From observing to managing and alleviating hydrological droughts

By

Doris Elise Wendt

A thesis submitted to
the University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

Hydrological extremes and Water sciences research group
School of Geography, Earth and Environmental Sciences
College of Life and Environmental Sciences
University of Birmingham
December 2020

ABSTRACT

Groundwater is an essential source of water supply, particularly during meteorological droughts when the dependency on groundwater increases. However, the impact of human-influence, i.e. water use and water resource management on natural hydrological droughts remains unknown. This thesis aims to advance our understanding of human-influence on hydrological droughts, particularly groundwater droughts. For this, two methodologies were developed to analyse the impact of human-influence on regional groundwater droughts and assess impact of socio-hydrological feedbacks during droughts. The main results show an asymmetric drought response due to groundwater use resulting in in/decreased drought frequency and de/increased drought severity depending on the long-term balance between groundwater recharge and groundwater use. Results indicate that managed aquifer recharge can change this long-term balance, as found in a heavily-stressed aquifer where regional groundwater drought duration and severity reduced. Drought mitigation strategies are also found to alter this long-term balance. Modelled strategies reduce hydrological drought duration and severity, although the impact of mitigation strategies is sensitive to primary hydrogeological conditions and the overall water allocation. In summary, these results advance our understanding of human-influence on hydrological droughts. Findings highlight substantial impact on hydrological droughts and show the need of sustainable water resources management.

DEDICATION

This work is dedicated to the curious mind, stumbling upon this work.

May you brush past -read the acknowledgements and view the chapter illustrations-

show interest -read the abstract, introduction and conclusions-

or plunge into the depths of the groundwater droughts and read all.

ACKNOWLEDGMENTS

First of all, I would like to thank Anne Van Loon, John Bloomfield, and David Hannah for their supervision. Many thanks for the encouraging meetings, supporting notes, patience and feedback on my written work and dedication to the research. I would also like to thank Josh, Rosie, Jon, Steve, Kieran, Val, Adriane, Sally, Mel, and Neela for their guidance along the way in GEES and the BGS Wallingford colleagues for their support.

I am honoured to be part of the Drought in the Anthropocene working group, thanking their support and in particular Henny, Margaret, Benedikt and Ezra. I would like to thank Amir and his research group for hosting me. I would like to thank Bridget Scanlon for her support and guidance with the MAR research. I owe another thank you to Mike Jones, Claudia Faunt and Antonio Espriu for their thoughts on the ongoing research.

I would like to thank my peers in 325 for the productive time and much needed lunches, coffee breaks, get-togethers and zoom calls last months, in particularly Nicolai, Danny, Colin, Lucy, Marie, Nine, Ed, Adrià, Andrea, Sijeh, Ruben, Holtti, Angeliki and Sam. Special thanks to Alex, who introduced me to climbing and thanks to my climbing buddies, who kept me safe and sane! A big cheers to the 2016 CENTA cohort and CENTA team for their support during the pandemic that made all the difference.

A very special thanks to my Dutch friends, especially the ones visited! A warm hug for Charlie and family, Graham's family, my parents and my sisters & partners for keeping up with my stories. Thanks to Jos Zanders, who agreed to draw for my thesis, making this work a lot more interesting! And finally, I take my hat off to Graham, who supported me from day one on his bike, being very close or far away, and who managed to keep me calm in our home office. More relax times are ahead now.

I am grateful for the financial support of CENTA NERC and BGS.

List of publications

This thesis incorporates the following published articles:

- Chapter 3:

  Wendt, DE; Van Loon, AF; Bloomfield, JP and Hannah, DM (2020) Asymmetric impact of groundwater use on groundwater droughts. *Hydrology and Earth System Sciences*, *24*, p. 4853-4868, doi:10.5194/hess-24-4853-2020

- Chapter 4:

  Wendt, DE; Van Loon, AF and Scanlon, BR (2019) Exploring the long-term impact of MAR in Southern California. *In Proceedings: Managed Aquifer Recharge: Local solutions to the global water crisis*, Edited by Fernández Escalante, E., p. 141-147

- Chapter 5:

  Wendt, DE; Van Loon, AF; Scanlon, BR and Hannah, DM (2021) Managed aquifer recharge as a drought mitigation strategy in heavily-stressed aquifers *Environmental Research Letters*, *16:1*, 014046, doi:10.1088/1748-9326/abcfe1

Besides my own research, I also contributed to the following two articles:

- Margariti, J, Rangecroft, S, Parry, S, **Wendt, DE** Van Loon, AF (2019) Anthropogenic activities alter drought termination. *Elementa: Science of the Anthropocene*, *7:27*, doi:10.31223/osf.io/qjyrm

- Hurkmans, R; **Wendt, DE** and Van den Houten, G (2019) Sneeuw in Nederlands waterbeheer, *Stromingen*, *25:2*

Contents

List of Figures

List of Tables

Chapter One

Introduction

1.1 Rationale and aim

Groundwater is a crucial water source as it provides drinking water for nearly half the global population while also sustaining irrigated agriculture and industrial water use (Siebert et al., 2010; Gun et al., 2012; Döll et al., 2012). Even though groundwater storage is largely hidden from view, the widespread availability of the resource (Aeschbach-Hertig et al., 2012), long residence times (Cuthbert et al., 2019), and resilience during current and projected climate extremes (Taylor et al., 2013) result in large-scale use of groundwater (Döll et al., 2012). Groundwater also sustains important ecosystems, which existence can be jeopardised when groundwater is overused (overabstracted) periodically or permanently (Custodio, 2002; Graaf et al., 2019). The availability of groundwater during climate extremes defines its value during meteorological droughts defined as a deficit in precipitation (Mishra et al., 2010). As surface water availability declines, groundwater use increases enhancing pressure on groundwater resources that may result in periodically overabstraction. Permanent overabstraction may have irreversible consequences for ecosystems and water bodies (Custodio et al., 2019; Graaf et al., 2019), groundwater quality, i.e. salt water intrusion (Taniguchi, 2011), and even loss of groundwater storage due to large-scale subsidence that was aggravated during an extreme drought (Faunt et al., 2016; Ojha et al., 2017). Due to climate change, extreme meteorological droughts are likely to occur more frequently in near-future (Dai, 2013), adding further strain on water resources. Or perhaps sooner, as recent severe drought events in Europe confirm the increasing drought frequency already (Stagge et al., 2017; Hari et al., 2020). Most striking is the projected positive trend in evapotranspiration and lengthening of drought events that aggravates soil moisture deficits and crop water requirements for irrigated agriculture fuelling the dependency on groundwater (Siebert et al., 2010; Aeschbach-Hertig et al., 2012; Taylor et al., 2013). Overabstraction during droughts also results in lower baseflows (Konikow et al., 2014; Gleeson et al., 2018), which directly aggravates streamflow droughts, defined as a below-normal discharge or reservoir levels (Tallaksen et al., 2004). The projected streamflow droughts show a similar or worse increase in near-future scenarios compared to meteorological droughts (Prudhomme et al., 2014). However, increased water use amplifies near-natural streamflow droughts (Taylor et al., 2013; Wada et al., 2013; Wanders et al., 2015) that is already identified in number of case study areas around the world (Tijdeman et al., 2018; Margariti et al., 2019; Van Loon et al., 2019; Wang et al., 2020).

