water system. Whether the impact of the abstraction is or can possibly by compensated hydrologically is another sustainability issue. The spatial impact of the local drinking water abstraction facility may also be a sustainability issue: a drinking water facility requires a certain water storage area or reservoir, which might have a significant spatial impact in the area and thus might affect local stakeholders.

Table 4.4 *Summary of proposed hydrological sustainability characteristics, hydrological issues from case studies (see Tables 4.1-4.3), relevant SDG[1] indicators and JMP[2] issues, and hydrological sustainability criteria.*

Hydrological sustainability characteristics	**Water quality**	**Water resource availability**	**Impact of drinking water abstraction**
Sustainability issues from case studies	Monitoring and evaluation Sources of pollution Contaminants Emerging contaminants Groundwater quality Surface water quality Raw water quality	Other water resources Surface water quantity Groundwater quantity Vulnerability of the water system Drought impact Water discharge	Impact of abstraction Groundwater levels Abstraction volume Balance between annual recharge and annual abstraction Hydrological compensation
SDG 6 targets[1]	6.3, 6.5	6.4, 6.5	6.4, 6.6
JMP[2]	Health risks from microbial contamination Acceptability of the drinking water (salinization, hardness, colour)	Small- or large-scale emergencies caused by natural hazards, such as droughts, floods, earth quakes or forest fire	-
Sustainability criteria	Current raw water quality Chemical aspects of water quality Microbial aspects of water quality Acceptability aspects of water quality Monitoring and evaluation of water quality trends	Surface water quantity Groundwater quantity Other available water resources Vulnerability water system water for contamination Natural hazards and emergencies risk	Impact on surface water system Impact on groundwater system Balance between annual recharge and abstraction Hydrological compensation Spatial impact of abstraction facility/ storage/reservoir

[1] SDG = Sustainable Development Goal; see App. V for summary of Sustainable Development Goal 6 targets and indicators related to sustainability characteristics (UN, 2015)

[2] JMP = 2017 update of the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene(WHO and UNICEF, 2017)

4.4.2 Technical sustainability characteristics

Three technical sustainability characteristics are proposed that summarise the technical issues for the drinking water supply as found in the case studies: *reliability* and *resilience of the technical infrastructure* and *energy use and environmental impact* of the drinking water supply. Table 4.5 provides a summary of the results of the subsequent research steps (see Fig. 4.1).

The *reliability* of the supply system is defined in this research as “the (un)likeliness of the technical system to fail” (Hashimoto et al., 1982). The current technical state of the drinking water production facility and the distribution infrastructure, and the complexity of the water treatment are important technical sustainability criteria for the local drinking water supply system. Other technical criteria that should be considered are the supply continuity of the facility, which stands for the capability to achieve the set legal standards for drinking water supply under all circumstances, and the operational reliability, to solve technical failures without disturbance of the drinking water supply.

In this research the *resilience* of the drinking water supply system is defined as “the possibility to respond to short- and long-term changes in water demand or water quality” (Hashimoto et al., 1982). Climate change and other developments in water demand and quality call for the use of more resilient technologies and processes, and may require upgrades of water treatment and storage capacity (WHO and UNICEF, 2017). The cases “2018 Summer drought” as well as “Drinking water demand growth” emphasise the importance of the available abstraction permits, and treatment and distribution capacity compared to the annual and peak water demand respectively for the resilience of the local drinking water supply system. Furthermore, the flexibility of the treatment method determines whether a drinking water supply system can deal with variation in, or deterioration of water quality and emerging contaminants, the sustainability issues found in the case “Groundwater quality development”.

Energy use and environmental impact includes the sustainability issues from the cases “Groundwater quality development” and “Drinking water demand growth”: the energy use of abstraction, treatment and distribution, and the environmental impact of additional excipients, waste water and other waste products of the treatment. Especially when the raw water quality deteriorates, the required water treatment methods become more complex. In general, this leads to large investments, as well as an increasing energy use and environmental impact, e.g. when advanced membrane filtration methods are required. Additional global sustainability issues are the reliability of the energy supply, and the renewability of the energy that is used (WHO, 2017).

Table 4.5 *Summary of proposed technical sustainability characteristics, technical issues from case studies (see Tables 4.1-4.3), relevant SDG[1] indicators and JMP[2] issues, and technical sustainability criteria.*

Technical sustainability characteristics	**Reliability of technical infrastructure**	**Resilience of technical infrastructure**	**Energy use and environmental impact**
Sustainability issues from case studies	Drinking water pressure Drinking water treatment Reliability of abstraction, treatment and distribution infrastructure	Abstraction capacity Treatment capacity Treatment methods Distribution capacity Resilience of technical infrastructure	Energy use Environmental impact Additional excipients Waste water Waste materials
SDG 6 targets[1]	6.1, 6.4	6.1, 6.4	6.4
JMP[2]	Safely managed drinking water services, i.e. improved drinking water source on premises, available when needed and free from contamination	Resilient technologies and processes Upgrades of water treatment and storage capacity	Reliability of the energy supply Renewability of the energy
Sustainability criteria	Technical state abstraction and treatment facility Technical state distribution infrastructure Effectivity and complexity of water treatment Supply continuity for customers Operational reliability	Abstraction permit compared to annual drinking water demand Production capacity compared to peak demand Flexibility of treatment method Technical innovations to improve resilience Technical investments to improve resilience	Energy use of abstraction and treatment Energy use of distribution Environmental impact (additional excipients, waste water, waste materials) Reliability energy supply Use of renewable energy

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[1] SDG = Sustainable Development Goal; see App. V for summary of Sustainable Development Goal 6 targets and indicators related to sustainability characteristics (UN, 2015)

[2] JMP = 2017 update of the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene(WHO and UNICEF, 2017)

4.4.3 Socio-economic sustainability characteristics

Three socio-economic sustainability characteristics are proposed that summarise the socio-economic issues affecting the drinking water supply as found in the case studies: *drinking* *water availability, water governance*, and *land and water use*. Table 4.6 provides a summary of the results of the subsequent research steps (see Fig. 4.1).

***Table 4.6** Summary of proposed socio-economic sustainability characteristics, socio-economic issues from case studies (see Tables 4.1-4.3), relevant SDG[1] indicators and JMP[2] issues, and socio-economic sustainability criteria.*

Socio-economic sustainability characteristics	**Drinking water availability**	**Water governance**	**Land and water use**
Sustainability issues from case studies	Customers Drinking water availability Drinking water demand Drinking water tariff Drinking water quality Drinking water volume Drinking water shortage Emergencies, disturbances Water saving	Abstraction permits Drinking water standards Water authorities Water legislation, policy and regulations Drinking water suppliers Compliance Stakeholders	Water use Land use Agriculture Nature, groundwater-dependent ecosystems Financial compensation Spatial impact
SDG 6 targets[1]	6.1	6.3, 6.4, 6.5, 6.6, 6.a, 6.b	6.3, 6.4
JMP[2]	Water safety plan	Small- or large-scale emergencies for the drinking water supply caused by human activities or conflicts	-
Sustainability criteria	Percentage connected households Drinking water quality Drinking water tariff Water saving strategy Water safety plan	Availability of (drinking) water legislation and policies Compliance of drinking water supplier Decision-making process by (local) authorities Local stakeholder interests Emergency risk caused by human activities or conflicts	Land use (including subsurface use) Water use for other purposes than drinking water Regulations on land and water use Limitations to land or water use Financial compensation of economic damage from impact of abstraction or limitations to land use

[1] SDG = Sustainable Development Goal; see App. V for summary of Sustainable Development Goal 6 targets and indicators related to sustainability characteristics (UN, 2015)

[2] JMP = 2017 update of the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene(WHO and UNICEF, 2017)

The *drinking water availability* can be quantified by the percentage of households connected to the drinking water supply. A sustainable local drinking water supply provides sufficient drinking water of a quality that meets the national or international drinking water standards, for a tariff that is affordable to all households. Water saving strategies will reduce the drinking water demand growth. The JMP monitors the availability of water safety plans (including emergency plans) on how to act in case of drinking water supply disturbances, shortages, or drinking water quality emergencies, which are essential to ensure drinking water availability (WHO and UNICEF, 2017).

Water governance focuses on policies and legislation, enforcement and compliance of regulations. Good governance also includes decision-making processes considering different stakeholder interests, to ensure accountable, transparent and participatory governance (UNESCAP, 2009). The availability of (inter)national and local policies and legislation on drinking water supply as well as on water management, including regulations and permits, and the level of compliance of the drinking water supplier to these policies and legislation, are important for the socio-economic sustainability. The sustainability of local drinking water supply is also characterised by the stakeholders interests related to the presence of a local drinking water abstraction, and by how local authorities weigh these interests in their decision-making processes. A final issue in water governance that reaches further than local stakeholder interests is the risk of small- or large-scale emergencies for the drinking water supply caused by human activities or conflicts (WHO and UNICEF, 2017).

The local *land and water use*, at surface and subsurface level, affects the water quality and quantity. It may have resulted in historical contaminant sources, causing point or non-point water pollution, but it may also lead to emerging contaminants that provide new risks to water quality. Additionally, water use for other purposes may limit the availability of water resources for drinking water. Regulations to protect water quality or water quantity may cause limitations for local land and water use. Financial compensation for suffered economic damage due to the impact of the abstraction or the limitations caused by protection regulations can be an important issue for the sustainability of the drinking water supply system.

4.4.4 Overview sustainability characteristics and criteria

Table 4.7 summarises the hydrological, technical and socio-economic sustainability characteristics and criteria for a local drinking water supply system from Tables 4.4–4.6.

Table 4.7 *Overview of the proposed sustainability characteristics and criteria for local drinking water supply systems.*

System	Sustainability characteristics	Sustainability criteria
Hydrological system	Water quality	Current raw water quality Chemical aspects of water quality Microbial aspects of water quality Acceptability aspects of water quality Monitoring and evaluation of water quality trends
	Water resource availability	Surface water quantity Groundwater quantity Other available water resources Vulnerability water system water for contamination Natural hazards and emergencies risk
	Impact of drinking water abstraction	Impact on surface water system Impact on groundwater system Balance between annual recharge and abstraction Hydrological compensation Spatial impact of abstraction facility/ storage/reservoir
Technical system	Reliability of technical infrastructure	Technical state abstraction and treatment facility Technical state distribution infrastructure Effectivity and complexity of water treatment Supply continuity for customers Operational reliability
	Resilience of technical infrastructure	Abstraction permit compared to annual drinking water demand Production capacity compared to peak demand Flexibility of treatment method for changing raw water quality Technical innovations to improve resilience Technical investments to improve resilience
	Energy use and environmental impact	Energy use of abstraction and treatment Energy use of distribution Environmental impact (additional excipients, waste water, waste materials) Reliability energy supply Use of renewable energy
Socio-economic system	Drinking water availability	Percentage connected households Drinking water quality Drinking water tariff Water saving strategy Water safety plan
	Water governance	Availability of (drinking) water legislation and policies Compliance of drinking water supplier Decision-making process by (local) authorities Local stakeholder interests Emergency risk caused by human activities or conflicts
	Land and water use	Land use (including subsurface use) Water use for other purposes than drinking water Regulations on land and water use Limitations to land or water use Financial compensation of economic damage from impact of abstraction or limitations to land use

4.5 Conclusions and discussion

The aim of this study was to identify a set of characteristics describing the sustainability of a local drinking water supply system. Based on the presented analysis, the following set of hydrological, technical and socio-economic sustainability characteristics is proposed, respectively: (1) *water quality*, *water resource availability*, and *impact of drinking water abstraction*; (2) *reliability* and *resilience of the technical system*, and *energy use and environmental impact*; (3) *drinking water availability, water governance*, and *land and water use*.

In this study we used an integrated systems approach to analyse the local drinking water supply system, combining hydrological, technical and socio-economic aspects of the system. The applied DPSIR approach is a socio-ecological framework originally developed to identify the impact of human activities on the state of the environmental system (Binder et al., 2013). The integrated systems approach of the local drinking water supply system as adopted in this research complicated the identification of pressures and impacts: the impact of a pressure to one system element presented pressures to other system elements. For instance, high temperatures and lack of precipitation caused a higher drinking water demand, and surface water quality deterioration. Both consequently presented pressures with an impact on the resilience and reliability of the technical drinking water supply infrastructure. Although this hampered the analysis, the use of DPSIR supported the systematic analysis of the local drinking water supply cases, and helped to identify the sustainability issues.

The analysis of the three selected cases with DPSIR supported the identification of issues that shape the sustainability of the local drinking water supply system. This was an unconventional use of DPSIR, and can be seen as a form of reverse engineering: “extracting knowledge or design blueprints from anything man-made” (Eilam, 2011), in this case from a local drinking water supply system. The results of the research show that DPSIR can be used to extract knowledge on the characteristics of a complex system. According to Pahl-Wostl (2015) DPSIR can be used to analyse the temporal and spatial dimensions of complex, multi-level environmental problems such as water resources management. This includes the complex system of local drinking water supply, which was analysed in this study. The case analysis did indeed help to account for differences between short-term and long-term developments, and for the impact of external influences that come from the national and international scale.

To increase the general applicability of the results from the analysis of the Dutch cases on drinking water supply, the identified sustainability issues were related to worldwide acknowledged sustainability issues, by cross-checking the targets set in the SDG 6 (UN, 2015), and the JMP (WHO and UNICEF, 2017). This put the issues in a broader perspective, which may contribute to the transferability of the proposed sustainability characteristics and criteria to other areas.

Assessments to understand the sustainability challenges as well as the impact of future developments and adaptation options are seen as powerful tools for policy making (Ness et al., 2007, Singh et al., 2012). Examples of sustainability assessments that relate to drinking water supply are the Sustainable Society Index (Van der Kerk and Manuel, 2008), the "EBC Performance Assessment Model" model (European Benchmarking Co-operation, 2017), the International Water Association Performance Indicator System (Alegre et al., 2006), the Groundwater Footprint (Gleeson and Wada, 2013) and the City Blueprint (Van Leeuwen et al., 2012). Although these assessments include criteria that are relevant to sustainable drinking water supply on various spatial and organisational scales, they do not consider drinking water supply on a local scale. The sustainability characteristics as proposed in this research may be used to develop a sustainability assessment for the local drinking water supply system, that can help to identify sustainability challenges and trade-offs of adaptation strategies. Trade-off analysis supports decision-making processes and makes these processes more transparent to local stakeholders (Hellegers and Leflaive, 2015). Based on the local situation and data availability, adequate indicators and indices can be selected to quantify the sustainability characteristics in a certain area (Van Engelenburg et al., 2019).

This chapter is an extended version of:

Van Engelenburg, J., Van Slobbe, E., & Hellegers, P. (2019). Towards sustainable drinking water abstraction: an integrated sustainability assessment framework to support local adaptation planning. Journal of Integrative Environmental Sciences, 16(1), 89-122. doi:10.1080/1943815x.2019.1636284

5

Sustainability assessment to support local adaptation planning

Abstract

Globally, groundwater is the main resource for drinking water. Improving the sustainability of groundwater abstraction for drinking water requires adaptations on a local scale. In this study a locally oriented, integrated sustainability assessment framework to support adaptation planning for a local drinking water supply system was developed. The framework elaborates on the sustainability characteristics and criteria established in Chapter 4. Adaptation strategies were identified linked to water saving, protection and restoration of water quality, mitigation or reduction of the impacts of abstraction, and improvement of reliability and resilience of the technical infrastructure. Three drinking water supply cases representing various adaptation strategies were assessed using the developed framework. The results identified the main sustainability challenges in each case, as well as the trade-offs associated with the selected adaptation strategies. Findings from the analysis confirm that a sustainability assessment can provide decision-makers a better understanding of the trade-offs involved in decisions regarding drinking water supply. Information generated by the assessment, moreover, will enable transparent and careful balancing of relevant aspects in decision-making on adaptation of local drinking water abstraction. Continued development of the sustainability assessment by application in other contexts than the Dutch context could extend the general applicability of the assessment.

5.1 Introduction

Worldwide awareness of the urgency of sustainable development has increased ever since the Brundtland report defined this as the way “to ensure that development meets the needs of the present without compromising the ability of future generations to meet their own needs” (UN, 1987). In 2015 the “2030 Agenda for Sustainable Development” was presented, including Sustainable Development Goal (SDG) 6: to “ensure availability and sustainable management of water and sanitation for all”. Although improvement is visible, the World Health Organization (WHO) and UNICEF (2017) estimated that in 2015 still nearly 30% of the global population lacked safely managed drinking water services. SDG 6 enhances not only access to safe and affordable drinking water for all, but also improvement of water quality, sustainable withdrawal of freshwater and implementation of integrated water resources management (UN, 2015). Globally, groundwater is the major drinking water resource (Ekins et al., 2019). Although groundwater is increasingly important for drinking water supply, use of groundwater can be constrained by the complexity and costs of abstraction, or because the resource is polluted or non-renewable, and poor groundwater management may result in pollution or unsustainable abstraction (Ekins et al., 2019). In addition, future developments such as climate change and a growing water demand may also threaten the availability of groundwater resources for drinking water supply worldwide.

A drinking water supply system is a heterogeneous technical network of pipelines connecting local drinking water abstraction facilities to the (local) customers. Water infrastructures are known for their complexity, with cross-scale feedbacks between society, technology and environment as well as between the local, regional and global scale (Dermody et al., 2018). Because of the long lifecycles of water supply infrastructure, long-term developments require early adaptation (Bauer and Herder, 2009). Before adaptation options can be selected, the sustainability challenges must be identified, using knowledge on the current situation and future developments (Pahl-Wostl et al., 2007, Swart and Singh, 2013, Meijer, 2007).

This research focuses on the sustainability of local drinking water abstraction, which is shaped by technical infrastructure, geographical location and the used water resource. Because abstraction facilities are strongly embedded in the local environment and society, there are many stakeholders involved, often with competing interests and affecting the water system in different ways. Adequate adaptation policies and actions need to be taken to enhance the sustainable withdrawal of water, on the (inter)national level, as well as on a local scale.

The first long-term adaptation strategy that must be considered to adapt to an increasing drinking water demand, is water saving, which will limit the demand growth (Kumar et al., 2016). However, the majority of the current drinking water abstractions will still be needed to meet the future drinking water demand. To identify adaptation options for local abstractions an integrated approach on a local scale is necessary, because of the strong embeddedness of drinking water abstractions in the environment, and the strong spatial and temporal variability in water systems (Hering et al., 2015). Therefore sound data and knowledge of the local situation is required to be able to understand the sustainability challenges such as pollution of the water resources (Janža, 2015). Each abstraction may face different sustainability challenges caused by local hydrological, technical and socio-economic characteristics, and thus require specific adaptation strategies. An integrated sustainability assessment focusing specifically on these local characteristics can support adaptation planning for drinking water abstraction.

The aim of this research therefore is “to develop a locally oriented, integrated sustainability assessment that supports the adaptation planning process for local drinking water abstraction”. In this research we study current practice on adaptation planning of local drinking water abstraction in the Netherlands. The most extreme scenario for the drinking water demand in the Netherlands is an increase of 35% in 2050 (Wolters et al., 2018). The drinking water supply will not suffice to meet such an increase and adaptation strategies are considered. Currently approximately 65% of the drinking water supply in the Netherlands origins directly from groundwater, 35% from surface water (Geudens and Van Grootveld, 2017). The Dutch government puts large effort in sustainable groundwater management (Lijzen et al., 2014), but there is also an ongoing societal debate on compensation of groundwater abstractions and of (partial) transition to direct or indirect use of surface water instead of groundwater for drinking water. These measures will affect the sustainability of local abstractions.

5.2 Method

Sustainability science is defined by Kates (2016) as: “transdisciplinary research to solve problems of sustainability in practice, combining knowledge and action”. Transdisciplinary research brings together scientific and experiential knowledge (Regeer and Bunders - Aelen, 2009), aiming to produce essential information to solve complex problems (Groot et al., 2015). According to Kates (2016), sustainability science must study topics such as long-term trends, resilience, vulnerability and adaptability of society, trade-offs, and alternative pathways to better understand how to increase sustainable development.

In this research scientific knowledge on sustainability and integrated water management (Section 5.2.1) is combined with current practice on local adaptation planning (Section 5.2.2). The aim is to assess the sustainability of local drinking water abstraction, by means of an integrated sustainability assessment framework, which is developed based on a linear adaptation planning approach, and multi-criteria analysis (MCA, see Section 5.2.3). In three selected cases (Section 5.2.4) the sustainability of the local drinking water supply system and the impact of future developments and local adaptation options is assessed.

5.2.1 Sustainability and water management planning

Loucks (2000) defined sustainable water resources systems as “water resource systems designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity.” Although in the last decades many indicators have been developed for integrated water resources management, they often do not fulfil the commonly used sustainability criteria of social, economic, environmental and institutional components (Pires et al., 2017). In addition, for drinking water abstraction the highly technical character of the infrastructure must be considered (Bauer and Herder, 2009). The sustainability of local drinking water abstraction therefore includes hydrological, technical and socio-economic criteria.

In water management there are multiple approaches available to support adaptation planning, for instance: assessment of the water footprint (Hoekstra, 2009, Hoekstra et al., 2011) or water security (Dickson et al., 2016), and decision support by adaptive planning (Haasnoot, 2013) or multi-criteria analysis (Swart and Singh, 2013). Additionally many assessments have been developed to understand the sustainability challenges as well as the impact of future developments and adaptation options on different water system components, which are seen as a powerful tools for policy making (Ness et al., 2007, Singh et al., 2012). The Sustainable Society Index (Van der Kerk and Manuel, 2008), the "EBC Performance Assessment Model" model (European Benchmarking Co-operation, 2017), the International Water Association Performance Indicator System (Alegre et al., 2006), the Groundwater Footprint (Gleeson and Wada, 2013) and the City Blueprint (Van Leeuwen et al., 2012) are examples of sustainability assessments that include criteria that are relevant to sustainable drinking water supply systems.

This study aims to contribute to the existing body of literature on adaptation planning for sustainable water management on a local scale, by assessing the sustainability of local drinking water abstraction by means of a sustainability assessment framework. The framework builds on the sustainability characteristics and criteria of local drinking water supply that were proposed in Chapter 4 of this thesis. In this chapter the sustainability criteria are related to the sustainability issues in the Dutch drinking water supply.

5.2.2 Current practice on local adaptation planning

Vitens is a Dutch drinking water company that yearly supplies 350 million m^3 drinking water from mainly groundwater resources to approximately 5.6 million people in the Netherlands, produced at 110 local drinking water abstractions (Fig. 5.1).

Vitens made an inventory of the issues that the local drinking water abstractions currently face or may have to face in the future and how to adapt to these issues. The development of this adaptation planning approach was an iterative process supported by an internal expert-panel combining relevant expertise on hydrology and hydrochemistry, drinking water supply and distribution, stakeholder interests, real estate and asset management, communication and investment planning, which was led by the first author of this paper. In the Vitens approach a sustainable drinking water abstraction facility was defined as a facility that (1) is in good balance with the surrounding land and water system, (2) abstracts a groundwater quality that only requires a simple water treatment method, and (3) is accepted and valued positively by stakeholders.

Figure 5.1 *Drinking water supply area and local drinking water abstractions of drinking water company Vitens in the Netherlands. The sustainability of the highlighted drinking water abstractions is assessed (Section 5.4).*

The scope of the program was solely on local groundwater withdrawal and therefore excluded the drinking water treatment and distribution. A multi-criteria analysis was used to identify an overall sustainability deficit, and to compose an adaptation agenda for each of the 110 individual local drinking water abstractions. First the issues and adaptation options (i.e. all possible adaptation measures) to ensure a well-functioning drinking water supply were identified. The sustainability of the abstractions is often debated amongst stakeholders, and therefore a wide range of adaptation options was considered that also satisfied the interests of stakeholders. Not for all sustainability issues adaptation options were available: for instance hydrological characteristics cannot be changed by adaptation. Finally the adaptation agenda for each drinking water abstraction facility was composed, combining the issues with the adequate local adaptation options. The sustainability deficit was appointed as a key performance indicator in the company's strategic management and therefore was planned to be updated quarterly.

The researcher that was involved in the development process made observations on the constraints Vitens experienced during the operationalisation of the adaptation planning approach (Table 5.1).

Table 5.1 *Observed constraints of Vitens approach.*

Topic	Constraints
System boundaries	The set system boundaries (regarding abstraction only, leaving out treatment and distribution) created a limited view of sustainable drinking water abstraction, disregarding important sustainability criteria such as energy use and drinking water availability.
Expert knowledge	Because only a part of the criteria was based on quantitative data, contextual expert knowledge was required. This limited the reproducibility of the results and may have caused a certain bias in the assessment.
Stakeholder involvement	The knowledge on stakeholders viewpoints was included in the approach. However, because there were no external stakeholders involved in the development process, stakeholders were critical on the results.
Workability	The first assessment of the criteria and composition of the local adaptation agendas for 110 local abstractions was time-consuming but valuable by the integration of knowledge from different departments and expertise to an overview of the sustainability challenges at the abstractions. The additional knowledge gained from the frequent updates of the key performance indicator for strategic management however is found limited.
Weights	The expert-panel set weights per *criterion* within each category to calculate the deficit per category, and weights per *category* that were used to calculate an overall sustainability deficit. A sensitivity analysis showed that the weights per criterion were robust, but the chosen weights per *category* did impact the result. If stakeholders with different interests would value the categories differently, this would have changed the outcome significantly.
Trade-offs	The "sustainability deficit" was summing up the results of the assessment of the criteria for a local drinking water abstraction. In this manner, the impact of future developments and adaptation options to different aspects of sustainable local drinking water abstraction and possible trade-offs between different criteria were disregarded.
Prioritisation	The program resulted in 110 adaptation agendas and thus multiple measures, which required prioritisation before implementation could start.