Responding accordingly to meteorological droughts is key to avoid crisis management and decrease vulnerability to current and future water shortages (Wilhite, 2000; Carrão et al., 2016; Ward et al., 2020). Maladaptation to meteorological droughts is to be avoided (Christian-Smith et al., 2015; AghaKouchak, 2015), as overabstraction of groundwater may result in aquifers becoming heavily-stressed and even depleted (Custodio, 2002; Rens et al., 2017). Regional groundwater models in large-scale aquifers show that groundwater depletion is a dynamic concept resulting from both negative and positive influence of climate variability and water resources management on groundwater storage (Konikow, 2011; Rateb et al., 2020). Sustained and periodic overuse of groundwater may be balanced in a sustainable manner and does not necessarily result in degraded aquifer systems, if groundwater use is balanced with long-term groundwater recharge in a sustainable manner (Cuthbert et al., 2019; Gleeson et al., 2020). Examples across the world show impact on adaptation and mitigation strategies by introducing (integrated) water supply and demand management yielding in increased drought resilience and avoiding groundwater depletion (Low et al., 2015; Scanlon et al., 2016; Jakeman et al., 2016; Rodina, 2019; Jacobs et al., 2020). Examples of both positive and negative management impact on long-term groundwater storage highlight the significance of human influence on groundwater droughts. Hydrological droughts in managed environments, defined as a below-normal surface water, reservoir storage, and groundwater levels (Mishra et al., 2010; Van Loon, 2015) result from the combined impact of climate and anthropogenic factors (Van Loon et al., 2016a). A deficit in streamflow, reservoir storage or groundwater may be modified due to water management interventions: a human-modified hydrological drought, or it may be driven due to water management alone: a human-induced hydrological drought (Van Loon et al., 2013; Van Loon et al., 2016a). The question is to what extend the increased groundwater use modifies near-natural hydrological droughts, particularly groundwater droughts, and how these groundwater droughts differ in a human-modified setting (Van Loon et al., 2016b).

In this context, the PhD thesis **aims** to better understand hydrological droughts, particularly groundwater droughts, in a human-modified context. In the presented research, the first results chapter (chapter 3) aims to observe and categorise groundwater droughts in a human-modified context. Following from this, the next results chapters (chapter 4-6) aim to identify hydrological droughts that are managed and alleviated. The results chapters thereby observe not only natural processes, but focus on management interventions on hydrological droughts in human-modified environment.

1.2 Background

1.2.1 Hydrological droughts in natural systems

Prior to the investigation of human-modified droughts, natural drought propagation and characteristics of hydrological droughts in a (near-)natural setting need to be explained. Natural or near-natural settings refer herein to (relatively) undisturbed hydrological conditions for streamflow and groundwater level variation. Near-natural hydrological droughts develop as a result of cascaded precipitation deficits that propagate through the hydrological cycle (Yevjevich, 1967; Tallaksen et al., 2004; Van Lanen, 2006a). Precipitation deficits result in drying up of soils that can be aggravated by high temperatures and increased evapotranspiration leading to soil moisture deficits (Van Loon, 2015; Teuling, 2018; Manning et al., 2019). Deficits in soil moisture reduce runoff and percolation to deeper soil columns and groundwater resulting in lower discharge and eventually a reduction in groundwater storage. (Yevjevich, 1967; Van Lanen, 2006a). Natural water stores such as snow and glaciers, wetlands, and thick soil moisture columns and groundwater can delay or even mitigate the propagation of soil moisture anomalies. However, when natural stores disappear as a result of climate change, e.g. accelerated snowmelt, retreating glaciers, degraded soils, drought propagation changes and it can be debated whether these droughts are natural or also human-influenced (Van Tiel et al., 2018; Tijdeman et al., 2020; Huning et al., 2020). Streamflow droughts develop from the soil moisture deficits, antecedent conditions in a catchment, and the buffering effect of natural water stores that determine the spatial extend of absent runoff and reduced baseflow (Tallaksen et al., 2009). Deficits in groundwater occur latest in the hydrological cycle, depending on the antecedent conditions of the subsurface storage, delay in groundwater recharge, and non-linear response of aquifers (Eltahir et al., 1999; Tallaksen et al., 2009). The storage capacity and memory of groundwater systems determines the response time to a recharge and consequently baseflow generation. Groundwater systems that respond slower to recharge have a longer offset compared to quickly responding aquifer systems (Peters et al., 2006; Van Lanen et al., 2013). This also impacts river systems connected an aquifer, as the slow drought propagation corresponds to a slower reacting baseflow component and consequently, slower in their determination of droughts events (Stoelzle et al., 2014; Parry et al., 2018). Large-scale meteorological processes may thus result in different near-natural groundwater droughts depending on small-scale catchment characteristics, present/absent water stores and variability in the hydrogeological setting (Tallaksen et al., 2009; Bloomfield et al., 2013).

1.2.2 Hydrological droughts in human-modified environments

Natural drought propagation, as explained above, can be altered in many ways by humans managing and exploiting water resources for drinking water, food production, and industry (Siebert et al., 2010; Döll et al., 2012). Previously, this impact has been excluded and reviewed as external disturbance, but in socio-hydrology and in this study, the aim is to evaluate the dynamic influence of both natural and anthropogenic drivers (Sivapalan et al., 2012). The intertwined hydrological cycle that includes anthropogenic impact is altered in various ways compared to natural settings, and we are at the beginning of understanding the impact on hydrological extremes (Sivapalan et al., 2012; Di Baldassarre et al., 2015; Van Loon et al., 2016a; Ward et al., 2020). Analysing hydrological droughts in a human-modified context requires knowledge of both natural and anthropogenic drivers to assess the anthropogenic impact on hydrological droughts (Van Loon et al., 2016a).

The dynamic, primarily increasing, anthropogenic impact on the water cycle is an essential element when evaluating hydrological droughts in human-modified settings. In general, anthropogenic impact on the water cycle increased past decades in terms of increasingly more reservoir being built (Chao et al., 2008) and considering the disappearance of natural landscapes into urban areas, croplands, and irrigated fields (Foley et al., 2005). These long-term incremental anthropogenic changes to hydrology also alter water storage, water use and hydrological extremes. For example, when introducing reservoir to store water upstream and thereby altering river regimes and their drought and flood response (Di Baldassarre et al., 2015; Di Baldassarre et al., 2018; Rangecroft et al., 2019). Expanded irrigated area affects regional hydrological processes by the introduced return flow of excess water and increased water abstractions (Döll et al., 2014; Rateb et al., 2020). These examples highlight the long-term increasing anthropogenic impact, but short-term variability of anthropogenic impact has considerable effect too. For example, domestic water use can increase suddenly during heatwaves or meteorological droughts, adding stress to the water supply systems to meet water demand (Garcia et al., 2016) and irrigated areas also fuelling an increase in surface water and groundwater use and thereby aggravating droughts (AghaKouchak, 2015; Faunt et al., 2009; Wada et al., 2013). Water use can also suddenly reduce, when water conservation measures are in place during droughts (Low et al., 2015; Rodina, 2019) or when water users become aware of shortages (Garcia et al., 2020). Water management regulations or drought policies can introduce and encourage specific behavioural responses to drought conditions that may be effective on relatively short-term time scales (Bhanja et al., 2017; Dountcheva et al., 2020). In general, drought policies seek to increase the overall resilience to droughts (Wilhite et al., 2014) by introducing water conservation measures and alternative water sources during droughts. Integrating water use or managing surface water and groundwater in an adaptive response is another approach to increase storage capacity and resilience to droughts using water management (Jakeman et al., 2016; Scanlon et al., 2016). However, the actual impact of these drought policies or altered water resource management is often unknown (Urquijo et al., 2017; Wilhite et al., 2014). The short-term and long-term variability in anthropogenic impact on the water cycle contributes to a highly dynamic set of drivers that influence hydrological droughts in a human-modified settings that require careful unravelling to assess the relative influence of climate and anthropogenic impacts on hydrological extremes (Viglione et al., 2016).