5.2.3 Assessment approach

In practice, decision-making in a complex governance environment is a “fuzzy” process that must deal with many uncertainties and calls for involving stakeholders with different interests in the process (De Roo and Porter, 2016). For analytical purposes however, we may consider the planning process as a linear sequence of steps (Pahl-Wostl et al., 2007, Hinkel et al., 2015). Therefore we propose to use a linear approach on adaptation planning (Fig. 5.2). First an assessment of the current sustainability is used to identify current sustainability challenges. The impact of future developments as driving forces indicates a possible future sustainability that helps to identify future sustainability challenges. These current and future sustainability challenges are input to identify and appraise local adaptation options that may help to meet these challenges in the future.

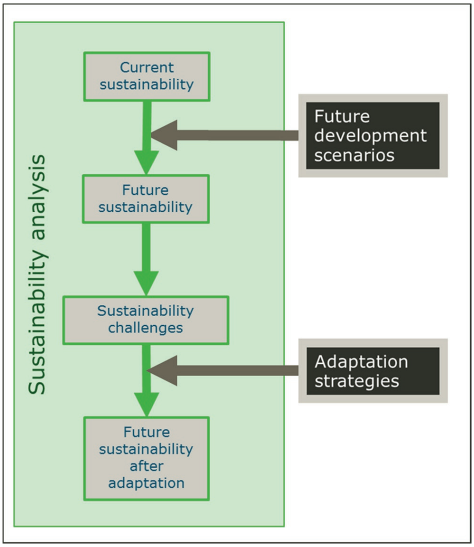


Figure 5.2 *Proposed adaptation planning approach.*

We propose to use MCA for the sustainability assessment, an integrated assessment tool that is based on a systems analysis approach, and can be used for complex issues and at local scale projects such as local drinking water abstraction (Ness et al., 2007). MCA can incorporate both quantitative and qualitative data, has been applied in the environmental domain frequently, and helps to find trade-offs (Swart and Singh, 2013, Huang et al., 2011). The definition of sustainable local drinking water abstraction is the core of the sustainability assessment. We relate the hydrological, technical and socio-economic sustainability characteristics and criteria as proposed in Chapter 4 to the sustainability issues in the Dutch drinking water supply and elaborate them using available indicators from existing assessments as well as on policy assessments such as the status of water bodies according to the European Water Framework Directive (European Union, 2000), the Dutch Drinking water Law (Dutch Government, 2009) and performance data of drinking water utilities (App. VI).

5.2.4 Case and data selection

The sustainability assessment was applied to three cases. The researchers chose to assess Vitens abstractions, because the required data and knowledge were already available. As mentioned in Section 5.1, there is a societal debate in the Netherlands on compensation of groundwater abstractions and (partial) transition of groundwater use towards direct or indirect use of surface water. The first two cases are on compensation of groundwater abstractions: the Managed Aquifer Recharge by infiltration near Epe, as analysed in Chapter 2 of this thesis, and partial redistribution of abstraction volumes in the Veluwe area, as studied in Chapter 3 of this thesis. Additionally the abstraction Vechterweerd is selected, a so-called 'riverbank' abstraction, which abstracts groundwater that includes 60% recently infiltrated surface water. Decisions on these strategies will benefit from understanding the impact of these measures to the sustainability of a local drinking water abstraction. The assessment of each criterion requires knowledge on different scales, varying from the local and company's scale to national scale (Table 5.2).

Table 5.2 *Overview of used data.*

Data	Type	Publicly available	Scale
National and regional statistics on drinking water supply	Quantitative	Yes	National and regional
Governmental data on legislation and regulations	Quantitative	Yes	National, regional and local
Stakeholder interests	Qualitative	No	Local
Hydrological data	Quantitative	Yes	Regional and local
Drinking water company's general data	Quantitative	Yes	Company's scale
Drinking water company's operational data	Quantitative	No	Local

Where possible, quantitative, publicly available data is used. Local operational data of drinking water companies is usually not publicly available, and data on stakeholders interests are qualitative.

5.3 Sustainability assessment

The adaptation planning approach (Fig. 5.2) is used to develop the sustainability assessment (Fig. 5.3). First current sustainability is assessed, followed by identification of future sustainability based on the estimated long-term (>25 years) impact of relevant future developments. Then adaptation strategies are identified and the impact of these strategies to the future sustainability of the local drinking water abstraction is estimated, in order to identify the future sustainability after adaptation.

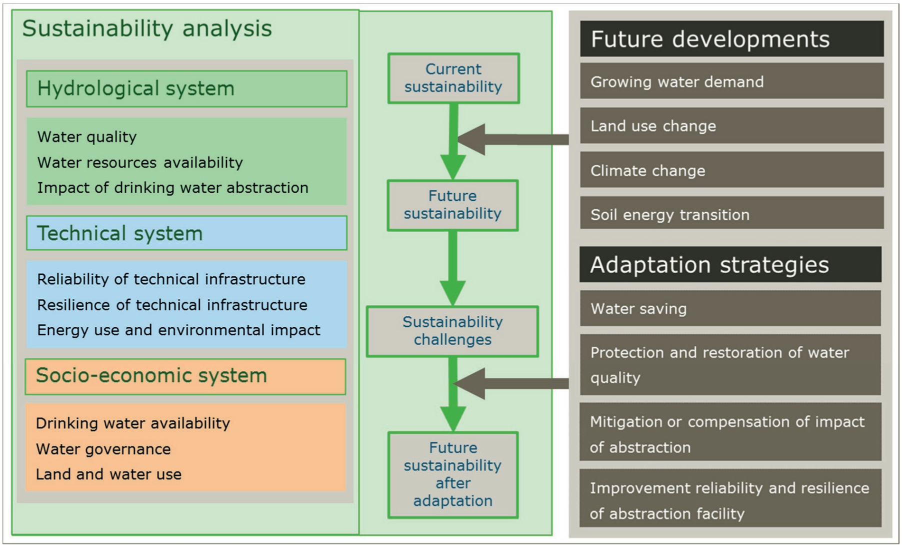


Figure 5.3 *Framework for the sustainability assessment, comparing current and future sustainability of a local drinking water supply system, taking into consideration various future developments and adaptation strategies.*

5.3.1 Sustainable local drinking water supply

The hydrological, technical and socio-economic sustainability characteristics as proposed in Chapter 4 were elaborated, relating to the Dutch sustainability issues (Fig. 5.4). Each criterion is assessed, referring to various indicators and data resources, and accordingly categorised in "*sustainable*" via "*under pressure*" to "*unsustainable*" (App. VI). Just as in the Vitens approach, the criteria within each sustainability characteristic is weighed in the assessment framework. To ensure that trade-offs between different sustainability characteristics are visualised, a spider diagram is used to present the results of the assessment, thereby also avoiding the need to assign weights per sustainability characteristic, which was a constraint in the Vitens approach. The scale is a gradient, where the red centre represents "*unsustainable*", the green outer circle "*sustainable*" and the yellow area in between shows that the sustainability is "*under pressure*" (Fig. 5.4). When a sustainability characteristic is entering the red centre, this is considered to be a sustainability challenge.

5.3.2 Future developments

As is supported by the cases analysed in Chapter 4, future developments that influence drinking water demand, water quality and water resource availability cause the main future sustainability challenges for local drinking water supply.

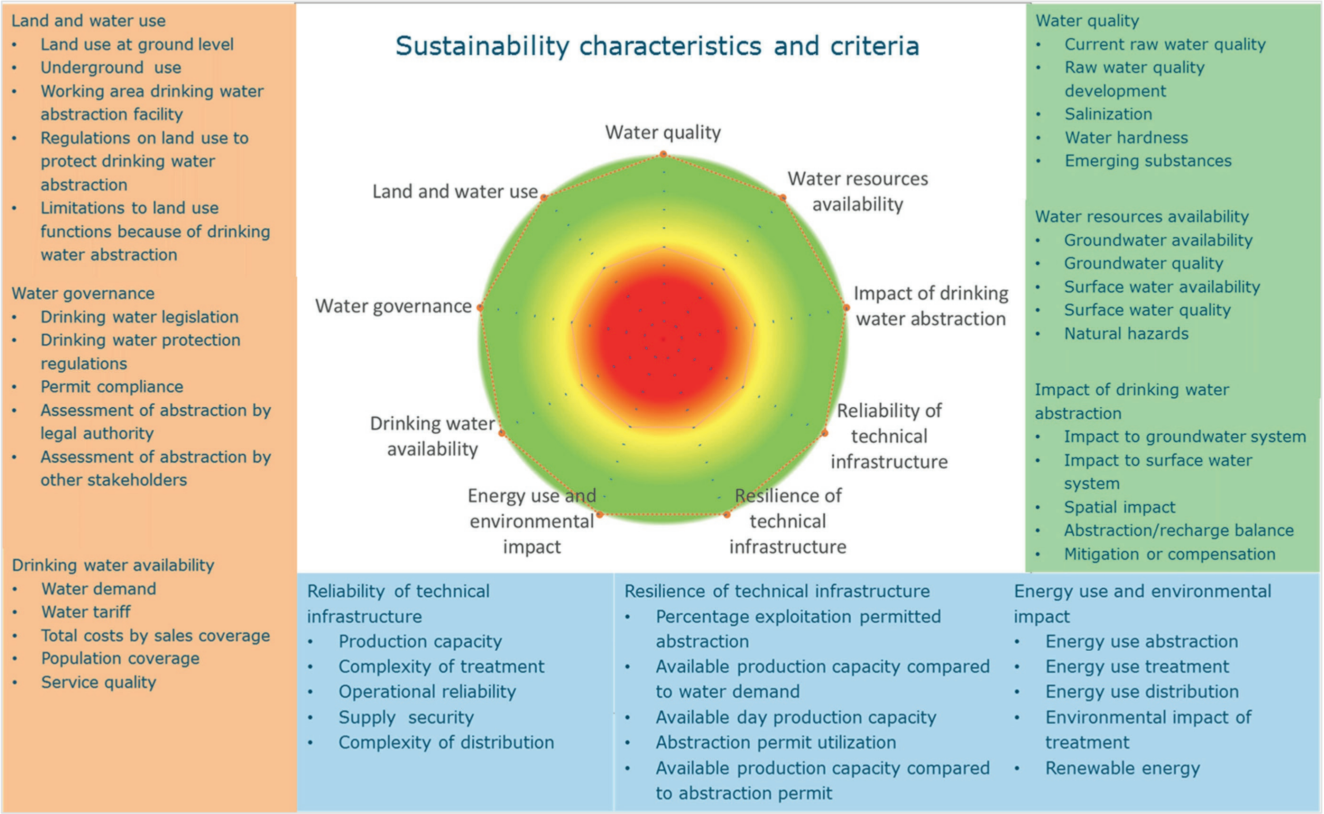
Currently the global water demand is still growing (Hanasaki et al., 2013). In the Netherlands a maximum increase of drinking water demand of 30% in 2040 may occur (Van der Aa et al., 2015a). This will put the current drinking water supply under pressure. In this research we assume that the volume of abstracted water in a local drinking water supply system will increase as a result of the growing water demand.

Land use change such as urbanisation, extension and/or intensification of agricultural use, and increase of industrial areas affects the water system (Van den Brink and Wuijts, 2016), both water quality and quantity (Lerner and Harris, 2009), and therefore is a relevant future development for local drinking water supply (Van Rijswick and Wuijts, 2016). In this research we assume that land use change will have a negative impact on the water quality, which is reasonable to expect given the current economic development (Klijn et al., 2012).

Climate change is an important future development that will affect the water system and thus the drinking water supply (Staben et al., 2015). In the Dutch situation already more warm, dry summers and wet winters occur, and this is expected to increase (Van den Hurk et al., 2014). Lower precipitation and higher evapotranspiration rates will cause a diminishing water resource availability and recharge to the water system in summer, and a deteriorating surface water quality during summer (Bonte and Zwolsman, 2010). This may eventually lead to groundwater quality deterioration too through infiltration of surface water. The requirements for water treatment will therefore also change as a result from climate change (Staben et al., 2015). In this research we assume that climate change will reduce water resource availability as well as deteriorate water quality.

Next to transition to wind and solar energy, the current transition from fossil-based energy to renewable energy may also include the development of projects for geothermal and other forms of soil energy. This development may have an impact on groundwater quality through thermal changes (Bonte et al., 2013), and through the introduction of pollution risks from calamities or negligent use, and thus may threaten the drinking water abstraction. In some countries there are legal limitations on where soil energy is allowed to avoid irreversible damage to drinking water resources (Haehnlein et al., 2010). However, policies may change with the increasing urge to find sufficient sources of renewable energy and thus interference between soil energy and drinking water abstraction may increase. In this research we consider soil energy transition a relevant future development with a long-term negative impact on groundwater quality.

The selected future developments will affect multiple sustainability criteria in different ways (Table 5.3). For instance, a changing water quality as a result of land use change or climate change may affect the raw water quality, which will have an impact on the complexity and energy use of the treatment. An increasing abstracted water volume as a result of growing water demand may affect the *reliability*, i.e. the likeliness of the technical system to fail (Hashimoto et al., 1982), and *resilience*, i.e. the possibility to recover from failure or to respond to changes (ibid) of the facility, but will also increase the recharge area of the drinking water abstraction and this may affect the water quality. The factual impact of future developments depends strongly on the local situation. If the land use in the recharge area is mainly nature, it is unlikely that land use change or soil energy transition will affect the water quality strongly, whereas in an urbanised recharge area this will be a serious threat. Assessing the impact of the future developments to a specific local drinking water supply system thus requires local expert-knowledge.



Land and water use
- Land use at ground level
- Underground use
- Working area drinking water abstraction facility
- Regulations on land use to protect drinking water abstraction
- Limitations to land use functions because of drinking water abstraction

Water governance
- Drinking water legislation
- Drinking water protection regulations
- Permit compliance
- Assessment of abstraction by legal authority
- Assessment of abstraction by other stakeholders

Drinking water availability
- Water demand
- Water tariff
- Total costs by sales coverage
- Population coverage
- Service quality

Water quality
- Current raw water quality
- Raw water quality development
- Salinization
- Water hardness
- Emerging substances

Water resources availability
- Groundwater availability
- Groundwater quality
- Surface water availability
- Surface water quality
- Natural hazards

Impact of drinking water abstraction
- Impact to groundwater system
- Impact to surface water system
- Spatial impact
- Abstraction/recharge balance
- Mitigation or compensation

Reliability of technical infrastructure
- Production capacity
- Complexity of treatment
- Operational reliability
- Supply security
- Complexity of distribution

Resilience of technical infrastructure
- Percentage exploitation permitted abstraction
- Available production capacity compared to water demand
- Available day production capacity
- Abstraction permit utilization
- Available production capacity compared to abstraction permit

Energy use and environmental impact
- Energy use abstraction
- Energy use treatment
- Energy use distribution
- Environmental impact of treatment
- Renewable energy

Figure 5.4 *Sustainability characteristics, criteria and output spider diagram of the sustainability assessment. The outer border of the green area represents the maximum sustainability score. A sustainability characteristic that scores within the red centre area (< 50% of maximum sustainability) represents a sustainability challenge.*

Table 5.3 *Impact of future developments and adaptation strategies to sustainability criteria in the framework for the sustainability assessment of a local drinking water supply system.*

			Future developments				**Adaptation strategies**			
System	**Category**	**Criterion**	Growing water demand	Land use change	Climate change	Soil energy transition	Water saving	Protection and restoration of water quality	Mitigation or compensation of impact of abstraction	Improvement of reliability and resilience
Hydrological system	Water quality	Current raw water quality	-		-			+		
		Raw water quality development	-		-			+	+/-	
		Salinization			-			+		
		Water hardness						+	+/-	
		Emerging substances			-			+	+/-	
	Water resources availability	Groundwater quantity							+	
		Groundwater quality		-	-	-		+		
		Surface water quantity			-				+	
		Surface water quality		-	-			+		
		Natural hazards			-					
	Impact of drinking water abstraction	Impact to groundwater system	--/0				++/0		++/0	
		Impact to surface water system	0/--				0/++		0/++	
		Spatial impact	-	-				+		+/-
		Abstraction/recharge balance	-		-		+		+	
		Mitigation or compensation	--				+		+	
Technical system	Reliability of technical infrastructure	Production capacity	--				++			++
		Complexity of treatment		-	-	-		+	0/-	
		Operational reliability	--				++		+/-	++
		Supply security	--				++			++
		Complexity of distribution	--				++			++
	Resilience of technical infrastructure	Percentage exploitation permitted abstraction	--				++			
		Available production capacity compared to water demand	--				++			++
		Availiable day production capacity	--				++			++
		Abstraction permit utilization	--				++			++
		Available production capacity compared to abstraction permit	-				++			++
	Energy use and environmental impact	Energy use abstraction	--				++		-	+
		Energy use treatment	--	-			++	+	+/-	+
		Energy use distribution	--				++			+
		Environmental impact of treatment	--	-			++	+		+
		Renewable energy								+
Socio-economic system	Drinking water availability	Water demand	--		-		++			
		Water tariff		-	-	-		+	-	
		Total costs by sales coverage					+/-	+		+/-
		Population coverage	-				+			
		Service quality	-				+			++
	Water governance	Drinking water legislation								
		Water protection legislation	-	-				+		
		Permit compliance	--				++		+	
		Assessment of abstraction by legal authority					++		+	
		Assessment of abstraction by other stakeholders	-	-		-	++		+/-	+
	Land and water use	Land use at ground level	-	-			+	+	+/-	
		Underground use	-			-	+	+		
		Working area drinking water abstraction facility								+
		Regulations on land use to protect drinking water abstraction	-	-	-	-	+	+		
		Limitations to land use functions because of drinking water abstraction	-	-	-	-	+	+		

-(-)= (strong) negative impact to sustainability, +(+)= (strong) positive impact to sustainability, 0=no impact to sustainability and combinations (local knowledge required)

5.3.3 Adaptation strategies

Based on the sustainability characteristics, future developments and current practice, four adaptation strategies have been identified: water saving, protection and restoration of water quality, mitigation or reduction of impact of abstraction, and improvement of reliability and resilience of the technical infrastructure. Every adaptation strategy must be elaborated into local adaptation options, which may affect sustainability criteria in different ways, depending on the local situation. To assess the projected impact of each adaptation strategy to a specific local drinking water supply system, the effects of each individual adaptation option must be rated. Adaptation options can be one-time or permanent measures with a stepwise or gradual, and medium- or long-term impact on different sustainability criteria: for instance the technical realisation of managed aquifer recharge or managed water supply as a mitigation option may reduce the impact of drinking water abstraction directly, but the long-term exploitation of these measures will affect energy use permanently and may affect the water quality gradually.

Water saving is a long-running adaptation strategy that will affect the water demand in general. The expected water demand growth is yet already an incentive for water saving strategies to reduce the use of drinking water. Possible adaptation options are raising consumers awareness on the need of water saving, technical innovations that reduce consumer or industrial water use, and (re-)use of other water resources such as waste water or rainwater, and regulations to enforce water saving. A final option is increasing consumer or industrial water tariffs, or introducing a progressive tariff (the larger the use, the higher the water tariff per m^3), which may present an incentive for water saving in the Netherlands, where drinking water tariffs are low. The impact of water saving as adaptation strategy will become gradually visible in the long term in a decreasing water demand, and thus will impact the reliability and resilience of the local drinking water supply system in the long term.

There are many adaptation options to protect or restore the water resources quality for drinking water. Options are joint monitoring of water quality and raising awareness of the importance of water quality protection among regional and local stakeholders, prevention of water pollution resulting from calamities, but also initiating measures to improve protection of water quality by reduction of the impact of agriculture, built-up area or point sources of pollution to water quality. Environmental legislation and regulations, and their enforcement is a precondition for protection and restoration. Adaptation options to protect or restore water quality focus on influencing land use and remediation of pollution, and therefore require adequate policies to effectively influence surface runoff and leakage to groundwater (Lerner and Harris, 2009). Influencing water quality through land use change is a long-term process and the effects are only noticeable in the long term, especially when considering groundwater quality improvement, which is a very slow process. Measures must be taken in a large area to improve water quality and thus ask for cooperation with local stakeholders such as farmers, industries, and municipalities. This adaptation strategy will therefore not solve all water quality problems, but will help to prevent further deterioration.

The adaptation options to mitigate or compensate the impact of a specific local drinking water supply system to nature values, agriculture or buildings depend on the local situation. It requires an integrated stakeholder process to find out which option is effective and feasible in this specific local situation. The actual design and construction of the selected measure to mitigate the environmental impact of this local drinking water supply system is following the stakeholder process. The mitigation measure may impact some sustainability criteria adversely. For instance, managed aquifer recharge will reduce the hydrological impact of the drinking water abstraction and thus improve the hydrological sustainability, but may also put pressure on the reliability of the technical infrastructure and increase the energy use and environmental impact. Compensation of the impact may also be financial, or by measures elsewhere, and thus will not reduce the hydrological impact of an abstraction in that situation. However, it may contribute to a positive assessment of the local drinking water supply system by stakeholders and legal authorities.

The reliability of a local drinking water supply system can be improved by technical measures such as optimisation or adjustment of operational management, treatment or distribution within the existing abstraction permit capacity. The resilience to future developments will increase by extension of the abstraction permit and the expansion of the technical infrastructure that is necessary to subsequently increase the drinking water production capacity. Acquiring a new or extended abstraction permit is a complex and time-consuming process, involving legal procedures and local stakeholder processes. Whether, and under which conditions, extension is possible depends on the local situation. After obtaining the abstraction permit, the required extension of production capacity will entail investments and additional time for engineering and the required building permits, as well as for realisation of the expansions.

5.4 Application in adaptation cases

The sustainability of three Vitens cases in the Netherlands is assessed by means of the assessment framework: the Epe drinking water supply system with MAR by infiltration to compensate for the hydrological impact of the abstraction as analysed in Chapter 2, the partial redistribution of abstraction volumes in the Veluwe area as studied in Chapter 3, and additionally the Vechterweerd drinking water system.

5.4.1 Sustainability assessment infiltration Epe

General description

The Epe drinking water supply system (Fig. 5.1) is abstracting phreatic fresh groundwater of good quality and low hardness. The land use in the recharge area is mainly protected forest. A simple water treatment is used, to remove iron and manganese and to correct the pH-level. Day production capacity is insufficient in high demand situations and the distribution is complex. To reduce the impact of the abstraction to the groundwater system and nearby nature values, an infiltration through managed aquifer recharge (MAR) was constructed, where untreated surface water is infiltrated near the abstraction wells. This infiltration has introduced a new risk for the groundwater quality through the impact of surface water quality and land use in the upstream area. When there is a quality disturbance or insufficient surface water resource availability, infiltration is put on hold. The abstraction permit is 6 million m^3/yr, but there are limitations in the production capacity. There is a separate permit for infiltration of 6 million m^3/yr, which is linked to the abstraction permit. Because of technical problems and insufficient surface water resource availability the infiltration volume is currently limited, and to achieve the permit requirements the drinking water abstraction volume must be reduced. In Chapter 2 of this thesis the hydrological impact of the abstraction Epe and the Managed Aquifer Recharge by infiltration was analysed.

Sustainability assessment

The current sustainability challenge for the drinking water supply system Epe is the resilience of the facility (Fig. 5.5), which is partially caused by technical limitations in the production capacity. The resilience is also under pressure because of the infiltration permit conditions, that reduce the permitted production volume when the infiltration volume falls short. The future developments will put the water resource availability, and land and water use under pressure, mainly because of the infiltration of untreated surface water. An increase of the water demand will affect not only the required production volume of drinking water but also the required infiltration volume. Land use change and climate change are projected to cause deterioration of the surface water quality and therefore will influence the water quality and the availability of the water resources.

The assessment shows that the infiltration system to mitigate the impact of the abstraction to the groundwater system has a large effect on the current as well as future sustainability of the drinking water supply system Epe. Comparing the sustainability of the situation with infiltration to a situation without infiltration identifies clearly the trade-offs of the decision to construct this infiltration system (Fig. 5.5): without infiltration the hydrological impact of the abstraction would not be mitigated, which would also put pressure on the acceptance of the local drinking water supply system Epe by the legal authority and by stakeholders (sustainability characteristic “water governance”). However, the sustainability of the local drinking water supply system would not be influenced by surface water and land use in the recharge area, the water quality would not be under pressure, and the energy use would be limited. Also the resilience of the facility would improve, because the abstraction volume would not be limited by the actual infiltration volume.

Local adaptation options

To meet the sustainability challenges of drinking water supply system Epe four local adaptation options are selected (Table 5.4).