1.3 Research gap

The recent focus of hydrological drought research in the human-modified environments shows the value of including anthropogenic impact, but it also reveals the various aspects that are represented within the term 'human-influence' (Van Loon et al., 2016a; Van Loon et al., 2016b). For example, human-influence on hydrological droughts can refer to reservoir building or changing reservoir regulations that alter streamflow droughts (Garcia et al., 2016; Di Baldassarre et al., 2018; Rangecroft et al., 2019; Margariti et al., 2019; Garcia et al., 2020). Human-influence can also refer to either surface water or groundwater use altering both surface water and groundwater droughts (Wada et al., 2013; Van Loon et al., 2013; Wanders et al., 2015; Tijdeman et al., 2018). Intentionally increasing groundwater recharge receives less attention in drought research, but again, alters both streamflow and groundwater droughts (Scanlon et al., 2016; Jakeman et al., 2016). And finally, drought mitigation strategies can also alter hydrological droughts, even though this is rarely quantified (Wilhite et al., 2014; Urquijo et al., 2017; Özerol, 2019). Despite these recent studies, the different aspects of human-influence and possible feedback between societal response and hydrology are not fully understood (Van Loon et al., 2016b; Gleeson et al., 2020). There is a need for obtaining a better understanding given the significant modifying impact of human water consumption (Siebert et al., 2010; Döll et al., 2012), increasing number of depleted aquifers (Custodio, 2002; Gleeson et al., 2012b; Konikow, 2011), and alignment of short-term and long-term sustainable management objectives (Gleeson et al., 2020). In this thesis, three aspects of human-influence on hydrological droughts are assessed that focus on the influence of 1) groundwater use, 2) enhanced recharge, and 3) drought management strategies on particularly groundwater droughts. In the following three sections, a specific research gap is explained followed by the research objectives, structure of the thesis, and research design in Chapter 2.

1.3.1 Impact of groundwater use on hydrological droughts

The impact of groundwater use on hydrological droughts is thus far mainly investigated using either models or a combination of observations and models in heavily-stressed and depleted aquifers (Van Loon et al., 2013; AghaKouchak, 2015; Rens et al., 2017; He et al., 2017; Van Loon et al., 2019). Hydrological (mainly stream flow) droughts in these examples are significantly impacted by groundwater use that (partly) cause the degradation of the groundwater resource. Other studies focusing on river flow or ecology conclude that groundwater use jeopardises low flows and results in serious reductions in environmental flows and aggravates streamflow droughts (Gleeson et al., 2018; Tijdeman et al., 2018; Graaf et al., 2019). These studies show the significance of groundwater use impact, but up to now, there is no common framework or methodology to analyse the impact of groundwater use on hydrological droughts systematically. Current methods are often applicable to streamflow droughts only, as surface water catchments characteristics can be used to compare hydrological drought response (Tijdeman et al., 2018; Van Loon et al., 2019). The diffused nature of groundwater hydrology, unknown groundwater catchment area, and heterogeneity of aquifer characteristics complicate a direct comparison between natural or near-natural groundwater droughts (Van Lanen, 2006a; Bloomfield et al., 2013; Haas et al., 2017). Alternative approaches to compare groundwater droughts have been advanced by statistical analysis, introducing a method to standardise groundwater level time series that allows a comparison of groundwater monitoring sites for near-natural groundwater systems (Bloomfield et al., 2013). This method also allows observation-based research to scale up from catchment scale to regional and even national scale despite various hydrogeological conditions (Marchant et al., 2018). The regional groundwater analysis is key for investigating droughts in human-modified settings, because groundwater use and water management is often regulated at regional (administrative) level that might not align with surface water or groundwater catchment boundaries. The first studies to apply this regional approach to groundwater droughts in human-modified environments found that seasonal groundwater use aggravated droughts (Lorenzo-Lacruz et al., 2017; Lee et al., 2018). However, both studies highlighted the need for a modified method, as their results could not distinguish natural and anthropogenic drivers. Therefore, there is a need 1) to develop a framework that assess regional groundwater droughts at a relevant management scale, 2) to investigate groundwater droughts in a systematic manner and 3) to summarise main features of human-modified droughts.

1.3.2 Impact of enhanced groundwater recharge on hydrological droughts

The impact of enhanced groundwater recharge on hydrological processes receives less attention compared to the impact of groundwater use and even though fewer studies focus on the potential impact of managed aquifer systems. This is remarkable, as the capacity of managed aquifer recharge (MAR) is growing globally with a substantial representation in India (31%) and the USA (26%; Stefan et al. 2018; Dillon et al. 2019). MAR in Europe and Australia, representing a smaller proportion of global MAR capacity, show the value of MAR in securing drinking water and increasing drought resilience (Sprenger et al., 2017; Grant et al., 2013; Radcliffe, 2015). However, the impact of MAR facilities is often investigated on a relatively small and short spatio-temporal time scales, as small-scale groundwater models are often used to evaluate infiltration capacity and performance to improve operations (Bouwer, 2002; Niswonger et al., 2017; Maples et al., 2019). A complicating factor in upscaling MAR research is not only the significant effort to model groundwater at regional scale or national scale (Rens et al., 2017), but particularly to include MAR facilities that are smaller than the model resolution (Faunt et al., 2009; Brush et al., 2013). In addition to this, large proportion of MAR are not monitored (Tushaar, 2009; Dillon et al., 2019). As a result, a quantitative approach to assess the impact of enhanced recharge on hydrological extremes is missing. Theoretical examples and short observational records show that MAR could contribute to sustainable groundwater use (Sprenger et al., 2017; Cruz-Ayala et al., 2020; Alam et al., 2020; Dillon et al., 2020). Studies in exceptionally-well monitored sites highlight the importance and potential for drought resilience (Thomas et al., 2015; Scanlon et al., 2016), but a systematic approach is missing. Hence, there is a need for an observation-based study investigating the long-term, regional impact of MAR on hydrological droughts particularly in the light of the recent growth in MAR facilities globally and the potential for increased drought resilience.

1.3.3 Impact of drought policies on hydrological droughts

Drought policies introduce specific behavioural responses to drought aimed to increase drought resilience (Wilhite et al., 2014), but evidence of achieved drought resilience is rare (Bhanja et al., 2017; Dountcheva et al., 2020). This may be, because drought policy implementations are lengthy and different in each country depending on their history of water management, institutional and economic drives (Urquijo et al., 2017). For example, within Europe drought polices have been introduced as part of the Water Framework Directive in 2000 (Directive, 2000; Howarth, 2018). Studies investigating the process made since 2000 compare the drought policies in a qualitative manner, as introduced mitigation strategies vary widely (De Stefano et al., 2015b; Urquijo et al., 2017; Özerol, 2019). However, the actual achieved effectiveness of implemented measures remains unknown. Individual drought strategies or measures taken during droughts have been evaluated in various regions that all show the potential to reduce or alleviate hydrological droughts (Low et al., 2015; White et al., 2016; Di Baldassarre et al., 2018; Garcia et al., 2016; Dobson et al., 2020). Although none of these studies implemented drought strategies as part of a combined drought policy to evaluate the impact on surface water and groundwater resources. Jaeger et al. (2019) is the first to present a modelled drought policy showing how reservoir regulations are effective to mitigate droughts in a basin in the USA. However, groundwater use was not included in this first drought policy evaluation despite the importance and increased dependency on groundwater during droughts and the importance of managing groundwater use (Gleeson et al., 2012a; White et al., 2016; Gleeson et al., 2020). Therefore, there is a need to extend the current modelling work on drought policies to evaluate the impact of drought policies on both streamflow and groundwater droughts and obtain a better understanding of 1) the specific impact of different drought mitigation strategies and 2) potential sensitivities of these strategies to catchment characteristics.

1.4 Research objectives

To address these research gaps and the overall research aim, the aim has been subdivided into three research objectives that are discussed in the following four results chapters (see also conceptual Figure 1.1).

Assess the impact of groundwater use on groundwater droughts

The first research objective is to identify characteristics of human-modified droughts and relate drought characteristics to driving meteorology, hydrogeological setting, and groundwater use. This objective is addressed in chapter 3 in which near-natural groundwater level

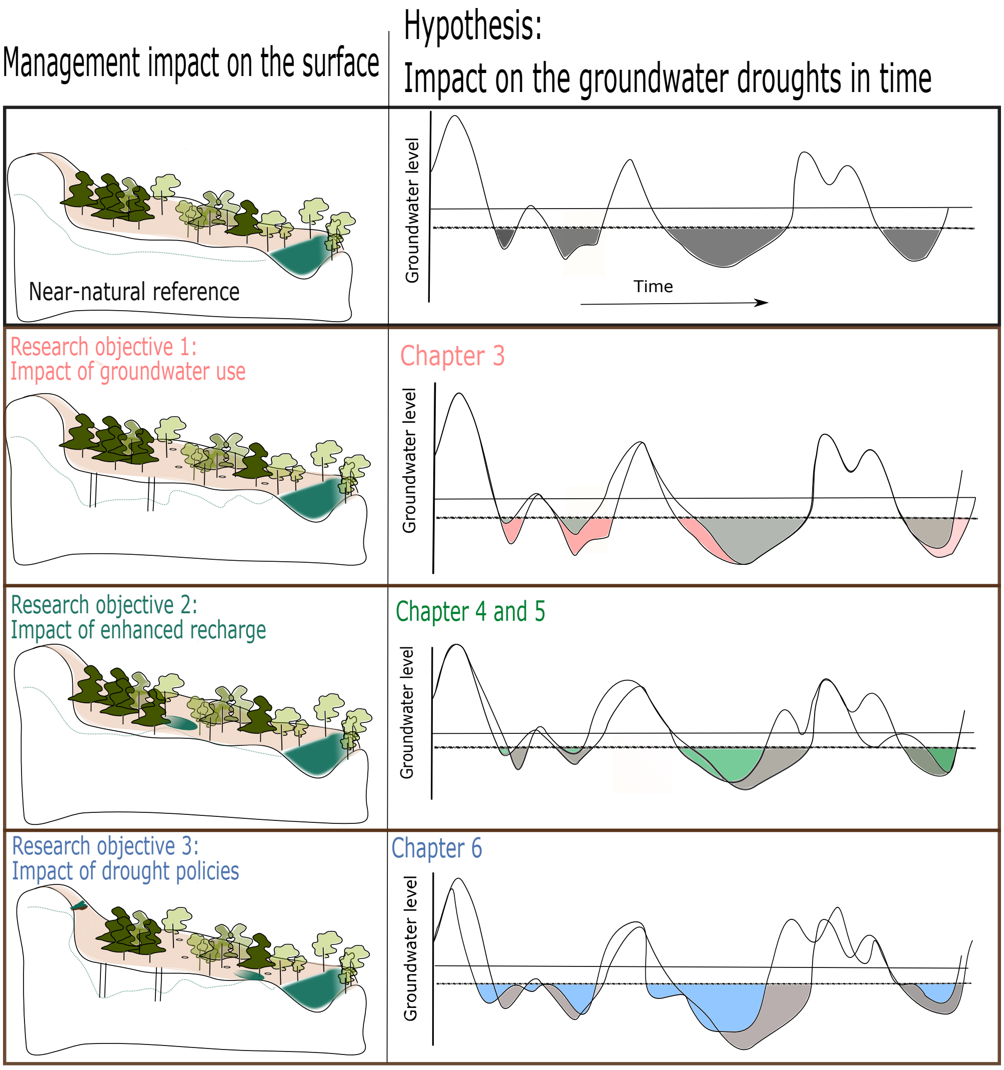


Figure 1.1: Conceptual diagram of the three research objectives and four results chapters that address different aspects of human-influence on groundwater droughts. Left is the management impact on the surface shown. Right shows the hypothesised impact on groundwater droughts in time (colours match the research objective colours).

observations and potentially impacted observations are compared in a regional groundwater drought analysis.

Impact of enhanced recharge on groundwater droughts

The second research objective is to assess the impact of enhanced groundwater recharge on groundwater droughts. This research objective is investigated in two results chapters that include an initial exploration of long-term impact of MAR on groundwater storage (Chapter 4) and a follow-up study (Chapter 5) that aims to investigate wider impacts of MAR on groundwater droughts. This investigation will also address the potential to expand MAR capacity and the implications for management of enhanced recharge to contribute to sustainable groundwater management.

Impact of drought policies on hydrological droughts and water resources

The final, third research objective aims to advance the conceptual understanding of the impact of drought policies on hydrological droughts. To this end, a conceptual model is developed in Chapter 6 that enables an assessment of temporal surface water and groundwater availability and water resource management. The impact of drought policies is herein evaluated using scenarios of separate and combined drought mitigation strategies.

1.5 Structure of thesis

The structure of the thesis follows these three research objectives that are applied to different, but appropriate, case study areas. The overall approach, relevance of the case studies, and developed methods are explained in the Research Design chapter (Chapter 2). Following on from the overall design, the three objectives are addressed across the four results chapters (Chapters 3-6; Figure 1.1). The first chapter (Chapter 3) evaluates the impact of groundwater use on groundwater droughts starting with observing and summarising hydrological droughts in human-modified environments. The observation-based approach is applied to regions with MAR to evaluate the impact on groundwater droughts (Chapter 4 and 5). In Chapter 6, drought policies are simulated in a conceptual model, showing the impact of managing and alleviating hydrological droughts in human-modified environments. The last chapter (Chapter 7) presents the overall conclusions and outlook of the thesis highlighting recommendations for future research on hydrological droughts in human-modified environments.

Chapter Two

Research Design

2.1 Introduction

This Research Design chapter presents the approach to investigate hydrological droughts in human-modified environments, addressing both variability in natural and anthropogenic drivers for streamflow and groundwater droughts. In the emerging field of hydrological drought research in human-modified environments, not all appropriate methods are fully developed yet. Recent studies presented new methods suitable to analyse human-influence on streamflow droughts, but not groundwater droughts specifically (Tijdeman et al., 2018; Rangecroft et al., 2019; Van Loon et al., 2019). To date, groundwater drought research has focused on near-natural settings primarily, excluding human-influenced groundwater level observations in drought analysis (Bloomfield et al., 2015; Kumar et al., 2016; Haas et al., 2017). This chapter combines the two approaches showing that a combination of statistical methods and socio-hydrological modelling can be used to advance and extend current analyses to groundwater droughts in human-modified settings. The chapter is subdivided by the three research objectives (introduced in section 1.4) and their relevant case studies (section 2.2), after which the various data and methods are presented (section 2.3 and 2.4) including modified statistical methods and the developed conceptual model.

2.2 Research objectives and relevant case studies

The research design follows from the three research objectives, which focus on 1) the impact of groundwater use on groundwater droughts, 2) the impact of enhanced groundwater recharge on groundwater droughts, and 3) the impact of drought policies on hydrological droughts. Different case studies were selected that are relevant exemplars for each research objective (Figure 1.1).

2.2.1 Research objective 1: impact of groundwater use

The first research objective builds further on the regional groundwater drought analysis of Bloomfield et al. (2013) and Bloomfield et al. (2015), but with a focus on human-modified groundwater observations. Both studies focus on primary aquifers in the UK using long-term observational groundwater level records to characterise groundwater droughts in near-natural conditions. Considering the intense groundwater use and management of water resources in the primary UK aquifers and the previously excluded human-impacted groundwater level records, the UK was selected as case study for the first research objective. The available long observational records of precipitation and groundwater levels were used to reproduce the near-natural drought analysis and define a reference for potentially impacted observations. Potentially impacted groundwater level observations were obtained from regular monitored boreholes in managed groundwater abstraction units (Catchment Abstraction Management Strategy (CAMS) units). The national water regulator, the Environment Agency (EA) overviews the catchment-based approach in CAMS units to manage (and restrict) groundwater abstractions (Environment Agency, 2016). These potentially impacted groundwater level records define the core of the research presented in Chapter 3 to address research objective 1. Multiple CAMS are selected to make a representative sample for the primary aquifers in the UK using both near-natural and potentially impacted groundwater level observations. Data used and available information about water resource management are discussed briefly in the next section and in more detail in Chapter 3.

2.2.2 Research objective 2: impact of enhanced recharge

The second research objective focuses on enhanced groundwater recharge, which is also practised in the UK, although this may not be the most representative case study. In the UK, enhanced groundwater recharge has been in use since 1995 to alleviate the pressure on London's water resources (Thames Water, 2020). Even though the capacity is enough to satisfy 1.2m Londoners, artificial recharge is injected into one isolated aquifer with limited regional impact (Thames Water, 2020). In the wider context of global Managed Aquifer Recharge (MAR) capacity, MAR in the UK represents a small proportion compared to more regional approaches that are present elsewhere in Europe (Thames Water, 2020; Sprenger et al., 2017; Dillon et al., 2019) and even larger regional approaches in the USA and India that represent the largest proportion of the global MAR capacity (31% and 26% respectively; Dillon et al. 2019). However, few of these MAR facilities are monitored. This limited monitoring hinders the option to distinguish impact of MAR from natural recharge or groundwater use that is key to this research. Therefore, a well-monitored case study was selected located in California (USA; Scanlon et al. 2012a; Scanlon et al. 2016). The Southern Californian MAR facilities have been in use and monitored since 1960s. Records of infiltrated and extracted water at these facilities are publicly available (KCWA, 2010), as well as regular groundwater monitoring elsewhere in the aquifer (CASGEM, 2017). The long-term regional MAR and available data in the aquifer facilitates regional groundwater drought research and the potential impact of MAR on groundwater droughts.