Table 5.4 *Projected main impact of local adaptation options of drinking water supply systems Epe, Veluwe, and Vechterweerd, in the Netherlands.*

Local drinking water supply system	**Adaptation strategy**	**Local adaptation option**	**Main impact on**	**Result**
Epe	Water saving	Water saving	Drinking water availability, water use, resilience of technical infrastructure	Fig. 5.6 (a)
	Protection and restoration of water quality	Protection surface water quality for infiltration	Water resource availability	Fig. 5.6 (b)
	Mitigation or compensation of impact of abstraction	Optimisation of infiltration	Impact of drinking water abstraction	Fig. 5.6 (c)
	Improvement of reliability and resilience	Construction of new production capacity	Reliability and resilience of technical infrastructure	Fig. 5.6 (d)
Redistribution Veluwe	Water saving	Water saving	Drinking water availability, water use, resilience of technical infrastructure	Fig. 5.8
	Mitigation or compensation of impact of abstraction	Redistribution of abstraction volumes	Impact of drinking water abstraction, reliability and resilience of technical infrastructure	Fig. 5.8 and 5.9
	Improvement of reliability and resilience	Adjustment of permit and technical infrastructure	Reliability and resilience of technical infrastructure	Fig. 5.9
Vechterweerd	Water saving	Water saving	Drinking water availability, water use, resilience of technical infrastructure	Fig. 5.11 (a)
	Protection and restoration of water quality	Protection surface water quality Protection groundwater quality Modification of groundwater protection zone	Water resource availability	Fig. 5.11 (b)

Water saving is a general option to limit the water demand growth, which will improve the resilience of the facility (Fig. 5.6a). Protection of the surface water quality will influence the water quality for the infiltration in the long term to help safeguard the raw water quality of the abstraction (Fig. 5.6b). Optimisation of the infiltration to increase the infiltration volume will solve the limitation to the abstraction volume and further reduce the impact of the abstraction to the groundwater system (Fig. 5.6c). Construction of new production capacity by adding abstraction wells and extra treatment capacity will improve the resilience as well as the reliability of the facility (Fig. 5.6d).

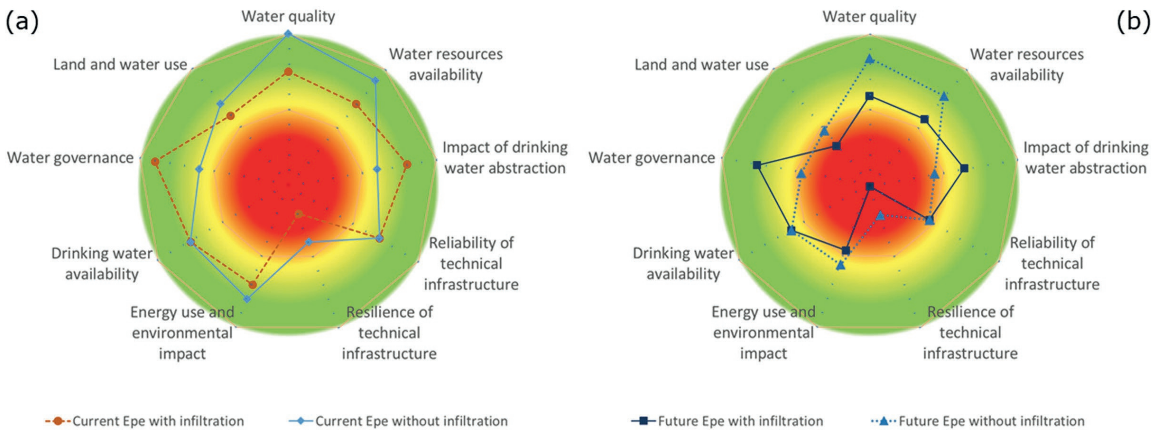


Figure 5.5 *Results local drinking water supply system Epe, the Netherlands: (a) current sustainability with (brown) and without (light blue) mitigation by infiltration and (b) future sustainability with (dark blue) and without (brown) mitigation by infiltration.*

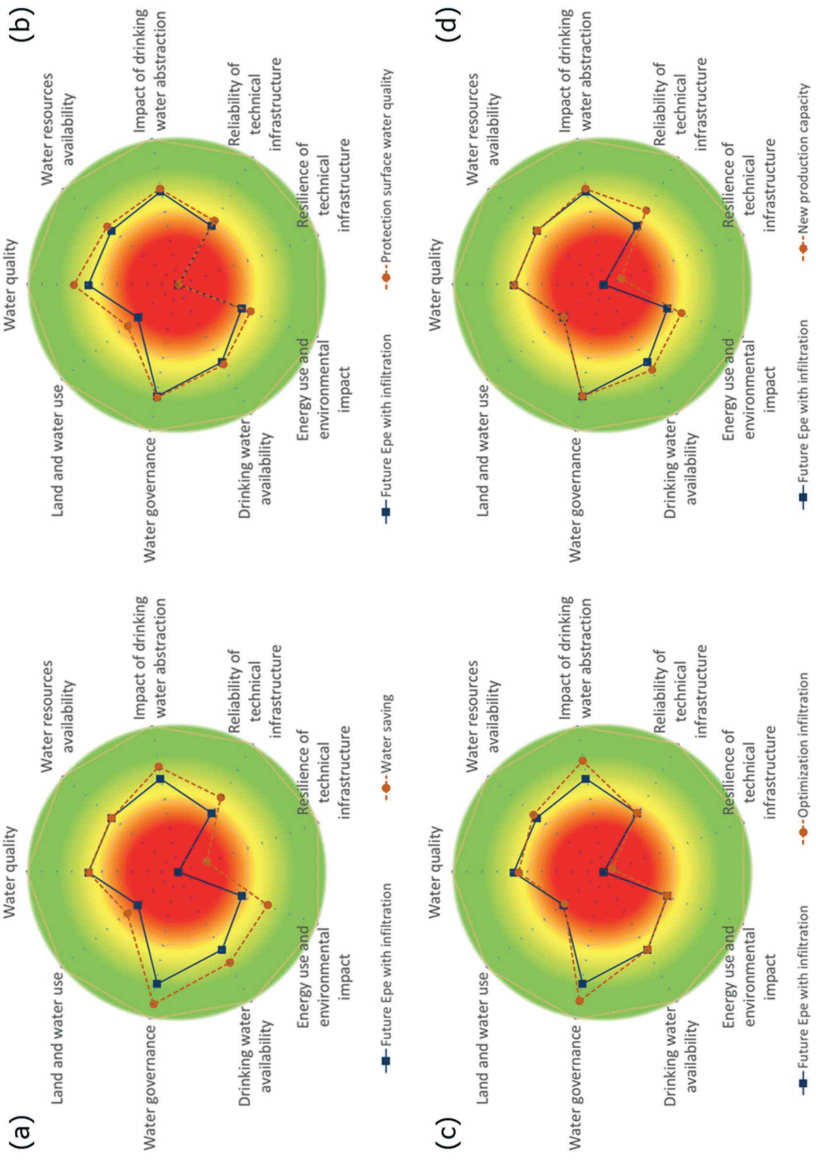


***Figure 5.6** Long term impact of the selected local adaptation options (a) water saving, (b) protection surface water quality, (c) optimisation of infiltration, (d) new production capacity to the future sustainability of the Epe drinking water supply system, the Netherlands.*

Future sustainability with adaptation

The future sustainability of the Epe drinking water supply system will improve by the total impact of the four selected adaptation options. However, the sustainability characteristics land and water use, water quality and water resource availability are assessed lower than in the current situation (Fig. 5.7). Protection and restoration of water quality will not solve all water quality problems, but will help to prevent further deterioration. Although important, the impact of this adaptation strategy to the sustainability is limited and will not compensate for the impact of the future developments to the water quality. This also influences the sustainability characteristics land and water use and water resource availability.

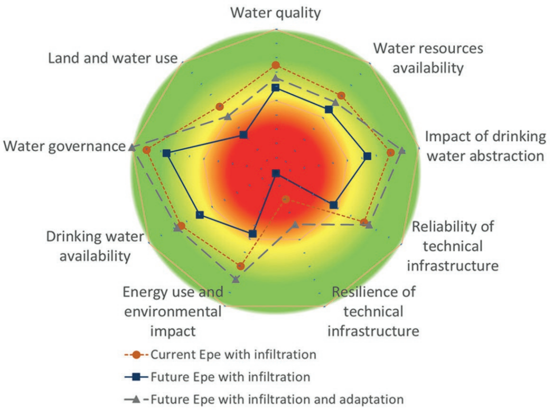


Figure 5.7 *Current sustainability (brown), future sustainability (blue) and future sustainability after adaptation with all selected local adaptation options (grey) for drinking water supply system Epe, the Netherlands with infiltration.*

5.4.2 Sustainability assessment redistribution abstractions Veluwe

General description

Near the drinking water abstractions Amersfoortseweg (AM), La Cabine (LC), and Ellecom (EL) in the Veluwe area there are groundwater-dependent ecosystems that potentially are influenced by these drinking water abstractions. The abstraction Hoenderloo is located near the central part of the Veluwe, which is rainwater dependent. Because it does not affect nearby nature, partial redistribution of the abstraction volumes of Amersfoortseweg, La Cabine and/or Ellecom is considered as a potential adaptation option. In Chapter 3 of this thesis the hydrological impact of this partial redistribution in the Veluwe area is modelled and compared to the impact of climate change. In this chapter it is found that a reduction of 1.5 million m^3/yr at Amersfoortseweg will lead to a significant increase in the nearby groundwater-dependent ecosystem, but reduction of 2 million m^3/yr at La Cabine or 1 million m^3/year at Ellecom will have no or only limited effect on the nearby ecosystems. At Hoenderloo the expansion of the abstraction volume is estimated to cause a decline in groundwater level between 0.5 and 2 m. Compared to the projected impact of climate change, redistribution of 1.5 million m^3/yr Amersfoortseweg would still have a strong positive impact on the Nieuwe Sprengen system. For the two other abstraction sites the projected impact of climate change is stronger than the impact of redistribution. The projected impact of climate change to the groundwater levels compensates more than fully for the decrease in groundwater level as caused by the expansion of Hoenderloo with 4.5 million m^3/year.

Sustainability assessment

The main sustainability challenge for the local drinking water supply system Amersfoortseweg, is the hydrological impact of the abstraction (Fig. 5.8a). The abstraction has a verified impact on the nearby Nieuwe Sprengen ecosystem, and therefore the local authorities and the drinking water company agreed on a reduction of 1.5 million m^3/yr to reduce the impact. The model results in Chapter 3 show that the hydrological impact of the abstractions La Cabine and Ellecom is limited, but stakeholders consider both abstractions unsustainable (Fig. 5.8a and c). Hoenderloo has no current sustainability challenges (Fig. 5.8d). All four local drinking water supply systems have some minor challenges on reliability and resilience of the technical infrastructure.

The increasing water demand will have a negative impact on the sustainability of the local abstractions. This is partially compensated by the impact of the projected climate change, which will also reduce the hydrological impact of the abstractions at Amersfoortseweg, La Cabine and Ellecom (Fig. 5.8a-c). No effect of climate change is projected for Hoenderloo (Fig. 5.8d). While most of the recharge area of these abstractions is forested and protected nature area, land use change and soil energy transition will not affect the sustainability of the abstractions.

Local adaptation options

To meet the sustainability challenges of the local drinking water supply systems Amersfoortseweg, La Cabine and Ellecom three local adaptation options are selected (Table 5.4). Water saving will partially compensate for the impact of the growing water demand, which will improve the resilience of the technical infrastructure. The most important option to compensate the impact of the abstractions, is partial redistribution of 1.5 million m^3/yr abstraction volume from Amersfoortseweg towards Hoenderloo, with or without additional redistribution of 2 million m^3/yr abstraction volume from La Cabine and 1 million from Ellecom. This will result in an extension of Hoenderloo with 1.5 or 4.5 million m^3/yr, which will require adjustment of permits and technical infrastructure. The land use of the central part of the Veluwe area has historically been limited to woodland, heath and sand drifts (Witte et al., 2019), and the groundwater quality in the aquifer is hardly affected by anthropogenic contaminations. Therefore additional groundwater protection or restoration is not necessary.

Future sustainability with adaptation

Partial redistribution of the abstraction volume at Amersfoortseweg towards Hoenderloo is projected to significantly reduce the impact of to the Nieuwe Sprengen system and thus improve the sustainability score for impact of the abstraction (Fig. 5.8a). Partial redistribution will have limited effect on the sustainability characteristic of the impact of the abstraction of La Cabine and Ellecom. (Fig. 5.8b-c). The extension of Hoenderloo with 1.5 million m^3/yr will have limited effect on the impact of the abstraction, but will affect the reliability and resilience due to the limited abstraction permit and technical infrastructure limitations. This adaptation measure can only be used when combined with an extension of the permitted abstraction volume and development of new production and distribution capacity (Fig. 5.9).

Extension of Hoenderloo with 4.5 million m^3/yr will increase the affected area, reaching up to the Renkum Brooks system at the edges of the Veluwe, and thus will reduce the sustainability score of Hoenderloo (Fig. 5.9b). This will limit the possibility of obtaining the required extension of the permitted volume and will need major adjustments to the technical infrastructure.

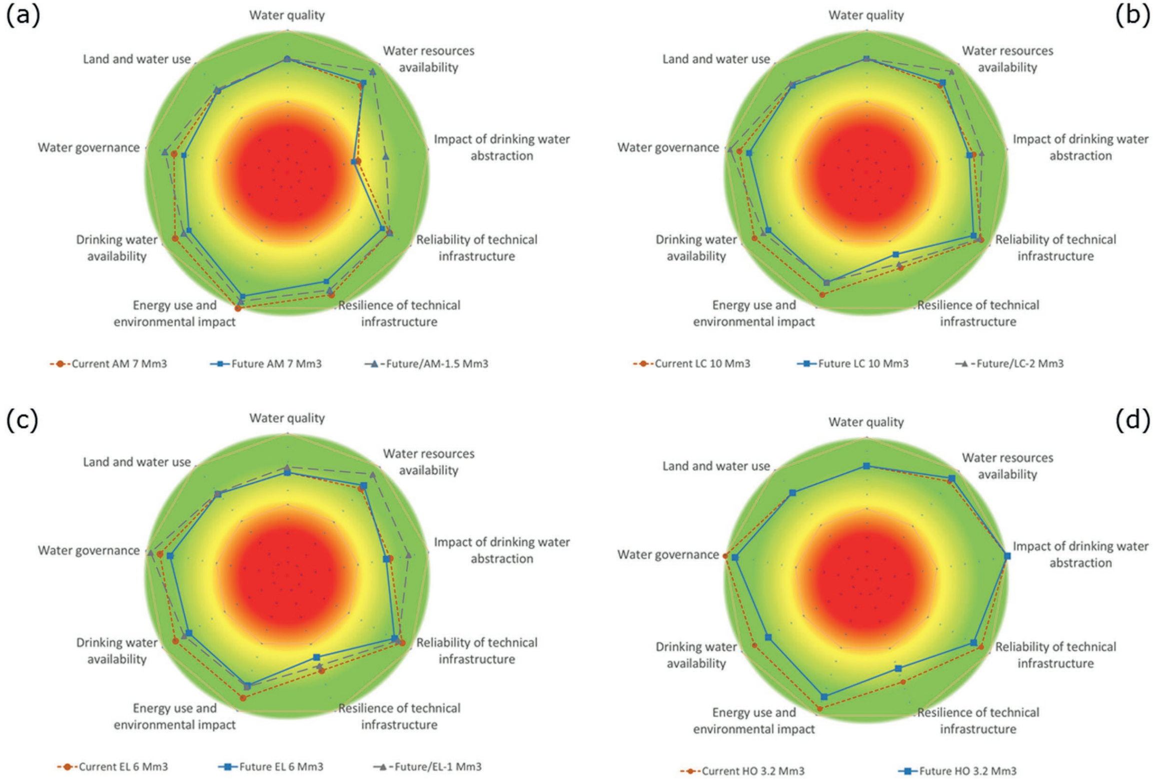


Figure 5.8 *Current sustainability (brown), future sustainability (blue) and future sustainability after redistribution (grey) of the local drinking water supply systems Amersfoortseweg (AM – 1.5 million m^3/yr), La Cabine (LC – 2 million m^3/yr) and Ellecom (EL – 1 million m3/yr) for drinking water abstraction (a) AM, (b) LC and (c) EL and Hoenderloo (HO).*

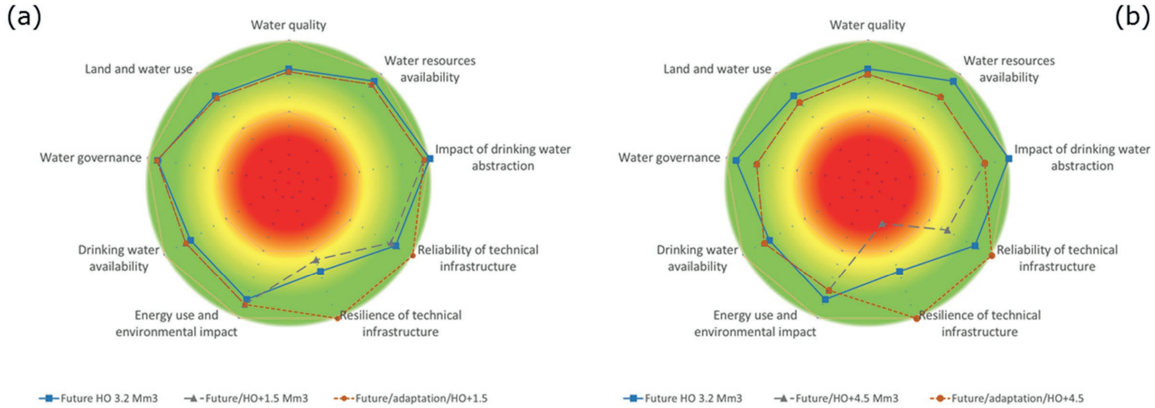


Figure 5.9 *Future sustainability of Hoenderloo (blue), future sustainability with redistribution (grey), and future sustainability with water saving, redistribution and adjustment of permit and technical infrastructure (brown), with (a) Hoenderloo + 1.5 and (b) Hoenderloo + 4.5 Mm3/yr.*

5.4.3 Sustainability assessment riverbank abstraction Vechterweerd

General description

Local drinking water supply system Vechterweerd is a so-called “riverbank” abstraction, situated close to a river, with groundwater wells that are abstracting a mixture of 40% groundwater and 60% recently infiltrated surface water. As a result of the large contribution of surface water, the water quality is also vulnerable to changes in the surface water system, for instance caused by calamities and climate change. Because of the uncertain water quality there is a complex water treatment using activated carbon, membrane filtration and UV, and a comprehensive monitoring program for ground- and surface water quality. The abstraction permit is 8 million m^3/year, the current production capacity is sufficient for 2 million m^3/yr. Because of the increasing water demand and limited availability of drinking water abstraction permits in the area, the legal authority has given Vitens the assignment to evaluate the possibilities of extension of the production capacity of Vechterweerd within the current permit.

Sustainability assessment

The current sustainability challenges for the local drinking water supply system Vechterweerd, the Netherlands, are on water quality, water resource availability, and energy use and environmental impact (Fig. 5.10a). In the future the reliability of the facility and land use may become sustainability challenges. These challenges are mainly caused by the impact of the large contribution of surface water to the water and the complex water treatment that is required to meet the drinking water standards. To evaluate the impact of extension of Vechterweerd to meet current and future water demand, we compared the actual situation with 2 million m^3/year production capacity with a situation with 6 million m^3/year production capacity (Fig. 5.10b). The results show that the current and future sustainability challenges will increase further because the impact of the surface water quality will increase and the complex treatment must triple, with a large increase in energy use and environmental impact. The future developments will enlarge this impact and with the extension the sustainability of Vechterweerd will deteriorate further in the future.

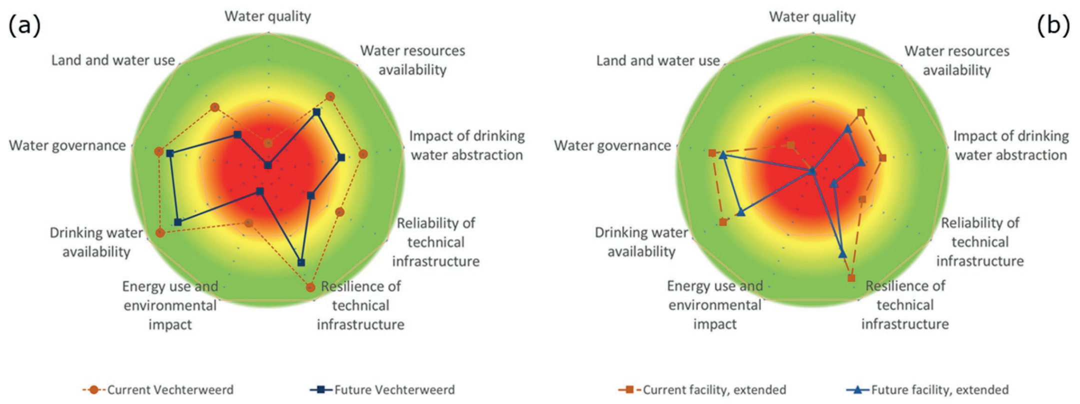


Figure 5.10 *Results Vechterweerd drinking water abstraction, the Netherlands: current (blue) and future sustainability (brown) of (a) the present production capacity of 2 million m^3/year and (b) an extended production capacity of 6 million m^3/year.*

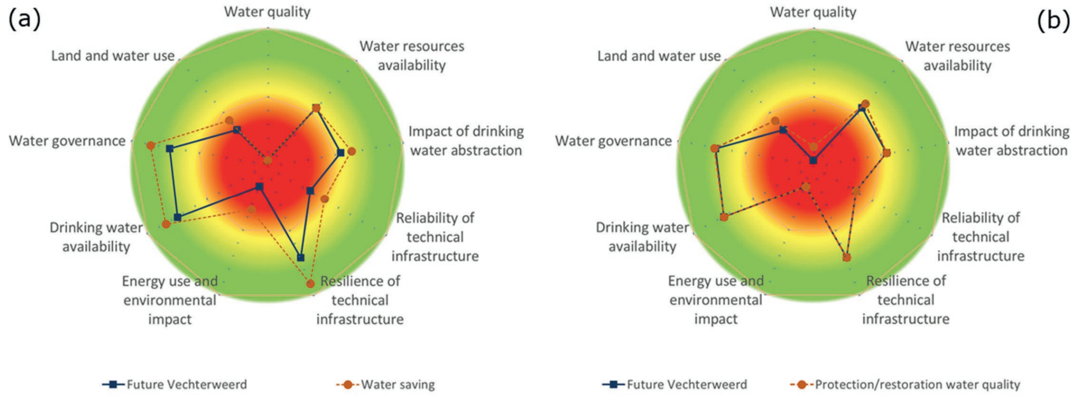


Figure 5.11 *Long term impact of the selected local adaptation options (brown): (a) water saving, (b) protection/restoration water quality compared to future sustainability (blue) of the Vechterweerd drinking water abstraction, the Netherlands.*

Local adaptation options

To meet the sustainability challenges of Vechterweerd two adaptation strategies are relevant: water saving and protection or restoration of water quality (Table 5.4). Water saving is a general option to limit the water demand growth, which will affect most sustainability characteristics positively (Fig. 5.11a). The selected local adaptation options are protection of the surface water quality, protection of the groundwater quality and improvement of the groundwater protection zone. These measures will not solve all water quality problems, but will help to prevent further deterioration. Because of the large contribution of surface water to the raw water quality the combined impact of these measures to the sustainability challenges is small (Fig. 5.11b).

Future sustainability with adaptation

The only available local adaptation options for Vechterweerd - next to water saving - are measures to protect and restore water quality. As explained in Section 5.3.3, the positive impact of these measures is limited, but they may prevent further deterioration of the raw water quality. While the future developments will negatively affect the surface and groundwater quality near Vechterweerd, these adaptation options will not fully compensate for the future developments (Fig. 5.12). As a result, the future sustainability will only slightly improve by the local adaptation options and will be less than the current sustainability.

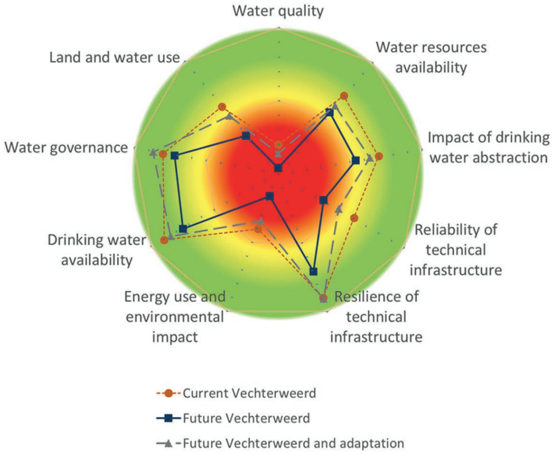


Figure 5.12 *Current sustainability (brown), future sustainability (blue) and future sustainability after adaptation with the selected local adaptation options (grey) of the local drinking water supply system Vechterweerd, the Netherlands.*

5.5 Discussion

Sustainability assessment

It is unlikely that for any local drinking water supply system all sustainability characteristics are assessed as sustainable at any moment in the future, because of trade-offs between criteria, and invariability of some hydrological criteria. The aim of adaptation is to improve the sustainability by sustainable development. While in general the direction of the impact of future developments and adaptation options can be indicated in terms of negative, positive or neutral to the sustainability, the extent of the impact is less distinct. Considering this, and knowing that there is no standard unit to measure sustainability, the researchers chose to use a gradual colour scheme to present the results of the sustainability assessment. The results thus compare current and future sustainability, providing insight into the development of sustainability challenges of the local drinking water supply system.

Stakeholders may have different views on how to define a sustainable local drinking water supply system. For instance, nature preservation organisations measure the sustainability by the impact of an abstraction to valuable nature, whereas households may value “safe and continuous drinking water supply” sustainable. The used criteria are defined as measurable as possible (App. VI). In the Sustainable Society Index, indicators are only used if they are measurable and if the required data are available (Van der Kerk et al., 2014). However, to ensure the full scope of a local drinking water supply system, the authors chose to include all relevant sustainability criteria, including criteria that can only be qualitatively valued.