2.2.3 Research objective 3: impact of drought policies

The third research objective focuses on the impact of drought policies on hydrological droughts. This topic has been qualitatively analysed and investigated in the USA (Wilhite, 2000; Wilhite et al., 2014) and in Europe (De Stefano et al., 2015b; Urquijo et al., 2017), revealing the variable implementation of drought mitigation strategies across countries. However, both comparisons are qualitative assessments, leaving the impact on hydrological droughts unknown. Other studies investigated the impact of isolated mitigation strategies, not necessarily a full drought policy, and modelled the impact on water resources in either small catchments or virtual environments (Low et al., 2015; White et al., 2016; Di Baldassarre et al., 2018; Garcia et al., 2016). Therefore, a relatively simple conceptual model was built continuing the modelling approach to evaluate the impact of drought policies on not only surface water, but also groundwater variability. The widely applicable HBV model structure (Bergström, 1976) was modified for this conceptual model that extended the hydrological drought modelling of Van Lanen et al. (2013). Without simulating a specific watershed or catchment, input data were sought to be largely representative for water availability and water resource management in a (climate) region. However, information about water resource management, drought policies, and mitigation strategies rarely publicly accessible or assessed previously that limited the selection for suitable case studies (De Stefano et al., 2015b; Urquijo et al., 2017). The availability of climate data, water resource management plans, and drought policies in England was therefore used as an opportunity to developed the conceptual model using England as a test bed in the last results chapter.

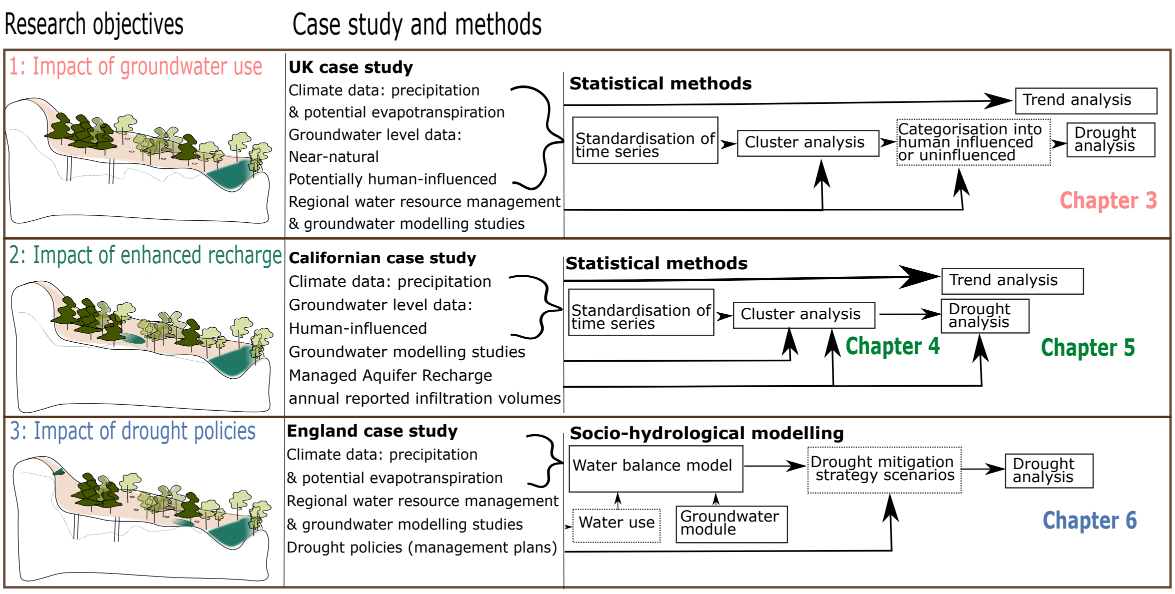


Figure 2.1: Flow diagram of the three research objectives (illustrated and coloured as in Figure 1.1 on the far left), case study areas used and the available data are listed in the centre, and methods applied in the four results chapter 3-6 are on the far right. Dotted boxes indicate methods that are specific to the result chapter and not explained in the Research Design chapter.

2.3 Data

Data gathered and background information used to address the three research objectives focuses on two case study regions (justified in section 2.2). The first is UK or England more specifically in chapter 6, for which climate data, groundwater level observations, and water resource management information was gathered to address the first and third research objective. The second case study is the Central Valley Aquifer in California (USA), where the long-term regional impact of enhanced recharge is studied, addressing the second research objective. This section presents an overview of the used data in the thesis. More detailed data descriptions can be found in the respective chapters.

2.3.1 UK case study

Groundwater is sourced for drinking water and industrial water use since the early 1900s and up to 100% of the UK's water supply is currently groundwater-fed (BGS, 2015). Management of main (or principal) aquifers is key to preserve the valuable resource during droughts. Groundwater storage is mainly replenished during winter months that varies widely across the UK. Modelled long-term groundwater recharge estimates range from 0-0.2 mm/d in the South East England up to 8 mm/d in North West Scotland (Mansour et al., 2018). Interestingly, most groundwater is used in Southern England, where groundwater provides water for public drinking water companies, agriculture, industry, and environmental purposes (BGS, 2015; Environment Agency, 2016; Agency, 2019a). To avoid overexploitation, groundwater abstractions are licensed and managed using the CAMS units (Environment Agency, 2016) and regional EA offices have access to a calibrated groundwater model to review wet, normal, and dry conditions given the licensed and maximum abstractions (Shepley et al., 2012). These reports are open and accessible in contrast to the records of actual abstractions that are not publicly available. The combination of classified near-natural groundwater level observations in the Hydrometric Register by Marsh et al. (2008) and the managed groundwater abstraction in the CAMS units defines the value of the UK as case study to address the first and third research objective.

Climate data

Data on climate drivers to hydrological droughts were obtained from spatially-distributed datasets and a regional product for precipitation. This regional precipitation product is based on regionally-averaged polygons that together present a representative value for daily precipitation across England and Wales (1931-2020; Alexander et al. 2001). Spatially-distributed precipitation data were obtained by the GEAR dataset of Tanguy et al. (2016). This gridded (1 km^2) UK dataset contains spatially-interpolated daily precipitation sums from 1890 to 2017 that are derived from the UK rain gauge network (see Tanguy et al. 2016 for details regarding the interpolation methodology). The other spatial climate data was the gridded (1 km^2) potential evapotranspiration dataset by Robinson et al. (2016). These data contain calculated daily potential evapotranspiration sums from 1961 to 2017, based on the Penman-Monteith equation calibrated for well-watered grass (see Robinson et al. 2016 for details). Regional long-term estimates of precipitation and evapotranspiration for selected CAMS units were provided by Mansour et al. (2018).

Groundwater level data

Groundwater level observation data were obtained from Marsh et al. (2008). These groundwater level sites have been qualitatively assessed by the British Geological Survey. Quality-checked data was available as early as 1836 (Chilgrove in the Chalk aquifer), but more generally from 1955 to 2015. Groundwater level observations in selected CAMS units were obtained from regional EA offices. Obtained data varied in quality and availability, although sufficient continuous observations were found for the period 1983-2014 (see section 3.5.1 for details regarding data quality assessment).