Case studies

In this research the sustainability of the managed aquifer recharge by infiltration near Epe, the partial redistribution of abstraction volumes of four Veluwe abstractions, and Vechterweerd in the Netherlands was assessed. In the case of Epe, mitigation of the hydrological impact of the abstraction was obligatory following legislation and regulations on nature protection. A better understanding of the impact and trade-offs of the infiltration to the sustainability of this local drinking water supply system might have led to additional measures to reduce energy use or to further protect surface water quality.

Redistribution of 1.5 million m^3/yr abstraction volume from Amersfoortseweg towards Hoenderloo may be an effective adaptation measure to reduce the hydrological impact of

Amersfoortseweg, but will require extra abstraction permit volume and adjustments of the technical infrastructure. An additional partial redistribution of La Cabine and Ellecom towards Hoenderloo, especially when compared to the impact of climate change, will hardly contribute to a sustainable development of these local drinking water supply systems, and moreover also will reduce the sustainability of Hoenderloo. It will also require further adjustments of the abstraction permit and the technical infrastructure of Hoenderloo. An extension of the production capacity of Vechterweerd will reduce the sustainability of this local drinking water supply system. However, this may be an adaptation option that can help to improve the overall sustainability of the drinking water supply in a larger area, when this option is used to replace other abstractions.

In general the assessment results show that all adaptation strategies may not be sufficient to compensate for the long-term impact of the future developments to local drinking water supply systems. Compensating the impact of groundwater abstraction may cause trade-offs, and all strategies require stakeholder involvement. Scaling the assessment up to a regional scale by including nearby interconnected local drinking water supply systems, may support finding sustainable adaptation strategies in a certain region.

Stakeholder involvement

As stated above, stakeholder involvement is essential in the adaptation planning process, because local drinking water supply systems are strongly embedded in the environment and thus relate to local stakeholder interests. In the planning process of Epe and Vechterweerd, the drinking water company worked closely together with local stakeholders such as governmental agencies and local interest groups.

All four main adaptation strategies require stakeholder involvement. The adaptation option of redistribution of abstraction volumes in the Veluwe area is one of the options that is considered in a large-scale stakeholder process led by the province of Gelderland to locate additional strategic reserves for drinking water supply within that province. A drinking water company can initiate improvement of the reliability or resilience of the abstraction, and can also start stakeholders processes on expansion, mitigation or compensation of the impact of drinking water abstraction. Although stakeholder processes may help to find common ground, legal authorities must of course follow the authorisation procedures for abstraction, nature and building permits, and stakeholders may legally appeal to the decisions on permits taken by the legal authorities. Adaptation strategies on water saving require commitment and co-operation from all stakeholders on national and regional level, as well as from local households, which makes the effectiveness of the strategy uncertain. The adaptation strategy protection and restoration of water quality is a valuable strategy, but also requires a collective effort from multiple stakeholders.

Usability of the framework

The developed sustainability assessment framework is based on the sustainability characteristics and criteria in Chapter 4, downscaling targets from Sustainable Development Goals 6 (UN, 2015) to a local level. It integrates the outcome of different types of models, such as hydrological and drinking water infrastructure models, rather than guiding new model development. Improving the sustainability of local drinking water supply systems is a challenge for drinking water companies and governments worldwide.

The sustainability assessment for local drinking water supply systems by means of the framework that is developed in this chapter, can be performed under various conditions in Europe as well as in other parts of the world. In this chapter the sustainability characteristics are elaborated for the Dutch drinking water supply challenges. However, in settings that are different form the Dutch situation, the sustainability characteristics and criteria proposed in Chapter 4 can be used as a basis for a sustainability assessment framework that fits the local situation.

Data availability is a precondition to perform the sustainability assessment, but the assessment can also be used to identify knowledge gaps on the sustainability of a drinking water supply system. The strong focus of the sustainability assessment to the local level limits the possibilities to directly scale up the results to a national or global level. However, it may be developed further into a higher aggregation level by for instance accumulating local results to an area or drinking water company’s level or defining composite criteria.

In the sustainability assessment economic aspects are taken into account in criteria such as the water tariff and the energy use. The investment costs of the adaptation options however are not part of the assessment. The decision-making process is complex and takes into account costs, legislation and regulations as well as stakeholder interests and opinions. The proposed sustainability assessment may provide valuable knowledge to this complex process.

5.6 Conclusion and recommendations

In this research a locally oriented sustainability assessment was developed, to support the adaptation planning process for local drinking water supply systems, by means of an integrated framework based on multi-criteria analysis. The research brings together scientific and experiential knowledge on sustainable local drinking water supply systems. Performing the sustainability assessment together with the stakeholders will help to integrate scientific and stakeholders knowledge and interests. Additionally it will provide stakeholders with an overview of the sustainability challenges, the impact of adaptation options and their trade-offs for the stakeholder interests as well as for the drinking water supply interests.

The results of the illustrative sustainability assessment of three cases indicate that this assessment framework may provide decision-makers with a transparent understanding of trade-offs that come with adaptation options. The information generated by the sustainability assessment may help to carefully balance relevant aspects playing a role in the decision-making process on adaptation of a local drinking water supply system.

To enhance the transferability, it is recommended to test and further develop the sustainability assessment. for example by scaling up the assessment to a drinking water company’s level or to a national level. This, may contribute to sustainable development of the drinking water supply system on a strategic level.

6

Synthesis

6.1 Introduction

The WHO and UNICEF (2017) estimated that in 2015 nearly 30% of the global population did not have access to a safely managed drinking water supply. Thus, SDG 6 seeks to “ensure availability and sustainable management of water and sanitation for all” by the year 2030. The targets associated with SDG 6 stipulate access to safe and affordable drinking water for all, water quality protection, sustainable and efficient use and withdrawal of freshwater, and implementation of integrated water resources management (UN, 2015). Developments such as climate change and population growth put drinking water supply worldwide under pressure, even in places where currently sufficient drinking water is available. In the Netherlands, for example, everyone has access to safe and affordable drinking water and adequate sanitation. However, water quality protection, water-use efficiency and protection of water-related ecosystems do pose sustainability challenges in the Netherlands. These challenges, moreover, will be exacerbated in the future by climate change and other environmental and socio-economic developments.

To achieve SDG 6, governments must develop policies, legislation and regulations for sustainable (drinking) water management, considering these developments but also the interests of the different stakeholders. Sustainability assessments are considered a powerful tool for understanding the sustainability challenges societies now face, as well as for weighing adaptation options regarding different water system components (Ness et al., 2007, Singh et al., 2012). Examples of sustainability assessments related to water management are found in the Sustainable Society Index (Van der Kerk and Manuel, 2008), the International Water Association Performance Indicator System (Alegre et al., 2006), the Groundwater Footprint (Gleeson and Wada, 2013) and the City Blueprint (Van Leeuwen et al., 2012). More specifically related to drinking water supply is the EBC Performance Assessment Model (European Benchmarking Co-operation, 2017), which provides benchmarks for water and wastewater utilities. Because drinking water production is embedded in the local environment and local societal interests, adaptation strategies for the sustainable supply of drinking water must be developed on the local scale. However, although the examples mentioned above do include criteria that are relevant on various spatial and organisational scales, they do not fully consider the specific local conditions important for drinking water supply with all of the various hydrological, technical and socio-economic interconnections.

This thesis sought to better understand the complexity and the sustainability challenges posed by drinking water supply on the local scale. As such it contributes to an evolving body of sustainability analyses and assessments oriented towards achieving the SDGs (UN, 2015). The definition of sustainability used here incorporates hydrological as well as technical and socio-economic elements. Two main objectives were set for this research:

- To quantify the impact of measures to improve the hydrological sustainability of local drinking water abstraction in a glacial moraine complex;
- To provide insight into the sustainability of local drinking water supply systems, by means of a sustainability assessment framework.

This synthesis chapter is organised as follows. Section 6.2 answers the four research questions formulated in Chapter 1, and Section 6.3 summarises the main findings. In Section 6.4 the research methodology and results are discussed. Section 6.5 presents the scientific contributions of the research. Finally, Section 6.6 and 6.7, respectively, offer recommendations for sustainable drinking water supply and future research.

6.2 Answering the research questions

This section returns to the research questions formulated in Chapter 1. Figure 6.1 presents an overview of the questions and the study output.

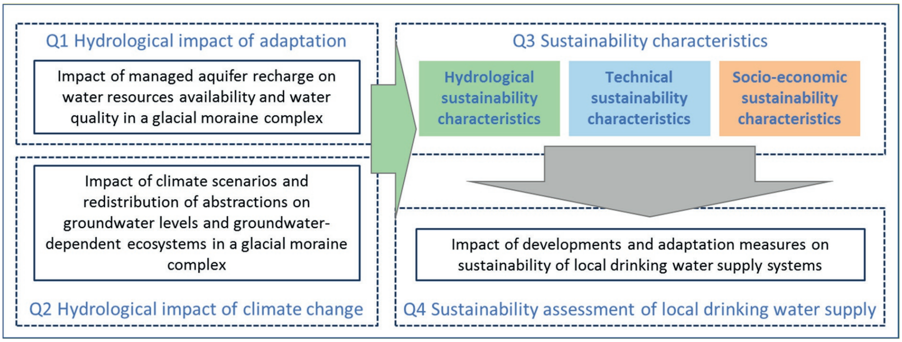


Figure 6.1 *Overview of the research questions and study output.*

Q1: What is the impact of managed aquifer recharge (MAR) as compensation for the hydrological impact of local drinking water abstraction in a glacial moraine complex? (Chapter 2)

The Veluwe area in the Netherlands is a glacial moraine complex, and an important resource for drinking water. Some of the local drinking water abstractions in the Veluwe area negatively affect nearby groundwater systems, for instance, near the town of Epe (for location see Fig. 2.1). Since 1998 this hydrological impact has been compensated by introducing a MAR strategy, through infiltration of surface water. The analysis in Chapter 2 found that local tilted clay layers in the glacial moraine complex of the Veluwe have strongly influenced the impact of the infiltration. Due to the limited hydraulic conductivity of these clay layers, the largest impact of the infiltration on the local groundwater system was found in the groundwater compartment between the clay layers adjacent to the MAR location. In the nearby Wisselse Veen wetland system, however, the model showed no impact of abstraction or infiltration. This is an area with a fast-responding surface water system that discharges groundwater, which suggests that the impact of MAR on local groundwater levels may be limited in comparably fast-responding hydrological systems.

The evaluation did find that 20 years of MAR near the local drinking water abstraction in Epe had a positive impact on nearby groundwater levels. However, it did not show a significant restoration of groundwater levels in the nearby groundwater-dependent ecosystem. The infiltration affected groundwater quality mainly through cation exchange and dispersion. In general, we can conclude that in a glacial moraine complex, MAR can be an effective adaptation strategy for storage of surplus surface water, as well as for compensation of groundwater abstraction and water quality improvement. However, if the hydrogeological system is not fully understood, MAR may cause unintended side effects, such as problematic changes in water quality and increased groundwater levels in other areas than expected.

Q2: What is the impact of redistribution of local drinking water abstraction volumes on groundwater levels in a glacial moraine complex, and how does this compare to the projected impact of climate change? (Chapter 3)

The Dutch Veluwe is a push moraine system, which is a complex hydrogeological setting. Groundwater in the Veluwe area is an important resource for drinking water for the Netherlands. However, some drinking water abstractions here have a negative hydrological impact on groundwater-dependent ecosystems. To reduce this impact, a redistribution of abstraction volumes among existing abstraction sites within the Veluwe area is being considered as adaptation measure, to restore groundwater levels and flows to nearby ecosystems. Redistribution was found to have merit as an adaptation strategy in only one of the studied locations. The results show that the effectiveness of this adaptation strategy strongly depends on the effect of the tilted clay layers between the abstraction points and the nearby groundwater-dependent ecosystems.

Additionally, the results on the redistribution scenarios were compared to the projected impact of climate change scenarios. In the central zone of the Veluwe, natural surface water is absent and precipitation evaporates or recharges the groundwater system. The water systems surrounding the Veluwe have very different hydrological characteristics, with dense surface water systems that discharge water from the area. Due to these differences, climate change will cause different impacts. Specifically, outside the Veluwe the dense surface water systems will discharge most of the projected extra precipitation, and climate change is expected to cause groundwater levels to drop by up to 1 m due to increased evaporation. In the Veluwe the extra precipitation is expected to further recharge the groundwater system, and thus climate change scenarios project that groundwater levels will increase by up to 2 m. The rising groundwater levels projected for the central Veluwe area will somewhat reduce the impact of abstractions on nearby groundwater-dependent ecosystems, and may even exceed the impact of redistribution of abstraction volumes in some parts of the Veluwe area. Improved understanding on the local hydrogeological system and on how climate change affects the groundwater system is needed to provide a solid basis for adaptation strategy development. Use of a state-of-the-art hydrological model is recommended for this purpose.

Q3: What sustainability characteristics are relevant for local drinking water supply systems? (Chapter 4)

An integrated systems approach was used to identify sustainability characteristics relevant for local drinking water supply systems, considering hydrological, technical and socio-economic aspects. Sustainability issues were derived from an analysis of three cases on drinking water supply in the Netherlands. In these cases on water shortage, water pollution and growing demand for drinking water the sustainability of drinking water supply is seriously affected. Impacts of these pressures ranged from water resource availability limitations and water quality deterioration, to technical infrastructure constraints and stakeholder conflicts. Given the long lifecycles and inflexibility of the technical infrastructure, responses to short-term events had to be implemented within the existing drinking water supply system. However, the cases also showed that adaptations in the short term are required to respond in a timely way to long-term developments, such as pressures on water quality and water resource availability. Long-term responses may include, for instance, new legislation and policies on drinking water management, water saving strategies and technical innovations to reduce drinking water demand, expansion of technical infrastructure and abstraction permits, and measures to compensate for the impact of drinking water abstraction.

Applying the integrated systems approach, the sustainability issues identified in the case studies were categorised into a set of hydrological, technical and socio-economic sustainability characteristics: water quality, water resource availability, the impact of drinking water abstraction, reliability and resilience of the technical system, energy use and environmental impact, drinking water availability, water governance, and land and water use. To increase the transferability of the proposed sustainability characteristics to other areas, the sustainability issues identified from the case studies were paired with global issues concerning sustainable drinking water supply. This resulted in a proposed set of generally applicable sustainability characteristics, each divided into five criteria. Elaboration of these characteristics in a sustainability assessment could help to identify the trade-offs associated with various adaptation strategies, which could increase decision-making transparency for local stakeholders (Hellegers and Leflaive, 2015).

Q4: How can the identified sustainability characteristics be used to assess the sustainability of a local drinking water supply system? (Chapter 5)

The hydrological, technical and socio-economic sustainability characteristics proposed in Chapter 4 were translated into criteria that fit local drinking water supply systems in the Netherlands. A multi-criteria analysis was conducted to assess the impact of local adaptation measures on the sustainability of local drinking water supply systems. Four overarching adaptation strategies to ensure a sustainable local drinking water supply were identified: water saving, protection and restoration of raw water quality, mitigation or compensation for the impact of drinking water abstraction, and improvement of the reliability and resilience of the technical infrastructure.

The impact of various local adaptation options on the sustainability of local drinking water supply was assessed. Specific options considered were managed aquifer recharge (MAR) through infiltration, redistribution of drinking water abstraction volumes and development of riverbank abstraction, all aiming to mitigate or compensate for the impact of the abstractions. For these adaptation options to work, additional measures were required, including improvement of the reliability of the technical infrastructure, and extension of abstraction permits and expansion of treatment capacity to improve the resilience.

The sustainability assessment produced an overview of challenges and trade-offs associated with future developments and adaptation measures. The results of this analysis will provide decision-makers and stakeholders a better understanding of potential impacts of both broader developments and local adaptation measures.

6.3 Main findings

The research demonstrates that the integrated systems approach adopted in this thesis, zooming in on the local scale, helps to understand the complexity of sustainable development of drinking water supply. The analysed cases emphasise the urgency to combine local hydrological, technical and socio-economic sustainability characteristics to provide a complete overview of sustainable drinking water supply on a local scale. They also help to identify the sustainability challenges in a specific local situation and to find adaptation measures suitable for these local challenges. Additionally, the results show that the temporal scale can be represented by taking into account the impact of short-term and long-term developments.

This thesis identifies four main adaptation strategies that aim to increase the sustainability of the local drinking water supply system. These were elaborated into potential adaptation measures for addressing the local challenges. The main findings on potential positive impacts and trade-offs related to the various adaptation measures are summarised in Table 6.1.

Table 6.1 *Summary of the impacts and trade-offs found in this research on adaptation strategies towards a sustainable drinking water supply*

Adaptation strategy	Adaptation measures	Impacts and trade-offs	Chapter
Water saving	Public campaign on water saving	Water saving has a positive impact to most of the sustainability characteristics. There are no significant trade-offs, unless the drinking water demand would for example halve in volume. Such an extreme reduction might lead to drinking water quality problems.	5
	Technical innovations, water re-use	Technical innovations and water re-use may help to significantly reduce the water demand.	5
	Increasing or progressive drinking water tariffs	Increasing or progressive drinking water tariffs may stimulate water saving and thus reduce the drinking water demand. In contexts where affordability is an issue, this may limit the drinking water availability due to the higher water tariffs.	4, 5
Protection and restoration of water quality	Regulations on water quality protection	All potential adaptation measures for protection and restoration of water quality will affect land and water use to a certain extent. Additional regulations may cause limitations or economic damage for current land and water users.	4
	Land and water use changes		
Mitigation or compensation of impact of abstraction	Managed aquifer recharge (MAR)	Mitigation or compensation of the impact of the abstraction by MAR may cause unexpected side-effects in other areas due to complex hydrogeology. It may also potentially introduce a risk of water pollution.	2, 5
	Redistribution (or relocation) of abstraction volumes	Redistribution (or relocation) of abstraction volumes to other areas may reduce current negative impact, but may also cause negative impacts to the water system near the new abstraction location.	3, 5
	Transition from groundwater to riverbank or surface water abstraction	Transition to riverbank or surface water abstraction will require new facilities and more intensive water treatment. This will affect the resilience and reliability of the technical infrastructure as well as enlarge the energy use and environmental impact. To ensure the water quality, protection and restoration of water quality may be necessary, which will affect land and water use as described above. The transition will require large investments, that may result in increasing drinking water tariffs. This may be an incentive for water saving, but could also limit the drinking water availability if the affordability is an issue.	5
Improvement of reliability and resilience	Extension of abstraction permits	Extension of abstraction permits will improve the reliability and resilience for a growing drinking water demand. Extension however may in certain areas result in a limited water resource availability depending on the water system conditions. The required protection of water quality will affect land and water use as described above. The impact of the abstraction will increase, and mitigation or compensation will be mandatory with the abovementioned impacts and trade-offs.	4

Adaptation strategy	**Adaptation measures**	**Impacts and trade-offs**	**Chapter**
	Expansion of production capacity	Expansion of the production capacity will ensure and improve the reliability and resilience of the technical infrastructure and enlarge the drinking water availability. However, additionally the energy use and environmental impact will increase due to the extra drinking water production.	4
	Adjustment of treatment method	If due to water quality deterioration a more intensive water treatment is required, this will enlarge the energy use and environmental impact of the drinking water supply.	4, 5

Considering these findings, it can be concluded that the effectiveness of adaptation measures that aim to reduce the hydrological impact of drinking water abstraction may be enhanced or limited by the local hydrogeological conditions. Moreover, adaptation measures may have positive impacts as well as trade-offs to various sustainability characteristics, In general the projected short-term and long-term developments affect the sustainability of local drinking water supply systems negatively. From the sustainability assessment it is expected that the available adaptation measures will not be sufficient to compensate for the impact of these developments, as is illustrated in Fig. 6.2 (see Section 5.4 for further explanation on the sustainability assessment).

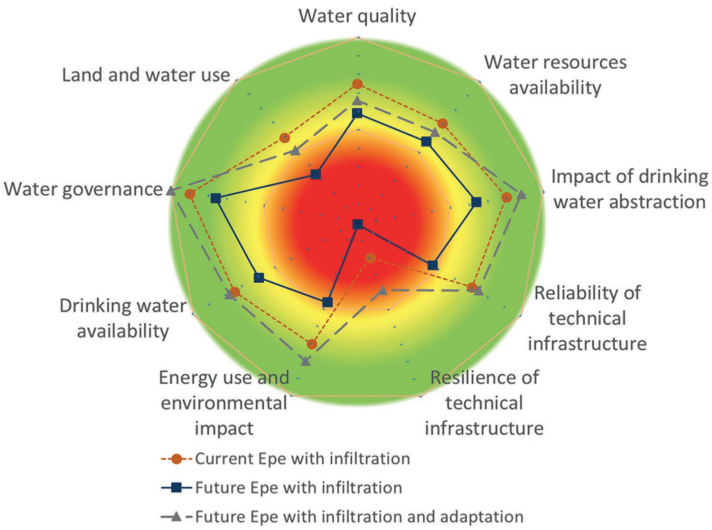


Figure 6.2 *Current sustainability (brown), future sustainability (blue) and future sustainability after adaptation with all selected local adaptation options (grey) for the Dutch drinking water supply system groundwater abstraction Epe with infiltration (see Chapter 5).*

The sustainability assessment as developed in this thesis thus can be used to provide an overview on important trade-offs associated with alternative adaptation measures for local sustainability challenges, and on the impact of projected future developments to the sustainability of drinking water supply on a local scale.

6.4 Discussion

This discussion section reflects on the main findings of my research, the research approach, its general applicability, and my own position as researcher.

Main findings

The findings of this research provide a better understanding of the complexity of sustainable drinking water supply on the local scale, and contribute to the larger literature on sustainable water management and adaptation to current and future developments. Dermody et al. (2018) for example already pointed out the complexity of water security, with its interdependencies and cross-scale feedbacks. Moreover, the trade-offs between human and environmental water needs are well known (Pahl-Wostl et al., 2013). A variety of sustainability assessment procedures have been developed for water management. One of these is benchmarking for water utilities (European Benchmarking Co-operation, 2017). Huskova et al. (2016) developed a method for screening trade-offs involved in promising interventions in drinking water supply infrastructure. Pahl-Wostl et al. (2013) concluded that multi-level and inter-sectoral governance strategies may help in overcoming the cross-scale interactions commonly found in water systems. The findings in this thesis complement this broad knowledge field on sustainable water management with the integrated assessment of the sustainability of local drinking water supply.

By translating the global challenges to a local scale, this research emphasised that local characteristics are determinant factors in the sustainable development of drinking water supply. The research, additionally, provided insight on the diversity of potential adaptation measures, the positive impacts as well as trade-offs involved in these measures, and the impact of cross-scale interactions between the temporal, spatial and organisational scales. Taken together, this knowledge expands understanding of the local challenges arising from the global aim of transitioning towards sustainable drinking water supply.

Research approach

The research approach employed focused on the sustainability of drinking water supply on a local scale, using various local-scale cases from the Dutch drinking water supply sector. Although case study research may be considered controversial, the broad concept of sustainability requires a holistic perspective, which pleads in favour of investigating its challenges through in-depth analysis of cases in their real-life context (Zainal, 2007). This research, rooted in the current practice of the drinking water company Vitens in the Netherlands, benefited from detailed data and knowledge gained from experience and insight into local sustainability challenges in the presented cases. This experiential knowledge was invaluable, given the emphasis of the research on the local scale. However, the importance of local knowledge is a limitation as well as a strength in the proposed sustainability assessment. Deep, experiential knowledge of the local context, as was available in this research, can ensure a good understanding of the local sustainability challenges and thus help in selecting adequate adaptation options for the local drinking water supply system. However, if there are data availability limitations, this may undermine the results. If, for instance, there is a lack of sufficiently detailed hydrological information, the sustainability assessment may be poorly substantiated, which could devalue its results.

General applicability

An important source of experiential knowledge for this research was provided by case studies on Dutch drinking water supply. The results of this research will therefore certainly be applicable in comparable settings in the Netherlands, for instance, for other Dutch drinking water companies than Vitens. However, the question may be asked of whether the results are more widely applicable, considering the substantial challenges faced worldwide in sustainable drinking water supply. The Netherlands is generally well-known for its characteristic “polder model” of governance, which is based on cooperation and consensus building between government and stakeholders. This may suggest that findings from the Netherlands may not be easily transferable to other countries (Schreuder, 2001). However, because of this “polder model” the Dutch cases included a wide perspective of sustainability issues, which provided valuable knowledge for the sustainability assessment. Moreover, the level of sustainability of the drinking water supply sector in the Netherlands is already rather high, compared to most other countries. This is due to the Netherlands’ high standard of drinking water supply and water management (Ministry of Infrastructure and Environment and Ministry of Economic Affairs and Climate Policy, 2019) and well-organised water regulation and governance (Van der Kerk et al., 2014). This high standard meant that this research had relatively easy access to detailed data and models.

In conclusion, drinking water availability, water quality and water resource availability, as well as water governance, are key challenges around the globe. The nature of the sustainability challenges encountered in the Dutch cases is comparable to these key challenges. Cross-checking and adapting the results of the analysis of the Dutch situation to the challenges faced worldwide, helped to further broaden the perspective to contexts outside of the Netherlands. Nevertheless, application of the developed sustainability assessment in other (local) areas in other contexts will further improve the general applicability.

My own position

I conducted this research while also working at Vitens, a public Dutch drinking water company responsible for drinking water supply to 5.6 million people in the Netherlands (Vitens, 2016). Following the Dutch Drinking Water Decree (Dutch Government, 2009) and the European Water Framework Directive (European Union, 2000), Vitens developed a strategy for the future focused on providing a drinking water supply infrastructure that is resilient to future developments (Vitens, 2016). While my research topic “towards sustainable drinking water supply” aligns with the aim of European and Dutch legislation and this strategy, Vitens gave me carte blanche in my research approach. My background, which included 23 years of work experience at Vitens, provided much practical knowledge for this thesis, and the cases used in this research were substantiated by data collected and validated by Vitens. This meant that the research benefited from valuable knowledge on drinking water supply that was not publicly available.

My work over the past 23 years has been aimed at safeguarding the drinking water supply for the future, by sustainably fitting drinking water abstractions into the local hydrological system, as well as by protecting the quality of groundwater at local abstractions by limiting the impact of land and water use. Due to the local embedding of drinking water abstractions, many stakeholders with various interests are connected to the abstractions. Given the Dutch “polder model” culture (Schreuder, 2001), safeguarding drinking water supply for the future requires initiating and participating in multiple local stakeholder processes, with participants representing agriculture, nature conservation, the built environment and local residents, as well as provincial and municipal governments, water boards and domestic and industrial customers. My multiple interactions with these various stakeholders have provided me a broad perspective on the interests involved in drinking water abstraction and supply.

Working at a drinking water company also gave me an understanding of the technical sustainability aspects of a safe and affordable drinking water supply. With a different background, I might have considered the technical issues of less importance for sustainable drinking water supply, compared to the hydrological and socio-economic issues. Given the importance of the technical infrastructure for drinking water supply (Bauer and Herder, 2009), this would have been a serious oversight in the research. My research results indicate that hydrological and socio-economic developments and adaptation measures can affect the reliability and resilience of the technical drinking water infrastructure. Energy use can be increased, additional excipients may be required or the production of wastewater and waste materials may be influenced, which can put the sustainability of drinking water supply under pressure. I did not focus on the financial aspects of these impacts in my research. However, my own experience at Vitens suggests that adaptation of drinking water supply infrastructure to such technical sustainability challenges requires large societal investments and may lead to higher exploitation costs. This could result in increased drinking water tariffs. In the Netherlands, higher drinking water tariffs may be an incentive to reduce drinking water consumption, but worldwide higher tariffs could put the affordability of drinking water under pressure, conflicting with the intentions of SDG 6.

6.5 Scientific contributions

This section synthesises the main scientific contributions of the research, subdivided into four themes.

Understanding how adaptation measures and other developments, such as climate change, affect drinking water supply

The research reported on here has increased our general understanding of the hydrogeological system associated with a push moraine complex with tilted clay layers. More specifically, it has produced new knowledge about the hydrogeological impact of climate change in the Veluwe area in the Netherlands. Findings from the research emphasise the importance of a full understanding of the hydrogeological system, in order to better project the impacts of the adaptation strategies being considered. The research also demonstrated that future developments may counteract or amplify the impact of an adaptation strategy, again pointing to the importance of taking future developments into account when modelling and comparing strategies.

Managed aquifer recharge (MAR) by infiltration (Chapter 2) was implemented as an adaptation measure to compensate for the hydrological impact of local drinking water abstraction on a nearby groundwater-dependent ecosystem. The evaluation presented in this research has shown that, although the infiltration has had positive impact on groundwater levels, due to the hydrogeology of the area it has not contributed significantly to restoration of groundwater levels in the nearby groundwater-dependent ecosystem. Furthermore, the projected impact of climate change was compared to the impact of redistribution of water abstraction volumes (Chapter 3). The findings confirm that it is essential to consider future developments when taking decisions on adaptation measures to reduce the hydrological impact of drinking water abstraction. In general, the results confirm that MAR by infiltration and redistribution of abstraction volumes can increase water resource availability in a glacial moraine complex and limit the impact of abstractions. These adaptation strategies therefore seem likely to contribute to sustainable use of a glacial moraine complex for drinking water supply.

Understanding the complexity of sustainable local drinking water supply

The scientific literature on water management points to many interactions between the hydrological, technical and socio-economic systems. In this research we therefore combine the socio-ecological and the socio-technical approach, describing the local drinking water supply system in terms of hydrological, technical and socio-economic characteristics. The results of this research confirm that water resource availability and quality are the product of a variety of interactions and feedback loops (Liu et al., 2015a). Analysis of these interactions and sustainability characteristics helps us to better understand the complexity of drinking water supply systems and the challenges inherent in drinking water abstraction.

The many interactions complicate adaptation planning for local drinking water supply. The case studies presented in Chapter 4 confirmed these interactions, demonstrating that sustainable drinking water supply requires well-functioning technical infrastructure that is sustainably embedded in the socio-economic and hydrological system (Sivapalan et al., 2012). The long lifecycles (30-90 years) characteristic of the technical components of a drinking water supply system, and the lock-ins and legacy effects caused by past decisions, limit the range of possible choices in the future (Liu et al., 2007). Adaptation to longer term developments may therefore require early actions today, even though the outcomes of these actions can seldom be fully understood in advance (Bauer and Herder, 2009). The insights provided by this research can help stakeholders select “no-regret” measures that can be implemented in the short term, without affecting or preventing other promising options (Loucks et al., 2017). By bringing into focus on a local scale the sustainability of drinking water supply systems in their local environment, these results contribute to overcome the scientific knowledge gap identified.

An integrated approach to sustainable drinking water supply

As stated above, the complexity of sustainable drinking water supply demands an integrated approach. This research demonstrated that, while it is important to reduce the local hydrological impact of drinking water abstraction, hydrological facts and figures alone do not determine whether an adaptation measure will increase the sustainability of a local drinking water supply. Introducing changes to drinking water infrastructure may increase energy requirements, or introduce a need for additional excipients or lead to greater production of wastewater or waste materials such as iron sludge. Changes may also require substantial public investment or take a long time before becoming effective. Additionally, legislation and regulations as well as stakeholder interests influence whether measures or strategies are acceptable. Therefore, technical and socio-economic impacts must be analysed in addition to the hydrological impact, to ensure effective and sustainable decisions on possible adaptation measures and strategies.

Scientific research on drinking water supply often uses systems approaches, which limits the number of variables that can be considered. In practice, however, all variables must be dealt with, which is why planning processes regarding drinking water supply are so complex. The research presented here contributes to sustainability science and water management science by proposing a sustainability assessment that addresses the complexity of the sustainable development of drinking water supply. It does so by combining the various sustainability characteristics, although the adopted approach is not fully integrative.

The importance of the temporal, spatial and organisational scales for drinking water supply
The research results presented here underline the need to consider various scales when planning measures to ensure a sustainable drinking water supply. Due to the long lifecycles and lock-ins inherent in the technical infrastructure, the consequences of short-term decisions often become clear only after a longer period of time. Nonetheless, to prepare for a sustainable future, timely, short-term actions are often required. These should preferably be “no-regret” measures, that do not compromise other actions or decisions in the future. In practice, “no-regret” measures can be difficult to identify in systems such as those for drinking water supply, as past decisions have already created lock-ins which prevent certain adaptation measures now (Liu et al., 2007). Moreover, the outcome of most measures will not be fully clear in advance (Bauer and Herder, 2009). Assessing the long-term impact of adaptation measures on the sustainability of a local drinking water supply system, even if done only qualitatively, can contribute to understanding whether an adaptation measure can be considered “no-regret”.

The results reported here emphasise not only the importance, but also the complexity of integrating various temporal, spatial and organisational scales in sustainability analyses. The sustainability assessment presented combined various spatial and organisational scales within the criteria used in the multi-criteria analysis. Moreover, by comparing the sustainability before and at various points in time after implementation of a measure, different temporal scales were incorporated. Although the sustainability assessment combined rather than integrated the various scales, it can nonetheless be seen as a first step towards a more integrative approach to sustainable drinking water supply.

6.6 Recommendations for sustainable local drinking water supply

The results of this research suggest a number of recommendations for the practice of sustainable local drinking water supply.

First, the findings of the current research emphasise the importance of an integrated approach to arrive at “best fits” between the local drinking water supply system and the changing environment. The decision-making process on the MAR project near Epe revealed a number of trade-offs associated with the adaptation measure, such as higher energy use and a risk of water quality deterioration. However, additional arguments, other than hydrological ones, led to the decision to implement the infiltration. Key among the arguments was societal pressure to compensate for the hydrological impact of abstraction. The results also confirm that, due to the long lifecycles involved, changes in drinking water supply systems have long-term impact. Projected and expected developments may over time reduce or enlarge this impact. It is therefore recommended that all impacts on sustainability be taken into account, as well as future developments, when considering adaptation strategies. Having a broad information base helps making trade-offs clear and provides a more complete overview of the gains and losses associated with alternative adaptation strategies. This will support decision-making processes. Even when there are societal arguments for choosing a certain adaptation strategy, understanding the trade-offs makes decision-making more transparent.

An integrated approach is indispensable given current practice in development of new legislation, policies and compensation measures and the required expansion of abstraction permits and technical infrastructure. The sustainability assessment framework considers all relevant sustainability characteristics, thus implicitly taking stakeholder interests into account. It provides an overview of the sustainability challenges, the impact of adaptation options, and the trade-offs in regard to both stakeholder interests and the interests of drinking water supply. This can help to substantiate policies and adaptation planning for sustainable local drinking water supply. It is recommended that the sustainability assessment be performed in cooperation with local stakeholders to identify common ground for how sustainability challenges and adaptation strategies can best be addressed for a specific local drinking water supply system.

The results from the case studies in Chapter 4 emphasise the limiting function of the long lifecycles, lock-ins and interdependencies associated with technical drinking water supply infrastructure. Major changes in a drinking water supply system, such as a transition from groundwater to surface water resources, are blocked by the substantial reforms and societal investments needed, for instance to adjust pipeline infrastructure. To respond to external developments, the technical infrastructure must not only be reliable and resilient, but also flexible. A modular approach using standard components could make these systems more flexible (Bauer and Herder, 2009). But the wide variety of local characteristics makes standardisation a complex undertaking. It is therefore recommended that strategies and techniques be sought with which system reliability can be safeguarded, while also increasing the resilience and flexibility of the technical drinking water supply infrastructure.

The case studies in Chapters 2 and 3 are illustrative of the sustainability challenges often presented by local drinking water abstraction. Understanding the hydrogeological characteristics of a local environment can contribute to adaptation strategies that optimise water resource availability, or limit or compensate for damage to valuable groundwater-dependent ecosystems. In the planning of such hydrological adaptation strategies, the same challenges of reliability, resilience and flexibility of the technical infrastructure arise as mentioned above. Adaptation measures may necessitate more complex water treatment methods that require more energy, due to a lower quality of inflow water. Or, legislation and regulations may need to be changed, concerning for instance the flexibility of abstraction permits and groundwater conservation. In this regard, policymakers and drinking water organisations could team up with researchers, for instance to develop new abstraction concepts and other adaptation strategies. The sustainability assessment developed in this research (Chapter 5) can be used as a model for assessing and comparing the sustainability of such new concepts and adaptation measures.

6.7 Research recommendations

The results and methodology presented in this research provide a scientific basis for the selection and valuation of adaptation measures for sustainable development of local drinking water supply systems. However, additional research on sustainable drinking water supply is recommended. Three issues in particular remain to be addressed: (1) comparison of the sustainability of different water resources, such as groundwater, surface water and reclaimed water; (2) investigation of ways to improve the resilience and flexibility of the technical infrastructure of drinking water supply on a local scale; (3) development of technical innovations to reduce drinking water use by households and industries.

The results of the current research demonstrate the need for a thorough knowledge of the hydrology and chemistry of the local water system and the employed water resources when designing hydrological measures and adaptations to protect water quality. Having such a full understanding can help avoid unintended side effects of measures, such as deterioration of water quality and unwanted impacts on groundwater levels elsewhere. To develop this knowledge, more local data on the water system needs to be made available, collected through a well-designed monitoring system, with structured data management and regular data evaluation. This will provide a solid hydrological knowledge base on the groundwater and surface water systems. Although this may seem obvious, collection and management of such data is usually a low priority activity. Once a minimum level of reliable hydrological data is available, the next step will be modelling of the hydrological system, to improve the understanding of local hydrogeology and the impact of abstractions and adaptation measures.

Due to the complexity of local drinking water supply systems, an integrated systems approach is invaluable to understand the sustainability challenges and find adequate adaptation strategies. The integrated systems approach presented in this research combined various sustainability characteristics, as well as different temporal, spatial and organisational scales. However, the approach does not yet fully integrate these characteristics and scales. It is recommended to further investigate how systems approaches, such as the socio-ecological, socio-technical and other integrated approaches, can be effectively used to analyse and integrate temporal and spatial dimensions of a complex, multi-level environmental problem such as sustainable local drinking water supply.

The sustainability assessment framework developed in this research provides an overview of the sustainability challenges and trade-offs associated with a local drinking water supply system. To broaden the perspective, the results of the analysis of the Dutch situation were cross-checked with the challenges experienced worldwide. To further enhance the general applicability of this approach, it is recommended that the sustainability assessment be applied in other contexts. Based on the local situation and data availability, suitable indicators can be selected to elaborate and quantify the criteria that describe the sustainability characteristics of a local drinking water supply system in another setting. This will enlarge the broader applicability of the sustainability assessment framework.

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Appendix I

Summary results Menyanthes time series analysis

In this Appendix a summary of the valid models is given. A model is considered valid with an explained variance percentage (EVP) > 70%, an evaporation factor between 0.5 and 1.5, and the root mean squared error (RMSE) smaller than 0.15. An overview of the Menyanthes results for all 101 time series is available in ESM1, electronic supplementary material to Van Engelenburg et al. (2020).

Table I.1 *Organisation of data.*

See	Method	Used explanatory series			Results (number of valid models)	
		P and E	Qn	A and I	Valid models	Valid models; Δ EVP > 5%
Table I.2	Menyanthes time series analysis	X	-	-	47	-
Table I.3		X	X	-	57	11
Table I.4		X	-	X	62	8
Table I.5	Analysis deep monitoring wells hydro(geo)logical data	-	-	-	-	-

***Table I.2** Valid models with explanatory series P (precipitation) and E (evaporation).*

Monitoring well ID	Screen number	Screen top elevation (m asl)	Screen bottom elevation (m asl)	EVP P and E (%)
B27B0328	1	11.32	10.32	82.8
B27B0485	1	8.53	7.53	92.3
B27D0090	1	-4.30	-5.38	88.0
B27D0091	1	-10.80	-11.88	85.4
B27D0132	1	12.46	11.40	81.0
B27D0133	1	8.78	7.72	86.9
B27D0134	1	13.54	12.48	83.7
B27D0138	1	16.62	15.56	86.3
B27D0139	1	17.96	16.90	82.0
B27D0140	1	18.01	16.95	74.5
B27D0141	1	16.01	14.95	83.5
B27D0146	1	13.67	12.82	80.5
B27D0147	1	9.96	9.11	86.1
B27D0148	1	10.44	9.59	84.3
B27D0256	1	6.70	5.62	74.8
B27D0376	1	14.47	13.47	83.7
B27D0377	1	15.74	14.74	76.7
B27D0378	1	13.49	12.49	88.2
B27D0384	1	11.06	10.06	83.8
B27D0385	1	10.44	9.44	76.5
B27D0387	1	0.00	0.00	84.8
B27D0487	1	11.90	9.90	81.4
B27D0488	1	11.06	9.06	82.9
B27D0489	1	16.60	14.60	78.0
B27D0490	1	11.20	9.20	91.5
B27D0492	1	10.39	8.39	83.9
B27D0513	1	18.38	17.38	88.7
B27D0514	1	18.65	17.65	79.8
B27D0515	1	18.52	17.52	90.6
B27D0516	1	17.11	16.11	83.1
B27D0517	1	17.01	16.01	80.4
B27D0521	1	-3.64	-5.64	86.2
B27D0525	1	14.70	13.70	90.5
B27D0526	1	16.91	15.91	88.2
B27D0527	1	16.95	15.95	81.8
B27D0528	2	18.08	17.08	88.3
B27D0534	1	18.29	17.29	89.5
B27D0535	1	17.07	16.07	89.8
B27D0536	1	15.39	14.39	88.0
B27D0537	1	13.90	12.90	92.3
B27D0538	1	19.03	18.03	87.0
B27D0539	1	19.46	18.46	83.6
B27D0540	1	18.97	17.97	84.4
B27D0541	1	18.13	17.13	93.1
B27D0543	1	18.63	17.63	89.1
B27D0559	1	-0.11	-2.11	89.0
B27D0559	2	-10.11	-24.11	90.5

Table I.3 *Valid models with explanatory series P (precipitation) and E (evaporation) and Qn (net abstraction), Δ EVP (improvement of explained variance percentage) > 5%, the impact of a net abstraction of 1 million m3/year in meters of groundwater-head change.*

Monitoring well ID	Screen number	Screen top elevation (m asl)	Screen bottom elevation (m asl)	EVP P and E (%)	EVP addition Qn (%)	Δ EVP (%)	Impact of Qn at 2800 m^3/day (M0×2800)
B27B0238	2	-164.7	-165.73	61.7	77.8	16.1	-0.13
B27B0279	1	10.6	9.63	64.2	79.4	15.2	-0.04
B27D0045	1	6.0	5.17	70.8	83.0	12.2	-0.16
B27D0121	1	13.6	12.63	63.5	82.3	18.8	-0.09
B27D0122	1	12.4	11.37	45.8	87.5	41.7	-0.20
B27D0124	1	12.4	11.40	55.2	73.4	18.2	-0.11
B27D0125	1	11.0	9.99	44.0	85.1	41.1	-0.25
B27D0137	1	14.1	12.99	57.9	75.9	18.0	-0.01
B27D0143	1	14.7	13.66	69.5	74.5	5.0	-0.22
B27D0372	1	15.3	14.20	63.1	79.1	16.0	-0.07
B27D0517	1	17.0	16.01	80.4	92.9	12.5	-0.06

Table I.4 *Valid models with explanatory series P (precipitation) and E (evaporation), A (groundwater abstraction) and I (surface water infiltration), Δ EVP (improvement of explained variance percentage) > 5%, and the impact of a gross abstraction or infiltration of 1 million m3/year in meters of groundwater-head change.*

Monitoring well ID	Screen number	Screen top elevation (m asl)	Screen bottom elevation (m asl)	EVP P and E (%)	EVP addition Qn (%)	EVP with A and I separate expl. series (%)	Impact of A-I compared to Qn to EVP	Impact of abstracting 2800 m^3/day (M0×2800)	Impact of infiltration at 2800 m^3/day (M0×2800)
B27B0155	5	-148.5	-149.50	63.2	69.0	87.3	18.3	-0.43	0.10
B27B0156	2	-86.9	-87.93	73.3	73.8	93.6	19.8	-0.14	0.03
B27B0156	3	-176.9	-177.94	64.3	63.8	89.2	25.4	-0.29	0.16
B27B0238	2	-164.7	-165.73	61.7	77.8	86.3	8.5	-0.36	0.18
B27B0255	5	-161.1	-165.89	61.2	64.0	85.3	21.3	-0.14	0.12
B27D0256	1	6.7	5.62	74.8	74.8	83.2	8.4	-0.24	0.03
B27D0539	1	19.5	18.46	83.6	83.6	94.5	10.9	-0.09	0.00
B27D0540	1	19.0	17.97	84.4	84.4	94.6	10.2	-0.14	0.14

***Table I.5** Data for deep monitoring wells.*

Monitoring well ID	Screen number	Surface elevation (m asl)	Well top elevation (m asl)	Screen top elevation (m asl)	Screen bottom elevation (m asl)	Average highest ground-water head (m asl)	Average lowest ground-water head (m asl)	Average ground-water head (m asl)
B27B0155	1	37.95	38.19	-18.29	-19.29	9.6	9.2	9.4
B27B0155	2	37.95	38.09	-52.84	-53.84	9.6	9.2	9.4
B27B0155	3	37.95	38.06	-72.88	-73.88	8.9	8.5	8.7
B27B0155	4	37.95	37.99	-93.44	-94.44	8.8	8.5	8.7
B27B0155	5	37.95	37.98	-148.50	-149.50	7.3	7.0	7.1
B27B0156	1	28.05	28.36	-13.92	-14.92	18.7	18.3	18.5
B27B0156	2	28.05	28.45	-86.93	-87.93	18.7	18.3	18.5
B27B0156	3	28.05	28.41	-176.94	-177.94	8.0	7.8	7.9
B27B0238	1	41.30	41.59	-87.22	-88.22	13.7	13.3	13.5
B27B0238	2	41.30	41.53	-164.73	-165.73	7.4	7.1	7.2
B27B0255	1	22.73	23.42	-51.52	-56.33	16.1	14.4	15.2
B27B0255	5	22.73	23.38	-161.08	-165.89	7.7	7.4	7.6

Appendix II

Hydrogeology, lithology and hydraulic conductivities in monitoring well B27B0255

Figure II.2 *Schematic representation of hydrogeology, lithology and hydraulic conductivities (Kh, Kv) in monitoring well B27B0255. For location, see Fig. 1b. Borehole logs with interpretation using BRO REGIS II v2.2; source data TNO (2020).*

Identification:	B27B0255
Coordinates:	194590, 487810 (RD)
Surface level:	22.71 m relative to sealevel
Depth relative to surface level:	0.00 m – 345.50 m

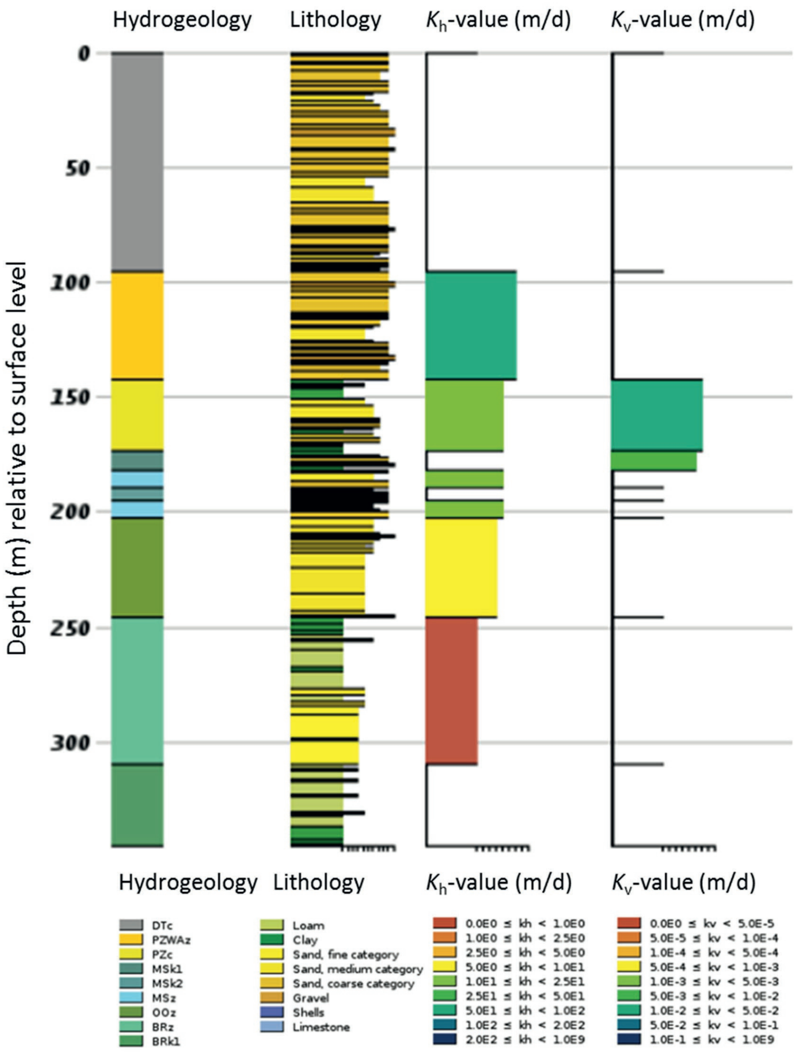

Table II.1 *Hydrogeological classification, depths, main lithological characteristics and hydraulic conductivities in differentiated hydrogeological units in monitoring well B27B0255. For location see Fig. 2.1b. Source data TNO (2020).*

Hydrogeological unit	**Unit range, top and bottom (m asl)**	**Lithology**	**K_h value (m/d)**	**K_v value (m/d)**
Ice-pushed deposits, complex unit	23 to -72	Alternating coarse and medium sand	-	-
Peize Formation and Waalre Formation, sandy unit	-72 to -119	Medium and coarse sand	50-100	-
Peize Formation, complex unit	-119 to -150	Alternating medium sand, sandy clay, coarse sand and clay	10-25	0.01-0.05
Maassluis Formation, first clayey unit	-150 to -159	Sandy clay, medium sand and clay	-	0.005-0.01
Maasluis Formation, sandy unit	-159 to -166	Medium and coarse sand	10-25	-
Maassluis Formation, second clayey unit	-166 to -172	Sandy clay, medium sand and clay	-	-
Maassluis Formation, sandy unit	-172 to -179	Medium and coarse sand	10-25	-
Oosterhout Formation, sandy unit	-179 to – 223	Medium and fine sand and shells	5-10	-
Breda Formation, sandy unit	-223 to – 287	Medium and fine sand and clayey sand	0-1	-
Breda Formation, first clayey unit	-287 to -323	Sandy clay and clay	-	-