Water resource management information

Information about water resource management and drought management plans was obtained both the first and third research objectives. For the first research objective, general information about groundwater management and changed national water law was sourced in published reports and studies (Environment Agency, 2016; Ohdedar, 2017; Howarth, 2018). More detailed information about groundwater use and modelled groundwater recharge, groundwater flow, and the ratio of recharge to abstractions were found in regional groundwater modelling reports (Whitehead et al., 2006; Shepley et al., 2008; Cuthbert, 2009; Environment Agency, 2010). Note that groundwater abstractions were unavailable for selected CAMS units. Additional information required to address the third research objective, was obtained by a national database presenting the primary water users in the UK (Agency, 2019a). Detailed descriptions of water resource management plans were obtained via the EA (Agency, 2019b) and via the public drinking water companies themselves, who publish both water resource and drought management plans online (see S18 for references).

2.3.2 California case study

Managed Aquifer Recharge in California is primarily located in the southern counties of the Central Valley in the Tulare Basin. In the Central Valley, groundwater is used to sustain the large-scale irrigation that benefits from the Mediterranean climate with hot and dry summers and mild winters when most precipitation occurs (on average 152-254 mm/y; Faunt et al. 2009). Despite the highly seasonal water availability via streams and recharge season in winter, food production is booming since the start of 1900s and large-scale irrigated agriculture resulted in overexploitation of the aquifer with irreversible consequences in terms of died up lakes (Bertoldi et al., 1991; Faunt et al., 2009) and subsidence (Faunt et al., 2016; Ojha et al., 2017). The long-term groundwater budget of Tulare shows that estimated groundwater recharge (from precipitation, streams, and landscape) represents 36% that is exceeded by the modelled groundwater abstractions (50%) and losses in aquifer due to (in)elastic matrix storage, compression of specific yield, and groundwater flow leaving the Tulare Basin (14%; Faunt et al. 2009). Additional surface water is imported from North California that was initiated to meet the agricultural demand (USBR, 2019; California Department of Water Resources, 2020); but this is insufficient to meet current dry years and droughts (Faunt et al., 2009; Famiglietti et al., 2011; Xiao et al., 2017). The initiated aquifer recharge projects seek to increase groundwater storage by enhancing groundwater recharge with the imported surface water that in some cases has increased drought resilience (Scanlon et al., 2016). The regional impact of MAR in Tulare basin is investigated in Chapter 4 and 5.

Climate data

Climate data for California were used from two datasets with different spatial and temporal resolutions. The first dataset used to assess the basin-wide drought status was from the North American Drought Monitor (NADM; Svoboda et al. 2002). Monthly NADM data are divided into climate regions, for which the Tulare Basin is represented by the (larger) San Jaoquin basin. More detailed spatially-distributed data were obtained from the DAYMET dataset (Thornton et al., 2017). This is a gridded dataset (1 km^2) providing spatially interpolated estimates of daily precipitation sums across California.

Groundwater level data

Groundwater level observations are publicly available in California, as part of the CASGEM dataset that is managed by Department of Water Resources (CASGEM, 2017). There is a large number of groundwater monitoring sites present, although the frequency of monitoring varies widely and often only recorded biannually. A common monitoring period for approximately 150 sites was found for the period 1980-2015 that would capture regional groundwater level variation during the most recent drought events in 1986–1992, 2006–2009, 2011–2015 (DWR, 2016). Details regarding data quality inspection can be found in section 4.4.2 and 5.5.2.

Managed Aquifer Recharge data

Data for enhanced recharge were obtained from KCWA (2010) and Scanlon et al. (2016), who presented the volume of water infiltrated and extracted in the MAR facilities from 1963 to 2015. Annual volumes were obtained of 11 out of 15 MAR facilities that were converted to mm/y using the reported size of infiltration basins (KCWA, 2010). The reported volumes varied, as some MAR facilities were earlier in operation than others. Also, due to a delay in reporting most recent MAR volumes, not all recharge was reported for 2010-2015 (see caption of Figure 4.2 for details). Even though this dataset varies in its temporal and spatial extent, the timing and indicated volume of MAR recharge has proven valuable to estimate short-term and long-term MAR impact.

2.4 Methods

The investigation of hydrological droughts in human-modified environments started by advancing previously applied statistical methods. The next section presents an overview of the applied statistical methods, i.e. drought analysis, standardisation of time series, cluster and trend analysis. These methods were used in multiple chapters (more detail is provided in section 3.5.2, 4.4.2, and 5.5.2). The conceptual model that is used to evaluate the impact of drought policies on hydrological droughts is also briefly introduced here and further explained in section 6.5.2.

2.4.1 Drought analysis

First and foremost, presented results in this thesis are largely defined by the applied drought analysis that was used to distinguish below normal conditions for precipitation, soil moisture, baseflow, and groundwater levels based on long observational records (Tallaksen et al., 2004; Mishra et al., 2010). The length of the observation records varied slightly in the chapters, but generally covered at least 30 years to represent both short-term and long-term climate variability. Drought thresholds are selected to represent a representative drought event, which is a 'once in 5 year drought' in Chapter 3 and Chapter 6, as this is a common drought threshold and in line with the UK overview of national droughts (Durant, 2015; Tallaksen et al., 2004; Peters et al., 2006). In Chapter 5, the commonly used NADM threshold of the Drought monitor is used that would be more appropriate for a drought study in California (Svoboda et al., 2002). Drought thresholds are applied to precipitation, soil moisture, discharge, and groundwater levels as either raw data or normalised (standardised) data. For standardised data that includes seasonal (monthly) variation, a fixed threshold is applied to indicate the below-normal threshold. From the identified droughts, the occurrence, duration, and magnitude are calculated to evaluate drought characteristics (Fleig et al., 2006; Van Loon, 2015). In the thesis, terminology for droughts as defined by Mishra et al. (2010) is used and therefore, precipitation deficits are also referred to as meteorological droughts and hydrological droughts refer to *both* streamflow and groundwater droughts. The terms streamflow or groundwater droughts are used when describing deficits in either streamflow or groundwater more specifically.

2.4.2 Standardising of time series

In all of the results chapters, standardised indices are used for precipitation and groundwater level observations. Even though standardised methods have their drawbacks in terms of introduced uncertainty fitting a distribution (Stagge et al., 2015; Svensson et al., 2017), normalised climate variables can be used for drought propagation and regional drought analysis. This regional drought analysis is particularly valuable to compare near-natural and human-influenced observations. In the regional groundwater analyses (Chapters 3-6), standardised precipitation indices (SPI) are calculated based on the fitted monthly precipitation sums, as defined by Mckee et al. (1993). Standardised groundwater indices (SGI) are calculated using an inverse normal distribution in which normalised SGI values are assigned to corresponding groundwater level observations (Bloomfield et al. 2013; see also section 3.5.2 for details).

2.4.3 Cluster analysis

The regional groundwater drought analysis as previously presented in Bloomfield et al. (2015) applies a cluster technique to group a large number of SGI based on the similarity in groundwater hydrographs to climatological drivers and hydrogeological setting. This approach was further extended by Marchant et al. (2018), who could also identify human-influenced observations in the identified clusters. Building further on these studies, a number of clustering techniques were trailed on the near-natural standardised groundwater datasets to minimise a biased choice in clustering technique (Aghabozorgi et al., 2015; Haaf et al., 2018). Clustering techniques in Chapter 3 and 4 were compared based on their Euclidean distance between computed clusters to have least overlap in their cluster composition (Aghabozorgi et al., 2015). Selected cluster groups were evaluated with hydrogeological studies and were sought to be spatially representative within or across the aquifer section.

2.4.4 Trend analysis

Trends in climate data and groundwater level observations were tested using a linear Mann Kendall trend test (Mann, 1945; Kendall, 1948). Because the standardisation of time series can introduce uncertainty in the extreme values (Stagge et al., 2015), raw time series were used for the trend calculation. To minimise the effect of seasonal variation, annual observations were used for long-term trends. For precipitation, annual sums were used in a standard Mann Kendall trend test. Groundwater level observations were averaged for each calendar year. Due to the long memory of some groundwater systems, mean annual groundwater level observations were tested for their serial correlation (Hamed, 2008; Cuthbert et al., 2019). A modified trend test was applied to account for the serial correlation as developed by Yue et al. (2002). Trends in precipitation, evapotranspiration, and groundwater levels were tested in Chapter 3 and 5, for which a significance level of $\alpha < 0.01$ was used, i.e. trend Z values smaller than -2.56 or greater than 2.56 are considered significant.

2.4.5 Socio-hydrological modelling

The socio-hydrological modelling approach originates from the conceptual modelling of Garcia et al. (2016) and Di Baldassarre et al. (2015); they present relatively simple models to visualise dynamics in socio-hydrology. To this end, drought policies are modelled in a versatile HBV model, as previously applied to hydrological drought research by Van Lanen et al. (2013). This lumped model consists of a soil moisture balance, driven by potential evapotranspiration and precipitation, a surface water storage reservoir, and a linear groundwater model. The socio-hydrological model presented in this thesis uses the three types of water storage, although the groundwater component is extended. This groundwater extension is because, since the publication of Van Lanen et al. (2013), Stoelzle et al. (2014) found that some aquifers are better represented using a different model structure when using a lumped model approach. Considering the variety in the principal UK aquifers and the substantial groundwater use in the UK, it was appropriate to extent the linear groundwater model of Van Lanen et al. (2013) for a more optimal representation of the different aquifer types in England. The human interaction added to the existing model structure allowed the simulation of drought policies with respect to their planned mitigation strategies. Developed model scenarios were based on reported mitigation strategies and impact of these mitigation strategies on hydrological droughts and water availability were compared to the baseline conditions.

2.5 Chapter summary

In this chapter, the research design is presented that linked directly to the three research objectives. For each objective, a representative case study was selected based on data availability and supportive background information to investigate hydrological droughts in a human-modified environment. The first research objective is addressed by a regional groundwater drought analysis set in the intensively managed UK aquifers comparing near-natural and potentially human-influenced groundwater level observations. The second objective is also addressed using a regional groundwater droughts analysis, but the analysis focuses on the long-term impact of regional enhanced recharge in the Central Valley (USA). The third and last research objective is addressed using a conceptual socio-hydrological model that simulates the impact of drought policies on hydrological droughts. The model input data and developed scenarios are based on (regionally-averaged) English climate data, water resource management, and drought mitigation strategies. In the following chapters, more specific information on data and methods provided to investigate impact of groundwater use (Chapter 3), the impact of enhanced recharge (Chapter 4 and 5), and the impact of drought policies (Chapter 6). The main findings are concluded in Chapter 7 that highlights the contribution of the thesis and indicates directions for future research.

Chapter Three

Asymmetric impact of groundwater use on hydrological droughts

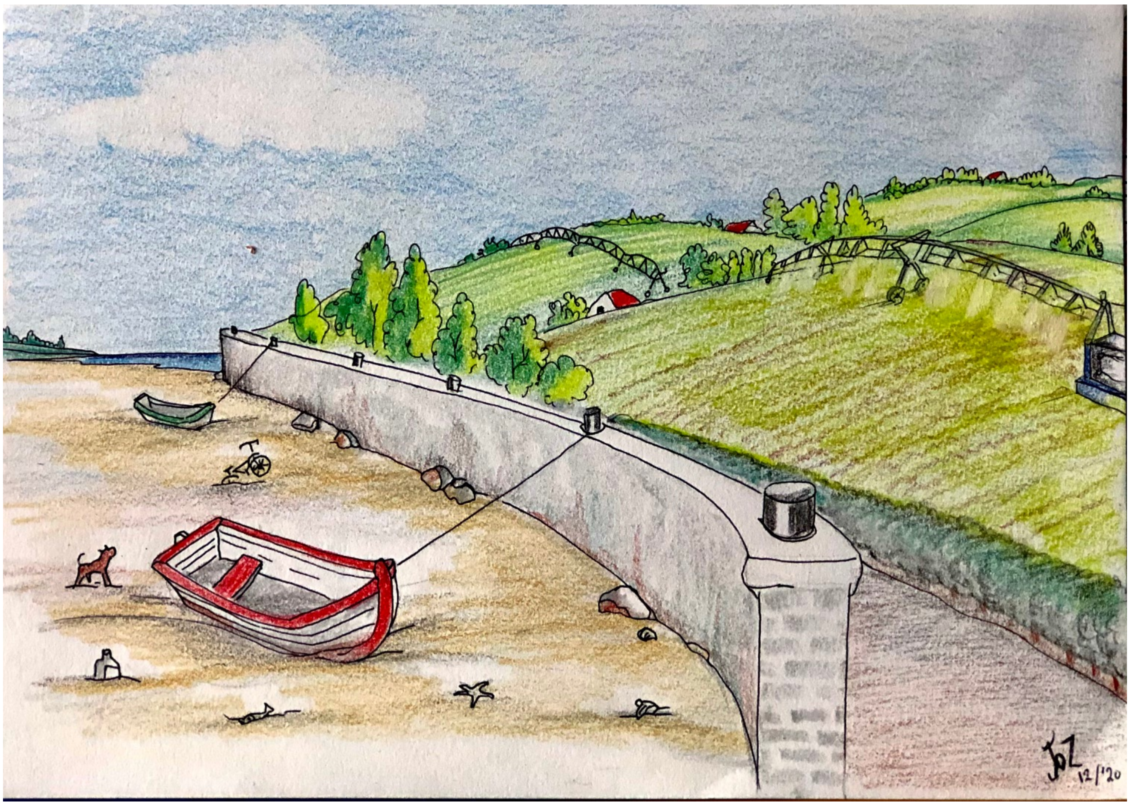


Figure 3.1: Observing the impact of groundwater use, illustration by Jos Zanders

3.1 Introduction

This chapter aims to meet the first research objective of this thesis by investigating the impact of groundwater use on groundwater droughts (see also Figure 1.1). Human influence on hydrological droughts is here thus approached as the impact of groundwater use on groundwater droughts. For assessing the impact of groundwater use, a framework was developed that compares near-natural groundwater sites to potentially impacted sites. The framework consisted of two methodologies that compared and quantified the relative impact of groundwater use on groundwater droughts using four regional study areas in England. Results are summarised in a conceptual typology showing the asymmetric impact on groundwater droughts. Further applications of the framework are discussed in chapter 4 and 5 showing that this methodology can also be used to identify other aspects of human-influence, such as the impact of enhanced recharge on groundwater droughts.

The presented chapter has been published in Hydrology and Earth System Sciences (Wendt et al., 2020) before completion of this thesis. For this publication, DW has designed the research and gathered data of the case studies. DW also developed the framework, conducted the time series analysis, data representation, and writing up of the manuscript. Co-authors (AVL, JB, DH) supervised and guided the research design and time series analysis and contributed to the editing of the manuscript into the final version of the published manuscript.

3.2 Background

Groundwater is an essential source of water supply, as it provides almost half the global population with domestic water (Gun et al., 2012), 43% of the irrigation water (Siebert et al., 2010), and 27% of industrial water use (Döll et al., 2012), as well as sustaining ecologically important rivers and wetlands (Graaf et al., 2019). Groundwater use and dependency on groundwater resources has grown in the past decades (Famiglietti, 2014), particularly during meteorological droughts, when groundwater is used frequently (Taylor et al., 2013; AghaKouchak, 2015).

Meteorological droughts propagate through the hydrological cycle, ultimately resulting in a groundwater drought (Wilhite, 2000; Van Lanen, 2006b), defined as below-normal groundwater levels that are associated with short-term reductions in storage (Chang et al., 1995; Tallaksen et al., 2004; Mishra et al., 2010). Increased use of groundwater before or during meteorological droughts can also lower groundwater levels and thereby aggravate groundwater droughts (Wada et al., 2013; Christian-Smith et al., 2015). Managing groundwater use during droughts is therefore important, as overexploitation of groundwater has disastrous consequences (Custodio, 2002; Famiglietti, 2014; Russo et al., 2017; Mustafa et al., 2017). However, to date groundwater droughts have been studied under primarily near-natural conditions and there is limited conceptual understanding of the impact of groundwater use on groundwater droughts despite this being of interest to water regulators and policy makers.