Appendix III

Statistics water quality data

In this Appendix the statistical data for Table 2.2 (see Chapter 2) are summarised. The full source data are available in ESM2, electronic supplementary material to Van Engelenburg et al. (2020).

n	= number of samples
min	= minimum concentration
max	= maximum concentration
average	= average concentration

Table III.1 *Summary of water quality statistics.*

Parameter	Location	Period	*n*	min	max	average
pH	Well B5	1997–1999	3	6.2	6.3	6.2
	Well B5	2014–2016	3	6.7	6.9	6.8
	Well group A9, B7, B9	1997–1999	9	5.9	7.1	6.3
	Well group A9, B7, B9	2014–2016	9	6.0	6.7	6.4
	Well group A6, A7, A8, B8	1997–1999	12	5.9	7.2	6.3
	Well group A6, A7, A8, B8	2014–2016	12	5.9	6.2	6.0
	Monitoring well 27BP0356.2	2008–2014	7	7.0	7.1	7.0
	Infiltration water	2008–2014	38	7.1	7.7	7.4
Cl (mg/L)	Well B5	1997–1999	3	13.9	15.2	14.4
	Well B5	2014–2016	3	14.0	15.0	14.3
	Well group A9, B7, B9	1997–1999	9	5.9	15.0	9.4
	Well group A9, B7, B9	2014–2016	9	11.0	15.0	12.9
	Well group A6, A7, A8, B8	1997–1999	12	5.9	19.0	9.3
	Well group A6, A7, A8, B8	2014–2016	12	9.0	14.0	11.4
	Monitoring well 27BP0356.2	2008–2014	7	12.0	18.0	14.1
	Infiltration water	2008–2014	40	11.0	21.0	14.3
HCO_3 (mg/L)	Well B5	1997–1999	3	18.0	22.0	19.7
	Well B5	2014–2016	3	61.0	61.0	61.0
	Well group A9, B7, B9	1997–1999	9	4.0	58.0	13.1
	Well group A9, B7, B9	2014–2016	9	32.0	49.0	37.6
	Well group A6, A7, A8, B8	1997–1999	12	5.9	65.0	12.2
	Well group A6, A7, A8, B8	2014–2016	12	16.0	31.0	22.8
	Monitoring well 27BP0356.2	2008–2014	7	57.0	65.0	59.3
	Infiltration water	2008–2014	40	50.0	67.0	60.8
NO_3 (mg/L)	Well B5	1997–1999	3	5.0	5.5	5.2
	Well B5	2014–2016	3	2.5	2.9	2.7
	Well group A9, B7, B9	1997–1999	9	0.8	58.0	10.5
	Well group A9, B7, B9	2014–2016	9	1.3	4.9	3.1
	Well group A6, A7, A8, B8	1997–1999	12	1.0	65.0	10.1
	Well group A6, A7, A8, B8	2014–2016	12	1.0	7.6	3.6
	Monitoring well 27BP0356.2	2008–2014	7	1.2	4.2	2.4

Parameter	**Location**	**Period**	***n***	**min**	**max**	**average**
	Infiltration water	2008–2014	40	1.0	5.3	2.0
SO_4 (mg/L)	Well B5	1997–1999	3	13.0	18.0	14.7
	Well B5	2014–2016	3	23.0	23.0	23.0
	Well group A9, B7, B9	1997–1999	9	0.8	58.0	10.3
	Well group A9, B7, B9	2014–2016	9	16.0	25.0	20.1
	Well group A6, A7, A8, B8	1997–1999	12	1.0	65.0	9.9
	Well group A6, A7, A8, B8	2014–2016	12	8.0	22.0	16.7
	Monitoring well 27BP0356.2	2008–2014	7	22.0	28.0	24.6
	Infiltration water	2008–2014	40	21.0	27.0	24.7
Na (mg/L)	Well B5	1997–1999	3	8.4	9.7	9.3
	Well B5	2014–2016	3	10.4	10.6	10.5
	Well group A9, B7, B9	1997–1999	9	0.8	58.0	10.0
	Well group A9, B7, B9	2014–2016	9	8.9	11.0	9.7
	Well group A6, A7, A8, B8	1997–1999	12	1.0	65.0	9.7
	Well group A6, A7, A8, B8	2014–2016	12	7.4	10.6	9.1
	Monitoring well 27BP0356.2	2008–2014	7	9.7	11.5	10.7
	Infiltration water	2008–2014	40	8.2	12.6	10.2
K (mg/L)	Well B5	1997–1999	3	1.1	1.2	1.1
	Well B5	2014–2016	3	2.7	2.8	2.7
	Well group A9, B7, B9	1997–1999	9	0.8	58.0	8.7
	Well group A9, B7, B9	2014–2016	9	1.0	1.4	1.1
	Well group A6, A7, A8, B8	1997–1999	12	0.9	65.0	8.5
	Well group A6, A7, A8, B8	2014–2016	12	1.0	1.4	1.2
	Monitoring well 27BP0356.2	2008–2014	7	1.8	4.5	2.7
	Infiltration water	2008–2014	40	1.9	4.2	2.8
Ca (mg/L)	Well B5	1997–1999	3	9.5	10.0	9.8
	Well B5	2014–2016	3	23.5	24.3	23.9
	Well group A9, B7, B9	1997–1999	9	0.8	58.0	8.7
	Well group A9, B7, B9	2014–2016	9	13.0	19.7	15.8
	Well group A6, A7, A8, B8	1997–1999	12	0.9	65.0	8.3
	Well group A6, A7, A8, B8	2014–2016	12	8.0	11.9	9.9
	Monitoring well 27BP0356.2	2008–2014	7	22.8	25.6	24.3
	Infiltration water	2008–2014	40	20.5	27.2	24.6
Mg (mg/L)	Well B5	1997–1999	3	1.8	1.9	1.9
	Well B5	2014–2016	3	2.8	2.9	2.9
	Well group A9, B7, B9	1997–1999	9	0.8	58.0	7.9
	Well group A9, B7, B9	2014–2016	9	2.2	3.5	2.7
	Well group A6, A7, A8, B8	1997–1999	12	0.9	65.0	7.6
	Well group A6, A7, A8, B8	2014–2016	12	1.7	2.7	2.2
	Monitoring well 27BP0356.2	2008–2014	7	2.7	3.2	2.9

Parameter	Location	Period	*n*	min	max	average
	Infiltration water	2008–2014	40	2.4	3.4	2.9
Al (µg/L)	Well B5	1997–1999	3	120.0	295.0	203.3
	Well B5	2014–2016	3	2.4	9.6	6.2
	Well group A9, B7, B9	1997–1999	9	0.8	144.0	10.1
	Well group A9, B7, B9	2014–2016	8	2.0	48.2	13.6
	Well group A6, A7, A8, B8	1997–1999	12	0.9	144.0	11.2
	Well group A6, A7, A8, B8	2014–2016	12	2.0	144.0	32.7
	Monitoring well 27BP0356.2	2008–2014	1	5.0	5.0	5.0
	Infiltration water	2008–2014	37	2.0	144.0	35.5
TDS	Well B5	1997–1999	3	75	77	76
	Well B5	2014–2016	3	141	141	141
	Well group A9, B7, B9	1997–1999	9	35	82	64
	Well group A9, B7, B9	2014–2016	9	85	127	103
	Well group A6, A7, A8, B8	1997–1999	12	53	71	62
	Well group A6, A7, A8, B8	2014–2016	12	70	89	77
	Monitoring well 27BP0356.2	2008–2014	7	137	147	141
	Infiltration water	2008–2014	40	97	153	141
EC (mS/m)	Well B5	1997–1999	3	11	13	12
	Well B5	2014–2016	3	18	18	18
	Well group A9, B7, B9	1997–1999	9	8	14	10
	Well group A9, B7, B9	2014–2016	9	11	17	14
	Well group A6, A7, A8, B8	1997–1999	12	8	14	10
	Well group A6, A7, A8, B8	2014–2016	12	10	12	12
	Monitoring well 27BP0356.2	2008–2014	7	18	19	18
	Infiltration water	2008–2014	40	12	20	18

Appendix IV

Results case studies Chapter 4

Table IV.1 *Results analysis of Case 1 "2018 summer drought". For each pressure the response and impacts to the state of the local drinking water supply system are described. The sustainability issues in the case are displayed in bold. The grey cells refer to Table 4.1 in Section 4.3.1.*

Driver	**Pressure**	**Impact**	**Short-term response**	**Long-term response**	**Sustainability issues**
Extreme weather event	High temperature, high evaporation, no precipitation	Extreme drinking water use, high drinking water demand.	Drinking water suppliers increased abstraction volume.	Development of water saving strategies.	Drinking water use, drinking water demand, drinking water suppliers, abstraction volume, water saving.
		The summer affected the **drinking water use**: filling swimming pools, watering gardens, extra showering all together led to a very high **drinking water demand**. Additionally there also were requests from concerned citizens for applying drinking water to refill ponds that fell dry due to the extreme drought.	**Drinking water suppliers** increased the **abstraction volume** to meet the increased drinking water demand.	The drought (re-)initiated a discourse on **water saving strategies**, including controversial measures such as progressive drinking water tariffs and differentiation in high-grade (household and sanitation, food production) and low-grade (pools, gardens, process water) use.	
Extreme weather event	High evaporation, no precipitation	Drought, falling water discharges and groundwater levels, damage to groundwater-dependent ecosystems and agriculture.	Water use limitations, water authorities applied existing drought water policy, risk for water quality.	Development of additional water shortage policy for water management and water governance.	Drought, water discharge, groundwater levels, groundwater-dependent ecosystems, agriculture, water use, water authorities, water policy, water management, water governance, water availability.
		The **drought** caused falling **water discharges** and **groundwater levels**: river discharges declined, springs and brooks fell dry, and vegetation withered or even died due to low groundwater levels and high temperatures. **Groundwater-dependent ecosystems** such as wetlands as well as **agriculture** produce suffered from the drought.	Limitations to **water use** from water system. **Water authorities** applied the special **water policy** that was developed for periods with low water availability. Drinking water supply has a high ranking because of its high societal relevance. In some ecologically vulnerable areas there is a **water policy** to resolve local surface water shortages by supplementing from larger water bodies such as rivers. This affects the local **surface water quality** and may also affect the **groundwater quality**.	Discourse and policy development on **water management** and **water governance** aiming at a further prioritisation and limitations of water use during water shortage, and retention of surface water and groundwater during periods with sufficient **water availability.**	
Extreme weather event	High evaporation, no precipitation	Customers worried about drinking water availability.	Drinking water suppliers called upon customers for drinking water saving.	Societal support for drinking water saving strategies.	Customers, drinking water availability, drinking water suppliers, water saving.
		Because of the visible damage to vegetation due to the drought, **customers** started to worry about the **drinking water availability.**	**Drinking water suppliers** communicated that there still was sufficient drinking water, but people were asked to spread the drinking water use to reduce the peak demand. Later that summer **customers** were called for **water saving.**	The drought raised awareness under customers that there are limits to the **drinking water availability**, thus creating (some) societal support for (drinking) water saving.	

Driver	Pressure	Impact	Short-term response	Long-term response	Sustainability issues
Extreme weather event	No precipitation	Declining surface water discharge and quality.	Drinking water supplies took measures to safeguard raw water quality.	Development of additional policies on water quality protection.	Surface water discharge, surface water quality, drinking water suppliers, raw water quality, water management policies, water use.
		Due to the lack of rain, the share of industrial waste water and treated sewage water to the **surface water discharge** increased, which caused the **water quality** in surface waters deteriorated.	**Drinking water suppliers** that use surface water as resource took measures to safeguard the **raw water quality.**	The **surface water discharge and quality** problems may induce development of **water management policies** that aim to reduce the impact of treated sewage and industrial waste water, by reduction of **water use** or improvement of treatment.	
Extreme weather event	Declining surface water quality	Groundwater quality deterioration.	No response possible due to lack of water.	Development of additional policies on water quality protection.	Groundwater quality, surface water quality, water shortage, surface water discharge, water management policies.
		The impact of an incidental warm and dry summer to the groundwater quality is limited, but when comparable droughts will happen frequently the **groundwater quality** may deteriorate due to the impact of a declining **surface water quality.**	In some surface water bodies refreshment was required to guard the **surface water quality**, but due to the lack of precipitation there was **a water shortage**, so insufficient water was available for this refreshment.	The fact that **surface water discharge** and **quality** may affect **groundwater quality** supports the need of **water management policies** that aim to refresh water bodies and to reduce the impact of treated sewage and industrial waste water.	
Extreme weather event	High temperature	Drinking water quality at risk due to rising water temperature in pipelines.	Sufficient refreshment due to high demand.	Changing the design standard of distribution pipelines to limit risk of temperature rise..	Drinking water quality, treatment method, distribution infrastructure.
		The extreme temperatures led to an increased surface water temperature, and soil temperature, that may have affected drinking water temperature in distribution infrastructure. This introduces a **drinking water quality** risk.	When surface water is the main resource for drinking water, the **water quality** risk will be limited by a **treatment** method that ensures the bacteriological quality of the drinking water. Sufficient refreshment within storage and high stream velocities in pipelines reduce the risk of temperature rise in the **distribution infrastructure.**	The risk of **drinking water quality** issues caused by increased drinking water temperature due to climate change may have consequences for the design of the **distribution infrastructure**.	
Extreme weather event	High drinking water demand	Increasing abstraction volume, resulting in increasing impact on land use.	Stakeholder complaints by agriculture and nature.	Increased societal pressure on reduction of impact of drinking water abstraction.	Drinking water demand, abstraction volume, impact of abstraction, land use,

Driver	Pressure	Impact	Short-term response	Long-term response	Sustainability issues
		To meet the high **drinking water demand**, the **abstraction volume** rose to a high level. In some local areas the **impact of the abstraction** added up with the extreme drought and high temperatures, affecting the **land use.**	**Stakeholders** on agriculture and nature complained about the impact of the extra abstraction to their land use.	The drought impact enlarged the societal pressure to **drinking water suppliers** to reduce the **impact** of local **drinking water abstraction** to the water system.	stakeholders, agriculture, nature, drinking water suppliers.
Extreme weather event	High drinking water demand	Exceedance of abstraction permits, limiting the resilience of the technical infrastructure.	Enforcement procedures by legal authorities.	Extension of drinking water abstraction permits and water saving strategies.	Drinking water demand, abstraction volume, abstraction capacity, abstraction permit, resilience of abstraction, legal authorities, water regulations, water legislation, drinking water saving.
		To meet the high **drinking water demand**, the **abstraction volume** rose to a high level. The available **abstraction capacity** combined with the high **abstraction volumes** led to exceedance of the **abstraction permits**. Some local drinking abstractions exceeded the monthly permitted volume, and some abstractions even exceeded the yearly permitted volume, failing drinking water regulations. This compromised the **resilience of the abstractions.**	**Legal authorities** (provinces and water boards) started enforcement procedures to meet the **water regulations**. The legal authority urged the drinking water supplier to stay within these limits. However, the drinking **water legislation** also had to be met to ensure continuous supply of good quality drinking water at all times.	The exceedance of **abstraction permit limits** set off enforcement actions by the government, resulting in an increased need for additional **abstraction permits**, as well as **drinking water saving** strategies to reduce the **drinking water demand.**	
Extreme weather event	High peak demand for drinking water	Shortage of drinking water during peak demand due to Insufficient resilience of treatment infrastructure.	Reduced drinking water supply volume.	Adjustment of resilience and reliability of treatment infrastructure.	Treatment volume, treatment capacity, drinking water shortage, reliability of the treatment, resilience of the treatment, drinking water standards, drinking water demand, drinking water suppliers.
		To meet the high peak demand, the **treatment volume** rose to a high level. In some parts of the drinking water supply there was insufficient **treatment capacity**, causing a temporary **shortage of drinking water** during peak demand, compromising **the reliability of the treatment**. These limitations showed that the treatment is not **resilient** for this extreme peak demand.	There is no response available when the treatment capacity is insufficient, except reducing the drinking water supply volume. Exceeding the treatment capacity (by e.g. increasing the filter flow velocity or reducing the cleansing frequency of the filters) would introduce the risk of not meeting the **drinking water standards.**	The drought identified various locations in the technical infrastructure where the **treatment capacity** was not reliable at **peak drinking water demand**, which set **drinking water suppliers** off to solve these local treatment issues. To adjust all issues will take several years.	
Extreme weather event	High peak demand for drinking water	Insufficient distribution capacity.	Lowering drinking water pressure to reduce drinking water volume.	Adjustment of resilience and reliability of distribution infrastructure.	Distribution capacity, resilience and reliability of distribution, drinking water suppliers, drinking water volume, drinking water standards.
		In some parts of the drinking water supply there was insufficient **distribution capacity** due to hydraulic limitations, insufficient storage	To reduce the drinking water volume that was supplied, **drinking water suppliers** lowered the drinking water pressure intendedly in	The drought identified locations in the technical infrastructure where the **distribution capacity** was not	

Driver	Pressure	Impact	Short-term response	Long-term response	Sustainability issues
		capacity, or age and quality of the pipelines. In some areas this caused unintended low drinking water pressures. These limitations put the **reliability** of the **distribution** under pressure and showed that the distribution capacity was not **resilient** for this extreme peak demand.	some areas. The impact of this pressure reduction is a decreased **drinking water volume** from taps. By reducing drinking water pressure the distributed drinking water volume was reduced, however this also led to falling short of the mandatory **drinking water standards** in some areas.	reliable at **peak demand**, which set **drinking water suppliers** off to solve these local distribution issues. To adjust all issues will take several years.	
Extreme weather event	High peak demand for drinking water	Major disturbances could cause a serious disruption of the supply.	Maximum personnel deployment by drinking water suppliers.	Investments to improve resilience and reliability of technical infrastructure by drinking water suppliers.	Drinking water demand, reliability of technical infrastructure, drinking water suppliers.
		The high **peak demand** required a maximum exploitation of the **technical infrastructure**. To ensure the **reliability of the drinking water supply**, many parts of the infrastructure are designed redundant, which limits the impact of disturbances for customers. However, a major disturbance in the infrastructure, such as failure of a large transportation pipeline, could have led to disruption of the supply, because the resilience was limited due to limited reserve capacity and reduced maintenance during the extreme drinking water demand period.	To ensure the **reliability of the drinking water supply**, disturbances are always solved with priority. During the extreme peak period **drinking water suppliers** had all personnel put on standby to immediately solve any disturbances.	The drought identified locations in the technical infrastructure where not reliable at **peak demand**, which set **drinking water suppliers** off to solve these local issues, and where necessary create redundancy to decrease the risk of disturbances, and thus improve the **reliability.**	
Extreme weather event	High peak demand for drinking water	High energy use and environmental impact of extreme drinking water production.	-	Incorporating impact on energy use and environmental impact in design of measures to improve resilience and reliability of technical infrastructure.	Drinking water demand, energy use, environmental impact, drinking water suppliers.
		The magnitude and duration of the **peak demand** forced a maximum exploitation of the technical infrastructure, causing a maximum **energy use** and **environmental impact.**	There was no short-term response available to reduce the energy use and environmental impact.	The drought identified locations in the technical infrastructure where not reliable at **peak demand**, which set **drinking water suppliers** off to solve these local issues. **Energy use** and **environmental impact** are important aspects that are considered in the design of the solutions for these issues.	

Table IV.2 *Results analysis of Case 2 "Groundwater quality development". The sustainability issues in this case are displayed in bold. The grey cells refer to Table 4.2 in Section 4.3.2.*

Drivers	**Pressure**	**Impact**	**Short-term response**	**Long-term response**	**Sustainability issues**
Changing climate variability	Less summer precipitation, higher summer temperatures	Surface water quality deteriorates due to limited surface water discharge.	Monitoring and evaluation of water quality development.	Water legislation on water quality and quantity protection, and drinking water savings strategies.	Surface water quality, surface water discharge, monitoring and evaluation, water legislation, water quality and quantity, drinking water saving.
		In summer **surface water quality** deteriorates due to limited **surface water discharge**, combined with increasing contribution of industrial and treated sewage water recharges compared to natural discharges due to lack of summer precipitation.	**Monitoring and evaluation** of water quality development is necessary to be able to timely respond to a changing surface water quality.	Land and water use must meet **water legislation** as set by the European Water Framework Directive and national water legislation to protect and improve **water quality and quantity**. Further improvement of sewage and waste water treatment will reduce the impact on the **surface water quality**. **Drinking water saving** strategies can also lead to reduction of treated sewage water recharges and industrial recharges.	
Changing climate variability	Surface water quality deterioration	Groundwater quality deteriorates due to deteriorating surface water quality.	Monitoring and evaluation of water quality development.	Improvement of sewage and waste water treatment, and water saving strategies.	Groundwater quality, surface water quality, monitoring and evaluation, water saving.
		Groundwater quality may be affected by the deteriorating **surface water quality** during summer periods through natural or artificial infiltration of surface water.	**Monitoring and evaluation** of water quality development is necessary to be able to timely respond to a changing **surface water quality.**	Further improvement of sewage and waste water treatment will reduce the impact on the **surface water quality**. **(Drinking) water saving** strategies can also lead to reduction of treated sewage water recharges and industrial recharges.	
Socio-economic developments	Increase in use of soil energy systems	Soil energy systems may affect groundwater quality.	Monitoring and evaluation of water quality development, research.	Groundwater protection regulations.	Groundwater quality, groundwater pollution, research, monitoring and evaluation, regulations, groundwater quality protection.
		There is a transition going on towards renewable energy resources, not only wind and solar energy but also towards use of soil energy. **Groundwater quality** may be affected by the use of soil energy, due to risk of **groundwater pollution** by soil energy systems and	**Research** on, and **monitoring and evaluation** of the impact of soil energy to the groundwater quality (including temperature impact) is necessary to avoid introduction of new **sources of pollution** by soil energy systems.	**Regulations** on soil energy help to limit the risk for **groundwater quality**. **Policy** is developed to exclude vulnerable groundwater systems that are used for drinking water supply for soil energy use for **groundwater quality protection**.	

Drivers	Pressure	Impact	Short-term response	Long-term response	Sustainability issues
		the risk of leakage through aquitards that protect aquifers.			
Population growth, industrial developments	Increasing sewage and waste water discharges	Local and upstream land and water use affects the surface water quality.	Monitoring and evaluation of water quality development.	Policy and measures to meet water legislation to protect and improve water quality and quantity.	Surface water quality, land and water use, contaminants, monitoring and evaluation, water legislation, water quantity.
		Surface water quality is affected by local and upstream **land and water use** activities. Discharge of treated sewage water as well as industrial waste water discharges introduce **contaminants** in the water system.	**Monitoring and evaluation** of the water quality development is necessary to be able to timely respond to a changing surface water quality.	Land and water use must meet **water legislation** as set by the European Water Framework Directive and national water legislation to protect and improve **water quality and quantity.** According to the **water legislation** in the European Water Framework Directive additional measures must be taken to reach the set goals in 2027.	
Population growth, industrial developments	Historical pollution, increasing sewage and waste water discharges (change)	Diffuse and point sources of pollution affect surface water and groundwater quality.	Monitoring and evaluation of water quality development.	Measures to remove historical sources of pollution and to prevent new sources of pollution.	Groundwater quality, nutrients, organic micro-pollutants, other contaminants, surface water quality, monitoring and evaluation, water legislation, water quality protection.
		Groundwater quality is affected by diffuse and point sources of pollution, such as **nutrients, organic micro-pollutants and other contaminants** caused by historic land and water use. Groundwater can be influenced by (historic and current) **surface water quality** through natural or artificial infiltration of surface water.	The impact of historical **contaminations** will proceed further into the groundwater system and cannot be undone, unless soil processes help to break down contaminants. **Monitoring and evaluation** is necessary to be able to timely respond to a changing **water quality.**	Historical **contaminations** from past land use will affect the **groundwater quality** for a long period of time due to the low stream velocity of groundwater. Some historical point-pollutions may be removed through soil and groundwater remediation, but diffuse pollution cannot be removed. However, according to the **water legislation** in the European Water Framework Directive additional measures must be taken to reach the set goals on **water quality protection** in 2027.	
Population growth, industrial developments	Increasing sewage and waste water discharges	Emerging contaminants in surface and groundwater require new drinking water treatment methods.	Enforcement of groundwater protection regulations on pollution incidents and monitoring and evaluation.	Development of treatment methods to remove emerging contaminants from sewage, industrial waste water and/or drinking water.	Emerging contaminants, groundwater quality, surface water quality, resilience and reliability of the drinking water treatment, groundwater protection, land and water use, water
		Emerging contaminants, such as new industrial pollutants, medicine residues and micro plastics, may pose new	**Groundwater protection regulations** on **land and water use** aim to reduce the risk of pollutions to avoid	According to the **water legislation** in the European Water Framework Directive known **sources of pollution**	

Drivers	Pressure	Impact	Short-term response	Long-term response	Sustainability issues
		threats to the **groundwater and surface water quality**, and consequently the **raw water quality**, especially when they cannot be removed using the currently available treatment methods. The changes limit the **resilience and reliability of the drinking water treatment**.	**groundwater quality** deterioration. This includes regulations for small incidents with point pollutions such as caused by a car accident to be reported and solved immediately by removing the source of pollution. Continuous **enforcement of these regulations** is essential. **Monitoring and evaluation** is necessary to be able to timely respond to a changing **water quality.**	must be reduced and new **sources of pollution** must be prevented. This may include prohibition by law or measures to reduce the use of specific chemical products. To deal with **emerging contaminants** it is essential to limit or remove the **contaminant source**. If all these measures fail, the contaminants must be removed by the drinking water treatment. Other or new **drinking water treatment methods** may be required. New treatment methods may cause an increase of **energy use** and **environmental impact** (excipients, waste water, waste materials). This may lead to a higher **drinking water tariff.**	legislation, sources of pollution, drinking water treatment methods, energy use, environmental impact, drinking water tariffs.
Population growth, industrial developments	Land use change	Land use (change) may cause groundwater quality deterioration.	Enforcement of groundwater protection regulations on land use change and monitoring and evaluation.	Combination of extensive land use functions with drinking water abstraction.	Land use change, groundwater quality, sources of pollution, groundwater protection regulations, water use, enforcement of regulations, monitoring and evaluation, drinking water abstraction, extensive land use, nature, agriculture, water system.
		Land use change may cause **groundwater quality** deterioration due to the risk of diffuse of point **sources of pollution.** The impact may be limited if land use changes towards less polluting land use functions.	**Groundwater protection regulations** on **land and water use** aim to reduce the risk of pollutions to avoid **groundwater quality** deterioration. This includes regulations on land use change developments. Continuous **enforcement** of these regulations is essential. **Monitoring and evaluation** is necessary to be able to timely respond to a changing **water quality.**	Combining extensive **land use** functions such as **nature** and sustainable **agriculture** with **drinking water abstraction** In local areas to reduce the **groundwater quality** deterioration rate, depending on the land use as well as hydrological and chemical characteristics of the **water system**.	
Changing climate variability, population growth, industrial developments	Surface water and groundwater quality deterioration	Surface water and groundwater quality deterioration determine the required drinking water treatment.	Monitoring of drinking water quality, in case of emergencies measures are taken to safeguard the drinking water quality.	Adjustment of treatment methods to be able to continue to meet the drinking water standards.	Raw water quality, drinking water standards, water quality, vulnerability of the water system for contamination, treatment methods, reliability and resilience of treatment, drinking water quality,
		The **raw water quality** of the abstracted groundwater or surface water determines the treatment that is	The **drinking water quality** is constantly monitored and checked with drinking water standards. In case of	A deteriorating raw water quality may require adjustment of **treatment methods** to meet the **drinking water**	

Drivers	Pressure	Impact	Short-term response	Long-term response	Sustainability issues
		necessary to meet the legal **drinking water standards**. When **water quality** deteriorates in general, due to the **vulnerability of the water system for contamination** different and more complex **treatment methods** become necessary to ensure the **reliability of the treatment** to meet the drinking water standards. The **resilience** of the treatment method or capacity may be insufficient to respond to variability in raw water quality.	drinking water quality **emergencies** local measures are taken, such as temporary boiling instructions to customers or temporary additional treatment, to safeguard the drinking water quality.	**standards** and to ensure the **resilience and reliability of the treatment**. In general a more complex treatment method leads to a higher **energy use**, and a higher **environmental impact** due to additional use of excipients, water loss and waste materials, which will lead to a higher **drinking water tariff.** If the raw water quality is under extreme pressure, adjustment of treatment methods may not be possible. This can ultimately lead to the decision to close the local drinking water abstraction, and force the drinking water supplier to find and develop a replacing abstraction location.	emergencies, energy use, environmental impact, drinking water tariffs.
Population growth, industrial developments	Incidental changes in surface water and groundwater quality	Variations in raw water quality can only be handled if treatment method is resilient to these variations.	Monitoring and evaluation of water quality development.	Increase of resilience and reliability of drinking water treatment.	Surface water quality, groundwater quality, resilience and reliability of the treatment, monitoring and evaluation, raw water quality, energy use, environmental impact, drinking water tariffs.
		Especially **surface water quality** can show strong water quality variations. They can enforce temporary interruption of the surface water intake. **Groundwater quality** is more stable, and therefore less vulnerable for incidental changes. However, incidents can cause a permanent change of groundwater quality. It depends on the **resilience and reliability of the treatment** whether sudden variations in raw water quality can be handled well.	**Monitoring and evaluation** is necessary to be able to timely respond to a changing **water quality.**	To handle a varying or deteriorating **raw water quality** the **resilience and reliability of the drinking water treatment** must be extended. This may require innovations in treatment, which can lead to large investments, and higher **energy use** and an increase in **environmental impact of the treatment**. This may lead to a higher **drinking water tariff.**	

Table IV.3 *Results of analysis of Case 3 "Drinking water demand growth", where additional to the analysis of the first two cases. The (additional) sustainability issues in this case are displayed in bold. The grey cells refer to Table 4.3 in Section 4.3.3.*

Drivers	**Pressure**	**Impact**	**Short-term response**	**Long-term response**	**Sustainability issues**
Changing climate variability, population growth, industrial developments	Limited water resource availability due to extreme weather events, other water use or limited abstraction permits	A limited water resource availability will affect the drinking water availability.	See Table IV.1.	See Table IV.1.	Water resource availability, drinking water availability, resilience of drinking water supply, drinking water demand, water legislation.
		A limited **water resource availability** will affect the **drinking water availability**. The abstraction permits may be insufficient to meet the drinking demand, and possibilities to extend the permits will be minimal. This will put the **resilience of drinking water supply** to respond to changes in **drinking water demand** under pressure. This may cause frequent exceedance of permit conditions, or failure to the drinking **water legislation.**	See Table IV.1.	See Table IV.1.	
Changing climate variability, population growth, industrial developments	Surface water and groundwater quality deterioration	A water quality deterioration affects the resilience and reliability of the drinking water treatment.	See Table IV.2.	See Table IV.2.	Water quality, drinking water treatment, reliability of treatment, drinking water standards.
		If the **water quality** deteriorates, this will affect the raw water quality of the water abstracted for drinking water production. The available **drinking water treatment** facilities may not be resilient to these changes. This affects the **reliability of the water treatment,** potentially causing exceedance of **drinking water standards.**	See Table IV.2.	See Table IV.2.	
Changing climate variability, population growth,	Growing drinking water demand	A growing drinking water demand will put the reliability and resilience of the technical infrastructure under pressure.	See Table IV.1.	Drinking water suppliers must adapt the technical infrastructure to the growing water demand. Water saving strategies may reduce the growth rate, which will limit the required extension of the technical infrastructure.	Drinking water demand, reliability of technical infrastructure, drinking water suppliers, drinking water availability,

Drivers	Pressure	Impact	Short-term response	Long-term response	Sustainability issues
industrial developments		The overall capacity of the technical infrastructure determines whether the supply is resilient to respond to a higher **drinking water demand**. The drought in 2018 displayed technical limitations in parts of the drinking water supply system, putting the **reliability of the technical infrastructure** under pressure	See Table IV.1	Depending on the effectiveness of the **water saving** strategies that are developed, the technical limitations must be solved to meet the growing **drinking water demand**. **Drinking water suppliers** must solve the local issues to ensure the **drinking water availability.** Because these adjustments take time, drinking water suppliers must start solving the issues now. This requires substantial investments and also lead to an increasing **energy use** and **environmental impact,** which may result in an increasing **drinking water tariff.**	treatment, energy use, environmental impact, drinking water tariffs.
Socio-economic developments	Decrease in drinking water demand	A declining drinking water demand may also put the resilience of the technical infrastructure under pressure.	Research on potential risks of a decline in drinking water demand.	Adaptation strategies that increase the resilience of the infrastructure to growth as well as a decline of the drinking water demand.	Drinking water demand, reliability and resilience of technical infrastructure.
		If at some moment the socio-economic developments reverse the **drinking water demand** growth, the **reliability and resilience of the technical infrastructure** will be put under pressure. Especially when the focus is on dealing with a growing **water demand**, there is the risk of over-dimensioning of the technical infrastructure. This will put the **drinking water quality** under pressure in case of a decreasing **drinking water demand**.	While working on solutions for the growing **drinking water demand**, it is important to consider the potential risks of a decreasing demand.	The chosen adaptation strategies for a growing drinking water demand must also be resilient and reliable under a decreasing drinking water demand.	

Appendix V

Summary Sustainable Development Goal 6 targets and indicators related to sustainability characteristics

Table V.1 *Summary Sustainable Development Goal 6 targets and indicators related to sustainability characteristics.*

		Hydrological system			Technical system			Socio-economic system		
Target	**Indicator**	Water quality	Water resource availability	Impact of drinking water abstraction	Reliability of technical infrastructure	Resilience of technical infrastructure	Energy use and environmental impact	Drinking water availability	Water governance	Land and water use
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1 Proportion of population using safely managed drinking water services				x	x		x		
6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	6.2.1 Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water									
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.1 Proportion of wastewater safely treated	x							x	x
	6.3.2 Proportion of bodies of water with good ambient water quality	x							x	x
6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.1 Change in water-use efficiency over time				x		x		x	x
	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources		x	x	x	x	x		x	x

		Hydrological system			Technical system			Socio-economic system		
Target	**Indicator**	Water quality	Water resource availability	Impact of drinking water abstraction	Reliability of technical infrastructure	Resilience of technical infrastructure	Energy use and environmental impact	Drinking water availability	Water governance	Land and water use
6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	6.5.1 Degree of integrated water resources management implementation (0–100)								x	
	6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation	x	x						x	
6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	6.6.1 Change in the extent of water-related ecosystems over time			x					x	
6.a By 2030, expand international cooperation and capacity-building support to developing countries in water and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government coordinated spending plan								x	
6.b Support and strengthen the participation of local communities in improving water and sanitation management	6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management								x	

Appendix VI

Sustainability assessment framework

Table VI.1 *Sustainability characteristics and criteria used in the sustainability assessment framework: categories and criteria, general definition, and classification of sustainable, under pressure and unsustainable.*

Sustainability characteristic	**Criterion**	**General explanation**	**Sustainable**	**Under pressure**	**Unsustainable**	**Weight**
Hydrological system						
Water quality	Current raw water quality	To which extent does the current raw water quality meet set standards?	Current raw water quality meets set standards	Occasionally the current raw water quality exceeds set standards	Current raw water quality is permanently exceeding set standards	0.3
	Raw water quality development	Which trends are found in raw water quality development?	The raw water quality is improving	Consistent raw water quality	Deteriorating raw water quality	0.4
	Salinization	To which extent is salinization a threat to the raw water quality?	No risk of salinization	Salinization is a risk but chloride content is not an issue yet	Chloride is an issue and salinization is increasing	0.1
	Water hardness	Water hardness of raw water	Water hardness within set standards	Water hardness below set standards (basic treatment required)	Water hardness above set standards (softening treatment required)	0.1
	Emerging substances	To which extent are emerging substances a threat to raw water quality?	No emerging substances detected yet	Some emerging substances have been detected, but contents stay within set standards	One or more emerging substances exceed set standards	0.1
Water resource availability	Groundwater quantity	Are there current limitations or future threats to the abstracted groundwater volume?	Abstraction is not limited because groundwater is recharged sufficiently (yearly abstraction<annual recharge minus environmental streamflow) or 'no groundwater abstraction'	Abstraction is not limited but exceeds annual recharge minus environmental streamflow	Abstraction volume is limited because groundwater is abstracted from a confined aquifer that is not recharged ('mining')	0.2

Sustainability characteristic	Criterion	General explanation	Sustainable	Under pressure	Unsustainable	Weight
	Groundwater quality	Are there limitations or threats to the quality of the abstracted groundwater that reduce the availability of the groundwater?	No limitations or threats to quality of abstracted groundwater because of groundwater abstraction below aquitard	Quality of abstraction is threatened by land use or under influence of quality of infiltrating surface water (phreatic aquifer) and thus may influence water availability	Current groundwater quality does not meet national groundwater quality standard and thus influences water availability	0.2
	Surface water quantity	Are there current limitations or future threats to the abstracted surface water volume?	Sufficient availability all year round or 'no surface water abstraction'	Surface water availability varies during the year and may occasionally be limited in case of dry weather conditions	There is regularly insufficient surface water volume available in the dry season	0.2
	Surface water quality	Are there current limitations or future threats to the quality of the abstracted surface water that reduce the availability of the surface water?	No limitations or threats from quality of abstracted surface water because of natural uninfluenced origin of surface water	Quality of abstracted surface water is influenced by land use or upstream surface water pollution and thus may influence water availability	Current surface water quality does not meet national water quality standard and thus influences water availability	0.2
	Natural hazards	To which extent are floods of other natural hazards, threatening the water resource availability?	No flood risk or risk of other natural hazards	There is a small risk of floods or other natural hazards (< 1 per 10 years)	Frequent floods or other natural hazards (> 1 per 10 years) are a threat to water resource availability	0.2
Impact of abstraction	Impact on groundwater system	The scale of impact of the abstraction to the groundwater system	Small (surface water abstraction)	Medium (river bank abstraction, groundwater abstraction below aquitard)	Large (phreatic groundwater abstraction)	0.2
	Impact on surface water system	The scale of impact of the abstraction to the surface water system	Small (groundwater abstraction below aquitard)	Medium (river bank abstraction, phreatic groundwater abstraction)	Large (surface water abstraction)	0.2
	Spatial impact	Size of required working area for abstraction facility	Small (groundwater abstraction with basic treatment facility)	Medium (groundwater abstraction with medium treatment facility)	Large (surface water abstraction with storage basins and extended treatment facility)	0.2

Sustainability characteristic	Criterion	General explanation	Sustainable	Under pressure	Unsustainable	Weight
	Abstraction/ recharge balance	The balance between abstraction and recharge of the water system	The net abstraction volume is less than 10% of the average annual recharge in the recharge area	The net abstraction volume is 10-40% of the average annual recharge in the recharge area	The net abstraction volume is > 40% of the average annual recharge in the recharge area	0.2
	Mitigation or compensation	The extent to which the impact of abstraction is mitigated or compensated	Small impact or impact of abstraction is mitigated	Impact is compensated (financially or by compensation elsewhere)	Mitigation or compensation required but not yet available	0.2
Technical system						
Reliability of facility	Production capacity	Is the drinking water production capacity of the facility sufficient and fully deployable?	Yes	Production capacity is sufficient but not fully deployable	Production capacity is insufficient	0.3
	Complexity of treatment	How complex is the required treatment?	Basic treatment (iron/manganese removal, pH-correction)	Medium complex treatment (decalcification)	Complex treatment (ultrafiltration, reversed osmosis)	0.4
	Operational reliability	Is the facility operationally reliable?	Facility meets corporate standard for operational reliability	Measures are taken to make facility meet corporate standard for operational reliability	Facility does not meet corporate standard for operational reliability	0.1
	Supply security	Is the facility supply secure, i.e. there is sufficient back-up from other facilities	Yes	Facility is supply secure, but also important back-up to other facilities	No	0.1
	Complexity of distribution	Are there issues that complicate the drinking water distribution?	No	At peak demand drinking water distribution becomes complicated	There are serious issues complicating regular drinking water distribution	0.1
Resilience of facility	Percentage exploitation permitted abstraction	The percentage of the permitted abstraction that is currently exploited	<85%	85-95%	>95%	0.4

Sustainability characteristic	Criterion	General explanation	Sustainable	Under pressure	Unsustainable	Weight
	Available production capacity compared to water demand	How does the available production capacity compare to the annual water demand at the facility?	Production capacity ≥ water demand + 10% reserve	Water demand < production capacity < water demand + 10% reserve	Production capacity < water demand	0.2
	Available day production capacity	How does the available production capacity compare to the maximum day water demand at the facility?	Production capacity > maximum day water demand	Production capacity = maximum day water demand	Production capacity < maximum day water demand	0.1
	Abstraction permit utilisation	Is the full permit capacity available for utilisation?	Full permit is available for utilisation	There is an agreement on limited use of the permit, but if necessary the permit may be used	Utilisation of permit is limited because of legal procedures or limitations in related permits	0.2
	Available production capacity compared to abstraction permit	How does the production capacity compare to the abstraction permit?	The available production capacity equals or exceeds the abstraction permit	The available production capacity is just sufficient to fully utilise the abstraction permit	To be able to utilise the full abstraction permit, the production capacity must be extended	0.1
Energy use and environmental impact	Energy use abstraction	Energy use for abstraction of water per m^3	Low (shallow groundwater abstraction, short distance to treatment)	Average (deep groundwater abstraction, short distance to treatment)	High (surface water abstraction, long transport distance to treatment)	0.1
	Energy use treatment	Energy use for treatment of water per m^3	Low (basic treatment groundwater)	Average (medium treatment groundwater)	High (complex treatment groundwater, surface water)	0.4
	Energy use distribution	Energy use for distribution	Low (average transport distances < 15 km)	Average (average transport distances < 30 km)	High (average transport distances > 30 km)	0.2
	Environmental impact of treatment	Are there materials used or produced in the treatment with an environmental impact?	No use or production of materials with an environmental impact	Use of materials with an environmental impact in the treatment	Production of waste materials with an environmental impact	0.2

Sustainability characteristic	**Criterion**	**General explanation**	**Sustainable**	**Under pressure**	**Unsustainable**	**Weight**
	Renewable energy	Use of renewable energy sources (own generation or acquired green energy)	All used energy is renewable energy	> 50% renewable energy is used	< 50% renewable energy	0.1
Socio-economic system						
Drinking water availability	Water demand	Average water demand in litre per person per day (national scale)	< 100 l pp pd	100-200 l pp pd	> 200 l pp pd	0.2
	Water tariff	Average water charges without public charges (company scale)	< 1 €/m^3	1 - 2 €/m^3	> 2 €/m^3	0.1
	Total costs by sales coverage	Total costs by sales coverage (company scale)	> 1.1	1-1.1	< 1	0.1
	Population coverage	Households directly connected to drinking water supply system	> 95%	80 - 95%	< 80%	0.3
	Service quality	Continuity and quality of supply (local scale)	Continuity and quality of supply guaranteed 24/7	Continuity under pressure at peak demand	Quality not guaranteed	0.3
Water governance	Drinking water legislation	Is there legislation on drinking water supply?	Yes, sufficient enforcement by legal authorities	Yes, but insufficient enforcement	No legislation on drinking water supply	0.2
	Water protection legislation	Is there (inter)national legislation on water quality protection?	Clear regulations and sufficient enforcement by legal authorities	Yes, but insufficient enforcement	No regulations on water quality protection	0.1
	Permit compliance	Are the required permits available, and is the facility compliant to the permit requirements?	All permits are available and the facility is compliant to the permit requirements	The permits are available, but the facility is not fully compliant to the permit requirements	Some permits have not been acquired	0.3
	Assessment of abstraction by legal authority	How is the facility assessed by the legal authority?	Positive/neutral	Negative, but planned measures will improve assessment	Negative, no solutions available yet	0.2

Sustainability characteristic	Criterion	General explanation	Sustainable	Under pressure	Unsustainable	Weight
	Assessment of abstraction by other stakeholders	How is the facility assessed by local stakeholders?	Positive/neutral	Negative, but planned measures will improve assessment	Negative, different viewpoints on the sustainability of the	0.2
Land use	Land use at ground level	Is water quality threatened by land use at ground level?	No (groundwater abstraction below aquitard or low risk land use)	Risk land use in recharge area through groundwater	High risk land use in recharge area through surface water	0.2
	Underground use	Is water quality threatened by underground use?	No underground activities in recharge area	Small scale underground activities in recharge area	Large scale underground activities in recharge area	0.3
	Working area drinking water abstraction facility	Are there limitations to the working area from the surrounding land use?	No limitations	Minor limitations	Major limitations threatening the drinking water availability	0.1
	Regulations on land use to protect drinking water abstraction	Are there regulations on land use and underground activities to protect the local drinking water abstraction?	There are regulations to remove unwanted activities from the recharge area to protect the local drinking water abstraction	There are regulations to prevent new unwanted activities by using the stand-still/step forward principle	No	0.2
	Limitations to land use functions because of drinking water abstraction	Is the presence of the facility a significant impediment for current or future land use of underground activities?	No	It is a significant impediment for future land use or underground activities	It is a significant impediment for current and future land use or underground activities	0.2

Table VI.2 *Used data for cases of Epe, redistribution Veluwe and Vechterweerd, and suggestions for general data sources.*

Sustainability characteristic	Criterion	Used data for cases	Suggestions for general data sources	Reference for general data sources
Hydrological system				
Water quality	Current raw water quality	Drinking water company's data	e.g. Status of water bodies according to European Water Framework Directive	European Union, 2000
	Raw water quality development	Drinking water company's data		
	Salinization	Drinking water company's data and local knowledge on hydrology		
	Water hardness	Drinking water company's data		
	Emerging substances	Drinking water company's data and local knowledge on land use and hydrology		
Water resource availability	Groundwater quantity	Local hydrological data	e.g. Status of water bodies according to European Water Framework Directive	European Union, 2000
	Groundwater quality			
	Surface water quantity			
	Surface water quality			
	Natural hazards		e.g. National flood risk inventory	
Impact of abstraction	Impact on groundwater system	Local hydrological data	e.g. Groundwater footprint	Gleeson and Wada, 2013
	Impact on surface water system		e.g. Status of water bodies according to European Water Framework Directive	European Union, 2000
	Spatial impact	Drinking water company's data		
	Abstraction/recharge balance	Local hydrological data	SSI (Renewable water resources)	Van der Kerk and Manuel, 2008

Sustainability characteristic	Criterion	Used data for cases	Suggestions for general data sources	Reference for general data sources
	Mitigation or compensation	Drinking water company's data and local hydrological data		
Technical system				
Reliability of facility	Production capacity	Drinking water company's data	IWA (Ph1 Treatment plant utilisation)	Alegre et.al., 2006
	Complexity of treatment		Drinking water company's standard	
	Operational reliability		Drinking water legislation standard or company's standard	e.g. Dutch Drinking Water Law (2009)
	Supply security			
	Complexity of distribution		Drinking water company's standard	
Resilience of facility	Percentage exploitation permitted abstraction	Drinking water company's data	Performance data of water utilities	
	Available production capacity compared to water demand			
	Available day production capacity			
	Abstraction permit utilisation			
	Available production capacity compared to abstraction permit			
	Energy use abstraction	Drinking water company's data	IWA Ph5 Standardised energy consumption	Alegre et al., 2006

Sustainability characteristic	Criterion	Used data for cases	Suggestions for general data sources	Reference for general data sources
Energy use and environmental impact	Energy use treatment		IWA Ph6 Reactive energy consumption	Alegre et al., 2006
	Energy use distribution		EBC (electricity use)	European Benchmarking Co-operation, 2017
	Environmental impact of treatment		EBC (climate footprint)	European Benchmarking Co-operation, 2017
	Renewable energy		IWA Ph7 Energy recovery	Alegre et al., 2006
Socio-economic system				
Drinking water availability	Water demand	National statistics	SSI (Sufficient to drink)	Van der Kerk and Manuel, 2008
	Water tariff	Drinking water company's data	IWA Fi28 Average water charges for direct consumption	Alegre et al., 2006
	Total costs by sales coverage	Drinking water company's data	IWA Fi30 Total costs coverage	
	Population coverage	National or regional statistics	IWA QS3 Population coverage	
	Service quality	Drinking water company's data	IWA QS12 Continuity of supply, QS18 Quality of supplied water	
Water governance	Drinking water legislation	Governmental data on legislation	SSI (Good Governance)	Van der Kerk and Manuel, 2008
	Water protection legislation	Governmental data on legislation		
	Permit compliance	Governmental data on permits, drinking water company's data on compliance	Permits	
	Assessment of abstraction by legal authority	Stakeholder interview		

Sustainability characteristic	Criterion	Used data for cases	Suggestions for general data sources	Reference for general data sources
	Assessment of abstraction by other stakeholders	Stakeholder interviews		
Land and water use	Land use at ground level	Local knowledge on land use and hydrology	e.g. Status of water bodies according to European Water Framework Directive	European Union (2000)
	Underground use	Local knowledge on underground use and hydrology		
	Working area drinking water abstraction facility	Drinking water company's data		
	Regulations on land use to protect drinking water abstraction	Governmental data on regulations		
	Limitations to land use functions because of drinking water abstraction	Governmental data and local knowledge on land use, hydrology		

Table VI.3 *Lay-out and working procedure excel worksheet.*

Name of sheet	Content	Row	Column	Action for assessment	Result	Adjustable
Current	Definition of criteria	Row 2-59	A-F		See table VI.2	Different scoring of criteria will lead to different results
	Weights		G		See table VI.2. Total of weights per characteristic is 1	Different weighing of criteria will lead to slightly different results
	Sustainable score		H		All criteria maximum score (2)	No
	Score of criteria		I/J/H	Fill in the initial score	Scored criteria	Yes
	Calculation	Row 65-122	I/J/H		Weighted value per criterion (weight*initial score)	No (formula)
	Score per characteristic	Row 125-133	I/J/H		Sum of weighted values per characteristic	No (formula)
Adaptation	Adaptation strategies and local adaptation options within these strategies					Adding local adaptation options will not affect results
Impact table	Possible impact of future developments and adaptation strategies to criteria					Change in this sheet will not affect results, but must be included in Impact work sheet
Impact	Impact of future developments and local adaptation options to criteria	Row 5-59	J-S	Fill in the expected impact	Impact on sustainability per criterion (0-1)	Yes
	Calculation of impact of each future development per characteristic	Row 10, 16, 22, 29, 35, 41, 48, 54, 60	J-M		Sum of weighted impact per future development per characteristic	No (formula)

Name of sheet	Content	Row	Column	Action for assessment	Result	Adjustable
	Calculation of sum of impact of all future developments per characteristic		N		Sum of weighted impact of all future developments per characteristic	No (formula)
	Calculation of impact of each local adaptation option per characteristic		O-S		Sum of weighted impact per local adaptation options per characteristic	No (formula)
	Calculation of sum of impact of all local adaptation options per characteristic		T		Sum of weighted impact of all local adaptation options per characteristic	No (formula)
Results	Calculation of results	Row 2-11	D-R		Current sustainability + weighted impact per characteristic. If value sum <0 then result =0, if value sum > 2 then result =2	No (formula)
	Graphic representation of results	Row 17-57	A-I	Select series	Graph with results	Adjust to combine different series

Authorship statement

PhD candidate’s name: Jolijn van Engelenburg
First promotor: Prof. Dr P.J.G.J. Hellegers
Title of PhD thesis: Towards sustainable drinking water supply in the Netherlands
Date of public defence: 1 July 2020

Chapter 1: I wrote the first draft, proposing the main objectives of the research and its general scientific and social perspective. I elaborated the objectives in the research questions, and described how it fits in the current scientific literature. I revised the text, after comments of my (co-) promotors.

Chapter 2: I proposed the research questions, and elaborated the methodology together with the co-authors. I performed the Menyanthes analysis and discussed the results with the co-authors. I composed the draft paper and revised it after comments of the co-authors and after the peer review for publication.

Chapter 3: The calculations were performed by an MSc-student. I contributed to the definition of the research question, proposed the methodology and supervised the student on behalf of Vitens. I contributed to the analysis of the results together with the student, the WUR-supervisor and a modelling expert. Based on the results I composed the draft paper and revised it after comments of the co-authors, and after the peer review for publication.

Chapter 4: I extensively reviewed literature, on which the final research question was based. I elaborated the methodology after discussing this with the co-authors. I gathered and analysed the case data, and cross-checked the results. I composed the draft, and revised it after comments of the co-authors.

Chapter 5: I developed the adaptation planning approach. I proposed the research question, methodology and graphical presentation of the results, and improved this after review of the co-authors. I composed the draft and revised it after comments of the co-authors.

Chapter 6: I wrote the first draft of the text. I revised the text after comments of my promotors and co-promotors.

March 2020

Jolijn van Engelenburg

Prof. Dr P.J.G.J. Hellegers

Hellegers

Title of PhD thesis: Towards sustainable drinking water supply
Date of public defence: 1 July 2020
PhD candidate: Jolijn van Engelenburg (J.v.E.)
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Introduction: Original draft preparation J.v.E.; all supervisors commented on content in an iterative process.

Chapter 2: Conceptualisation J.v.E.; methodology J.v.E., V.B., E.v.S; investigation J.v.E., M.d.J., S.R.; data curation M.d.J., S.R.; formal analysis J.v.E., M.d.J.; writing – original draft preparation J.v.E.; writing – review and editing J.v.E., V.B., M.d.J., S.R.; visualisation – J.v.E., M.d.J., S.R.; supervision – V.B., E.v.S.

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Chapter 5: Conceptualisation J.v.E.; methodology J.v.E., P.J.G.J.H., E.v.S.; investigation J.v.E.; data curation J.v.E.; writing – original draft preparation J.v.E.; writing – review and editing J.v.E., P.J.G.J.H., E.v.S.; visualisation J.v.E.; supervision P.J.G.J.H., E.v.S.

Synthesis: Original draft preparation J.v.E.; all supervisors commented on content in an iterative process.

(See CRediT taxonomy for term explanation)

Data availability statement

Chapter 2

The summarised results of the Menyanthes time series analysis, the used groundwater quality data and the PHREEQC modelling input file are available in the electronic supplementary material (ESM1, ESM2, ESM3) of the published paper (Van Engelenburg et al., 2020) The complete Menyanthes results are available on request from the author of this thesis. The hydrogeological and groundwater data are publicly available at Dinoloket.nl (TNO, 2019).

Chapter 3

The hydrogeological and groundwater data are publicly available at Dinoloket.nl (TNO, 2019). The climate datasets for the KNMI'14 scenarios are publicly available at https://data.knmi.nl/datasets?q=klimaat+ scenario.

The results of the model calculations with the hydrological model AZURE are saved at the AZURE server. Information on the model is available at https://oss.deltares.nl/web/iMOD/azure-showcase. To gain access to the modelling results please contact the author of this thesis.

Chapter 4

The Vitens data used for the illustrations is available on request from the author of this thesis.

Chapter 5

The results of the assessment of the cases MAR Epe, redistribution Veluwe and Vechterweerd are available at request. Researchers that are interested to use the assessment framework are invited to contact the author of this thesis.

Summary

Sustainable Development Goal (SDG) 6 seeks to “ensure availability and sustainable management of water and sanitation for all” by the year 2030 (UN, 2015). The World Health Organization (WHO) and UNICEF (2017) estimated that in 2015 nearly 30% of the global population did not have access to a safely managed drinking water supply. Developments such as climate change and population growth put drinking water supply worldwide under pressure, even in areas where currently sufficient drinking water is still available. In the Netherlands, everyone has access to safe and affordable drinking water and adequate sanitation. However, water quality protection, water-use efficiency and protection of water-related ecosystems do pose sustainability challenges. These challenges, moreover, will be exacerbated in the future by climate change and other environmental and socio-economic developments.

Sustainability in water management is a frequently studied topic, and various sustainability assessments have been developed focused on different water system components. These assessments use criteria relevant to sustainable drinking water supply on various spatial and organisational scales. However, they do not account for the various local sustainability challenges caused by the embeddedness of drinking water abstraction in a local hydrological and socio-economic environment.

The research presented in this thesis brings into focus the sustainability challenges associated with drinking water supply on a local scale. As such, it contributes to an evolving body of sustainability analyses and assessments oriented towards achieving the SDGs. The main objective of this research was twofold: to quantify the impact of measures to improve the hydrological sustainability of local drinking water abstraction, and to provide insight into the sustainability of local drinking water supply systems, by means of a sustainability assessment framework.

Because abstraction of groundwater for drinking water supply sometimes affects nearby groundwater-dependent ecosystems, adaptation measures may be taken or considered to reduce this impact. In the first part of this research, quantitative hydrological methods were

used to analyse the (potential) impact of local drinking water abstraction, adaptation measures and climate change, both historically and in the future.

The Veluwe area is an important drinking water resource for the Netherlands. It is a glacial moraine complex containing large groundwater volumes. However, in some places, the abstraction of groundwater from this area has negatively impacted nearby groundwater-dependent ecosystems. To compensate for the adverse effects of the drinking water abstraction near the town of Epe, groundwater has been artificially recharged since 1998 by infiltration of surface water near the abstraction. The current research evaluated the impact of 20 years of managed aquifer recharge (MAR) by infiltration using time series analysis and water quality modelling. The results demonstrate that the infiltration has increased groundwater levels near the infiltration, but has not significantly contributed to restoration of groundwater levels in the nearby groundwater-dependent ecosystem. Additionally, no significant deterioration of groundwater quality was found over the study period.

A second – potential – adaptation measure studied was redistribution of abstraction volumes with the aim of reducing impacts on a nearby groundwater-dependent ecosystem. Because climate change and other future developments are likely to influence the availability of groundwater resources for drinking water, this research compared the impact of this potential adaptation measure to the projected impact of climate change scenarios. Here again, the focus was on the Veluwe area of the Netherlands. Findings indicate that in an area with a slowly responding large aquifer and without a surface water system, climate change is likely to cause rising groundwater levels, despite the projected increase in summer dryness. This impact may even exceed the impact of redistribution of abstraction volumes. In addition, the combined effect of climate change and redistribution of abstraction volumes was found to be strongly dependent on local conditions, thus highlighting the need for local hydrological knowledge and high-resolution modelling when considering any such adaptation measures.

The second part of this research explored the sustainability challenges associated with local drinking water supply systems, given projected future developments, such as climate change and growth in drinking water demand. Recognising the need for an integrated approach, the full range of sustainability characteristics and challenges that local drinking water supply may face were identified and elaborated in a sustainability assessment. The assessment clarified the positive impacts and trade-offs involved in various adaptation measures for a sustainable local drinking water supply system. A trade-off is defined here as a diminishment of the sustainability of one characteristic, in return for gains in the sustainability of one or more other characteristics.

To identify the sustainability issues for drinking water supply, three cases were analysed. One case related to a short-term event, that is, the 2018 summer drought in the Netherlands. The two other cases concerned long-term phenomena, that is, changes in water quality and growth in drinking water demand. The sustainability issues identified in the cases were compared to globally recognised challenges in sustainable drinking water supply. This resulted in a set of hydrological, technical and socio-economic characteristics of a sustainable local drinking water supply system: water quality, water resource availability, the impact of drinking water abstraction, reliability and resilience of the technical system, energy use and environmental impact, drinking water availability, water governance, and land and water use.

The sustainability characteristics were elaborated into a locally oriented sustainability assessment framework, based on multi-criteria analysis. The characteristics were then tailored into criteria that fit current practice in in Dutch local drinking water supply context. The developed framework was used to analyse the projected impact of future developments and adaptation measures on various drinking water abstractions in the Netherlands. For example, with the framework the impact of the aforementioned MAR by infiltration near Epe was assessed, as well as the proposed redistribution of abstraction volumes in the Veluwe. The aim was to estimate their comparative effects on the sustainability of the local drinking water supply. Additionally, the sustainability was assessed of expansion of a riverbank abstraction, Vechterweerd, in another region of the Netherlands. In these cases, use of the framework resulted in a clearer picture of the positive impacts as well as trade-offs involved in the studied adaptation measures. Such results can support more transparent decision-making, that carefully balances relevant sustainability aspects.

This research revealed that climate change and a complex hydrogeology may amplify or counteract the effectiveness of measures to reduce the hydrological impact of drinking water abstraction. This highlights the need for local hydrological knowledge and use of high-resolution modelling when considering any such adaptation measures. Additionally, the cases analysed made clear that, while it is important to reduce the local hydrological impact of drinking water abstraction, hydrological facts and figures alone do not determine whether an adaptation measure will increase the sustainability of a local drinking water supply. To guide decisions on the required local adaptation measures, this research offered a sustainability assessment framework. Use of that framework provides the broad overview so essential for sustainability decision-making. The framework establishes a set of hydrological, technical and socio-economic sustainability characteristics for local drinking water supply systems. The analyses also identified four main adaptation strategies. These were elaborated into potential local adaptation measures for addressing local challenges. Analysis of these provided insight into potential positive impacts and trade-offs involved in the adaptation strategies in relation to the sustainability characteristics.

The research additionally showed that temporal, spatial and organisational cross-scale interactions strongly affect the sustainable development of a local drinking water supply system. The temporal scale is particularly important. It is also the most challenging cross-scale interaction, due to the long lifecycles and lock-ins of drinking water infrastructure. A timely response to future developments was found to be essential for sustainable development of a drinking water supply, even when the outcome of measures is not fully clear due to uncertainty about future developments. With regard to spatial interactions, zooming in on the local spatial scale revealed local sustainability challenges related to, for example, the local hydrogeology and stakeholder interests, in addition to the challenges on the global and national scales. Various organisational cross-scale interactions were found. Indeed, it can be difficult for drinking water companies to comply with all the relevant legislation imposed by international, national and local governments, as regulations and goals may conflict.

It is recommended that the sustainability assessment be applied in other contexts. Based on the local situation and data availability, suitable indicators can be selected to elaborate and quantify criteria describing the sustainability characteristics of a local drinking water supply system in other settings. This will further promote the general applicability of the presented approach to sustainability assessment.

Samenvatting

Eén van de duurzaamheidsdoelen van de Verenigde Naties, namelijk “Sustainable Development Goal” 6, is gericht op beschikbaarheid en duurzaam beheer van drinkwater en sanitatie voor iedereen (Verenigde Naties, 2015). De WHO en UNICEF (2017) hebben ingeschat dat in 2015 bijna 30% van de wereldbevolking geen toegang had tot een veilige drinkwatervoorziening. Ontwikkelingen zoals klimaatverandering en bevolkingsgroei zetten wereldwijd de drinkwatervoorziening onder druk, ook in gebieden waar nu nog wel voldoende drinkwater beschikbaar is. In Nederland heeft iedereen toegang tot veilig en betaalbaar drinkwater. Maar bescherming van de waterkwaliteit, het efficiënt gebruik van water en bescherming van waterafhankelijke natuur vormen uitdagingen voor een duurzame drinkwatervoorziening in Nederland, die in de toekomst nog verder zullen toenemen als gevolg van klimaatverandering en andere natuurlijke en sociaaleconomische ontwikkelingen.

Er is veel onderzoek uitgevoerd naar duurzaam waterbeheer, en er zijn verschillende methodes ontwikkeld om de duurzaamheid van het watersysteem te beoordelen. Deze methodes nemen vaak ook criteria mee die relevant zijn voor duurzame drinkwatervoorziening op verschillende ruimtelijke en organisatorische schalen. Maar meestal wordt er geen rekening gehouden met de vele lokale problemen die veroorzaakt worden door de sterke relatie van een drinkwaterwinning met haar directe hydrologische en de sociaaleconomische omgeving.

Het onderzoek dat in dit proefschrift gepresenteerd wordt, richt zich op een beter begrip van de complexiteit van het omgaan met de uitdagingen voor duurzame drinkwatervoorziening op lokale schaal. Daarmee draagt het bij aan de kennis op het gebied van duurzaamheidsanalyses en -beoordelingen, die als uiteindelijk doel hebben om de Sustainable Development Goals te bereiken die de Verenigde Naties in 2015 vastgesteld hebben. Het doel van dit proefschrift was tweeledig: het bepalen van het effect van maatregelen die gericht zijn op het verbeteren van de hydrologische duurzaamheid van lokale drinkwaterwinning, en het inzicht geven in de duurzaamheid van drinkwatersystemen op lokale schaal, door middel van een beoordelingsmethodiek.

Omdat sommige grondwaterwinningen voor de drinkwatervoorziening effect hebben op nabijgelegen grondwaterafhankelijke natuurgebieden, zijn er adaptatiemaatregelen genomen of worden deze overwogen om dit effect te verminderen. In het eerste deel van dit proefschrift zijn kwantitatieve methodes gebruikt om de (mogelijke) effecten van lokale drinkwaterwinning, adaptatiemaatregelen en klimaatverandering op het hydrologische systeem te analyseren, in verleden, heden en toekomst.

De Veluwe is een belangrijke bron voor drinkwater in Nederland. Het is een stuwwalcomplex, een complex hydrogeologisch systeem dat een grote grondwatervoorraad bevat. Ondanks die grote voorraad, zijn er toch ook plaatsen op de Veluwe waar de grondwateronttrekking een negatief effect heeft op nabijgelegen grondwaterafhankelijke natuur. Om het negatieve effect van de drinkwaterwinning nabij Epe op het grondwatersysteem van de Veluwe te compenseren, is daar sinds 1998 oppervlaktewater geïnfiltreerd in de bodem, om het grondwatersysteem aan te vullen ("managed aquifer recharge"). Het effect van deze infiltratie in de afgelopen 20 jaar is in dit onderzoek geëvalueerd met behulp van tijdreeksanalyse en waterkwaliteitsmodellering. De resultaten lieten zien dat, als gevolg van de infiltratie, de grondwaterstanden in de directe omgeving van de infiltratie gestegen zijn, maar dat de infiltratie niet significant bijgedragen heeft aan het herstel van de grondwaterstanden in een nabijgelegen grondwaterafhankelijk natuurgebied. Ook bleek de grondwaterkwaliteit niet verslechterd als gevolg van de infiltratie.

Een tweede, mogelijke, maatregel die onderzocht is, is het gedeeltelijk herverdelen van onttrekkingshoeveelheden tussen bestaande grondwateronttrekkingen. Het doel hiervan zou zijn het effect op grondwaterafhankelijke natuurgebieden te verminderen. Omdat klimaatverandering en andere toekomstige ontwikkelingen de beschikbaarheid van grondwater voor drinkwater kunnen beïnvloeden, heeft dit onderzoek het effect van deze maatregel vergeleken met het effect van een aantal klimaatscenario's. Ook hier is met name gekeken naar de Veluwe. Uit de resultaten bleek dat in een gebied met een groot, langzaam reagerend watervoerend pakket zonder oppervlaktewatersysteem klimaatverandering kan leiden tot stijgende grondwaterstanden, ondanks de verwachte toename in droogte gedurende de zomer. Dit klimaateffect zou mogelijk zelfs groter kunnen zijn dan het effect van het herverdelen van onttrekkingshoeveelheden. Daarnaast werd ook zichtbaar dat het effect van hydrologische maatregelen en van klimaatverandering sterk afhangt van lokale hydrogeologische omstandigheden, wat het belang van lokale hydrologische kennis en gedetailleerde hydrologische modellering benadrukt.

Het tweede gedeelte van dit proefschrift onderzocht de duurzaamheidsuitdagingen waar drinkwatervoorziening op lokale schaal mee te maken zal krijgen, als gevolg van verwachte toekomstige ontwikkelingen zoals klimaatverandering en een stijgende drinkwatervraag. Omdat een integrale benadering nodig bleek, richtte het onderzoek zich niet alleen op de hydrologische aspecten, maar op het identificeren van alle belangrijke karakteristieken en mogelijke uitdagingen voor duurzame drinkwatervoorziening. Deze zijn verder uitgewerkt met als doel niet alleen de positieve effecten te bepalen van verschillende adaptatiemaatregelen voor een duurzame drinkwatervoorziening, maar ook de bijkomende negatieve effecten. Een bijkomend negatief effect (“trade-off”) is hier gedefinieerd als een afname in de duurzaamheid van een karakteristiek, terwijl de duurzaamheid van één of meer andere karakteristieken toeneemt.

Om de belangrijkste aandachtspunten voor duurzaamheid van drinkwatervoorziening te identificeren zijn drie drinkwatercases geanalyseerd. Eén case betreft een kortdurende gebeurtenis: de zomerdroogte van 2018 in Nederland. De twee andere cases betreffen de lange termijn, te weten, de ontwikkeling van de grondwaterkwaliteit, en de groei van de drinkwatervraag. De aandachtspunten voor duurzaamheid die hieruit naar voren kwamen zijn vergeleken met de problemen waar (duurzame) drinkwatervoorziening wereldwijd mee te maken heeft. Dit resulteerde in de volgende hydrologische, technische en sociaaleconomische karakteristieken en aandachtspunten voor duurzame drinkwatervoorziening op lokale schaal: waterkwaliteit, waterbeschikbaarheid, het hydrologische effect van een drinkwaterwinning, de betrouwbaarheid en veerkracht van de technische drinkwaterinfrastructuur, het energieverbruik en andere milieueffecten van de drinkwatervoorziening, de beschikbaarheid van drinkwater, water governance, en land- en watergebruik.

De duurzaamheidskarakteristieken zijn gebruikt voor de ontwikkeling van een beoordelingsmethodiek op basis van multicriteria-analyse. Deze methodiek is uitgewerkt in criteria die passen in de huidige praktijk van de Nederlandse drinkwatervoorziening, gericht op de lokale schaal. Deze zijn gebruikt om het effect van toekomstige ontwikkelingen en adaptatiemaatregelen op de duurzaamheid van verschillende lokale drinkwaterwinningen te vergelijken. Met behulp van de methodiek is het effect op de duurzaamheid bepaald van de eerder genoemde infiltratie bij Epe en de gedeeltelijke herverdeling van grondwateronttrekkingen op de Veluwe. Het doel was om een inschatting te maken van het effect van deze maatregelen en toekomstige ontwikkelingen op de duurzaamheid van de betreffende onttrekkingen en deze vervolgens onderling te vergelijken. Aanvullend is ook de duurzaamheid van de oevergrondwateronttrekking Vechterweerd en een eventuele uitbreiding hiervan beoordeeld. Het gebruik van de methodiek in de onderzochte voorbeelden maakte zowel de positieve als de bijkomende negatieve effecten van adaptatiemaatregelen inzichtelijk. Dit inzicht kan bijdragen aan een transparantere besluitvorming over adaptatie van lokale drinkwaterwinning, waarin alle relevante duurzaamheidsaspecten zorgvuldig afgewogen worden.

Dit onderzoek liet zien dat klimaatontwikkeling en een complexe hydrogeologie de effectiviteit van maatregelen om het hydrologische effect van drinkwaterwinning te verminderen kan vergroten, maar ook kan tegenwerken. Dit benadrukt het belang van lokale hydrologische kennis en het gebruik van gedetailleerde hydrologische modellen bij de afweging over dergelijke adaptatiemaatregelen. Daarnaast maakte het onderzoek ook duidelijk dat het weliswaar van groot belang is om de lokale hydrologische effecten van een drinkwaterwinning te beperken, maar dat het niet alleen de hydrologische feiten en getallen zijn die bepalen of daarmee de duurzaamheid van de drinkwatervoorziening toeneemt. Om besluitvorming over de noodzakelijke lokale adaptatiemaatregelen te ondersteunen, is een methodiek ontwikkeld om de duurzaamheid te beoordelen. De methodiek geeft het brede perspectief dat zo belangrijk is voor besluitvorming over duurzaamheid. Het geeft een set van hydrologische, technische en socio-economische duurzaamheidskarakteristieken om de drinkwatervoorziening op lokale schaal te beschrijven. Daarnaast zijn er vier strategieën voor adaptatie geïdentificeerd. Deze zijn uitgewerkt in mogelijke lokale adaptatiemaatregelen die passen bij de lokale uitdagingen. Analyse van de adaptatiemaatregelen heeft inzicht gegeven in zowel de positieve als de bijkomende negatieve effecten voor de duurzaamheid van de drinkwatervoorziening die deze maatregelen met zich mee brengen.

Het onderzoek liet tenslotte ook zien dat de vele interacties tussen verschillende tijd-, ruimtelijke en organisatieschalen een groot effect hebben op de duurzame ontwikkeling van een lokaal drinkwatersysteem. De interactie tussen verschillende tijdschalen is niet alleen erg belangrijk, maar tegelijk ook de meest uitdagende, vanwege de lange levenscyclus van de drinkwaterinfrastructuur, en de inflexibiliteit van de infrastructuur voor wijzigingen die daar uit voortvloeit. Hierdoor is het voor de duurzame ontwikkeling van de drinkwatervoorziening essentieel om op tijd in te spelen op toekomstige ontwikkelingen, zelfs als op voorhand nog niet volledig duidelijk is wat het effect van de maatregelen zal zijn vanwege de onzekerheid over toekomstige ontwikkelingen. Door in te zoomen naar de lokale ruimtelijke schaal werden de lokale uitdagingen duidelijk, bijvoorbeeld als gevolg van de hydrogeologie en stakeholder-belangen in de omgeving, naast de al bekende uitdagingen voor duurzame drinkwatervoorziening op globale en nationale schaal. Ook op organisatorische schaal werden interacties gevonden. Het kan complex zijn voor drinkwaterbedrijven om aan alle relevante wet- en regelgeving op internationaal, nationaal en lokaal niveau te voldoen, omdat er soms tegenstellingen zitten tussen de vele regelingen en gestelde doelen.

Aanbevolen wordt om de ontwikkelde methodiek ook in andere contexten toe te passen. Door gebruik te maken van de lokale situatie en de beschikbare data in andere gebieden kunnen de criteria die op lokale schaal de duurzaamheid van drinkwatervoorziening beschrijven verder uitgewerkt worden. Dit kan bijdragen aan de algemene toepasbaarheid van de methodiek.

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Jolijn

About the author

Jolijn van Engelenburg was born on the 24th of July 1966 in Nijmegen, the Netherlands. After finishing secondary school in 1984, she studied hydrology at Wageningen University (1984–1990). An internship at Heidemij Adviesbureau (later: Arcadis) during her studies resulted in her first job as consultant after her graduation in 1990. There she worked on multiple different projects varying from water management in catchment areas to evaluation of national water policies.

In 1997 she left Arcadis and started as hydrologist at Nuon Water, a drinking water company, which merged with other drinking water companies into Vitens in 2003. Here she worked as a hydrologist/stakeholder manager on securing the fifteen local drinking water abstractions in the Veluwe area in the Netherlands for the future: by protecting drinking water resources quality against external threats as well as by ensuring that the drinking water abstractions were sustainably fitted in the local water system. She also worked as stakeholder manager on two large managed aquifer recharge projects near two local drinking water abstractions in the Veluwe area. The aim of these projects was to mitigate the impact of the groundwater abstraction by infiltration of surface water of local origin into the groundwater system.

In January 2016 she officially started her PhD at the Water Systems and Global Change Group, Water Resources Management Group, and Hydrology and Quantitative Water Management Group of Wageningen University, working part-time on her PhD-thesis, next to her job as stakeholder manager at Vitens. In March 2019 she switched jobs within Vitens and became an asset manager, and as such is contributing to the investment planning of the drinking water supply assets.

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- Training ‘Consultancy skills’ -in Dutch-, GITP, The Netherlands (2017)
- Training ‘Speaking with Impact’-in Dutch, Vitens, The Netherlands (2017)
- Training ‘Agile Foundation’ -in Dutch, Vitens, The Netherlands (2017, 2019)
- Training ‘Open Negotiations’-in Dutch, FP&P, The Netherlands (2019)

Management and Didactic Skills Training

- Supervising MSc student with thesis entitled ‘A study to increase the robustness of the drinking water supply at the Veluwe under different climate scenarios, the Netherlands’ (2016)
- Supervising MSc students with their Academic Consultancy Training project ‘Infiltration Project Epe’ (2016) and ‘Evaluation Vechterweerd’ (2018)
- Participation in EU-project BINGO (core team and Cop) (2016-2019)
- 30 years of working experience on project and stakeholder management at Vitens

Oral Presentations

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