Under near-natural conditions, the propagation of meteorological droughts to groundwater droughts depends on the antecedent condition of the land surface, subsurface controls on recharge, and non-linear response of groundwater systems (Eltahir et al., 1999; Peters et al., 2006; Tallaksen et al., 2009). These processes determine the spatial distribution, duration, magnitude, and recovery of near-natural groundwater droughts (Van Lanen et al., 2013; Van Loon, 2015; Parry et al., 2018). However, in human-modified environments, groundwater droughts are also impacted or driven by water use (Van Loon et al., 2016a). This type of groundwater drought is therefore distinguished from a natural drought and referred to as human-modified or human-induced drought (Van Loon et al., 2016c).

In human-modified environments, understanding the influence of groundwater use on groundwater drought requires information related to the natural propagation of a drought and groundwater use in time. Droughts are influenced by historical and recent abstractions, as these change both short-term and long-term groundwater storage (Gleeson et al., 2017; Thomas et al., 2015; Jackson et al., 2015). Unfortunately, information on groundwater abstraction, if available at all, is often considered commercially confidential. Abstraction records are usually unavailable for research, although often included in groundwater models developed for commercial and regulatory purposes (Shepley et al., 2012). Consequently, in absence of actual abstraction records qualitative information about groundwater use and management regulations is invaluable to investigate the influence of groundwater abstraction on groundwater droughts (Döll et al., 2014; Panda et al., 2007). However, the scale at which management regulations are organised is often regional including multiple catchments that might not cover the entire drought-impacted area (Tallaksen et al., 2009; Shepley et al., 2012). Studying groundwater droughts in human-modified environments would therefore require a regional approach to align the scale of a groundwater drought study with the scale at which management decisions are made.

3.3 Aim

The aim of this chapter is to investigate impact of groundwater use on regional groundwater droughts in the absence of actual abstraction data. To this end, a methodological framework is designed to investigate groundwater droughts in water management units under a broad range of conditions, i.e. from where groundwater use is a small proportion of the long-term annual average recharge to where it is a significant proportion of the long-term annual average recharge. A case study from the United Kingdom (UK) is used consisting of four water management units in two main aquifers. As is common elsewhere, no data is freely available on actual abstractions in the case study area. However, information indicating the annual maximum licensed abstraction is available and groundwater level observations are provided for 170 sites in the four water management units. Consequently, inferential approaches are used to assess the impact of abstraction on groundwater droughts. We used two complementary approaches. First, given the typically good correlation between precipitation and groundwater level time series under near-natural conditions (Bloomfield et al., 2013; Bloomfield et al., 2015; Kumar et al., 2016), we used correlations defined by a limited number of near-natural groundwater hydrographs as reference. Deviations from this reference correlation were then used to qualitatively subdivide sites in on average uninfluenced and influenced by abstraction. This subdivision was used to characterise the impact of groundwater abstraction on regional groundwater droughts. Second, long-term abstraction influence was investigated through the spatial distribution of trends in groundwater level time series in relation to the distribution of licensed abstractions. Results are discussed in terms of the role groundwater abstraction plays in modifying near-natural groundwater droughts. A conceptual figure is proposed suggesting that long-term groundwater abstraction may modify drought frequency, duration, and magnitude depending on the balance between groundwater abstraction and recharge.

3.4 Study area

The UK case study consists of four water management units (1: Lincolnshire, 2: Chilterns, 3: Midlands, 4: Shropshire) across Chalk and Permo-Triassic sandstone aquifers that are the two main aquifers in the UK (Figure 3.2). The two aquifers have contrasting hydrogeological characteristics. Regional groundwater flow and storage in the Chalk aquifer are dominated by its primary fracture network (Bloomfield, 1996) and secondary solution-enhanced fractures (Downing et al., 1993; Maurice et al., 2006). The response of Chalk groundwater hydrographs to driving meteorology is a function of regional variations in the nature of the fracture network, extent of karstification, nature of overlying superficial deposits amongst other factors (Allen et al., 1997). In the Permo-Triassic sandstone aquifer, groundwater flow and storage are influenced by variations in the matrix porosity, aquifer thickness, and to some extend on fracture characteristics (Shepley et al., 2008; Allen et al., 1997). Faults divide the Permo-Triassic sandstone in separate sections, but their impact on regional groundwater flow varies: some faults act as hydraulic barriers and others enhance permeability resulting in increased recharge (Allen et al., 1997). Hydrographs in the Permo-Triassic sandstones typically respond more slowly to driving meteorology than those in the Chalk (Bloomfield et al., 2013) and are influenced by local variation in aquifer thickness and confinement by superficial deposits.

Regional hydrological features of the four studied water management units in the aquifers are summarised in Table 3.1. Two of these water management units are situated in eastern England (Lincolnshire, unit 1) and central southern England (the Chilterns, unit 2) and are underlain by the Chalk aquifer. The other two water management units are situated in central England (East Midlands, unit 3) and north west England (Shropshire, unit 4) and are underlain by the Permo-Triassic sandstone aquifer. Groundwater is primarily abstracted for public drinking water. Industrial, agricultural and environmental water use represent a smaller proportion of groundwater use in the UK (Agency, 2019b). Abstractions are licensed, which have changed since their introduction in 1963 (Ohdedar, 2017). As a result of the implementation of the Water Framework Directive in 2000, abstraction licences follow a water balance approach to ensure 'good groundwater status' resulting in an overall reduction of licensed groundwater use (Environment Agency, 2016). Specific information regarding the change in water use in these water management units is presented in Table 3.1 (see also additional references in the last column).

Table 3.1: Regional features of the four water management units summarising the area size, long-term precipitation (P) and potential evapotranspiration (PET), as calculated by Mansour et al. (2018) based on daily data from 1962 to 2016, hydrogeological features, and main groundwater use changes in time. The location of water management units is shown in Figure 3.2. In Figure S1, the purpose and locations of recent abstraction licences are shown. Hydrogeological information and groundwater use is based on Allen et al. (1997) and complemented with additional references (see last column).

Water management unit & number of monitoring wells	**Area (km^2)**	**Annual average (mm/yr)**	**Hydrogeological features**	**Groundwater use**	**Additional literature**
1: Lincolnshire	1310	P: 589	Highly permeable outcrop due to dissolved fractures and weathering	Abstraction peaked in 1970 and reduced since 2000	Whitehead et al. (2006)
38 wells		PET: 454	South-East of aquifer increasingly confined by superficial deposits	Abstractions exceed average recharge only during droughts	Bloomfield et al. (1995), Hutchinson et al. (2012)
2: Chilterns	1650	P: 674	Chalk aquifer partly covered by superficial deposits	Abstractions increased during 1970-2003 and decreased after 2003	Jones (1980), Jackson et al. (2011)
45 wells		PET: 485	karstification in valleys	recent abstraction is estimated on 50% of average recharge	Environment Agency (2010)
3: Midlands	1100	P: 630	Varying aquifer thickness from 120-300m	Abstraction exceeded the average recharge rates by 25% in 1980-90	Zhang et al. (2010)
36 wells		PET: 476	Confined by superficial deposits in the East	Abstraction reduced in 2000 to meet average recharge	Shepley et al. (2008)
4: Shropshire	1400	P: 722	Highly variable aquifer thickness: 30-1400m	Abstraction represented 40-50% of recharge in 1970-90 and reduced after 2000.	Cuthbert (2009), Voyce (2008)
51 wells		PET: 471	Major faults interrupt groundwater flow across sandstone layers	River augmentation scheme increases abstractions during dry periods	Shepley et al. (2007)

3.5 Data and methods

3.5.1 Data

The analysis has been undertaken for a 30-year period (1984-2014) using precipitation, evapotranspiration, and groundwater level time series. This time period includes at least four major droughts of a national spatial extent, namely: 1988-1994, 1995-1997, 2003-2006, and 2010-2012 (Durant, 2015).

Precipitation and potential evapotranspiration data were obtained from the GEAR dataset (Tanguy et al., 2016) and the CHESS dataset (Robinson et al., 2016). The gridded (1 km^2) GEAR dataset contains interpolated monthly precipitation estimates derived from the UK rain gauge network. The CHESS dataset is also gridded (1 km^2) and contains climate data, from which potential evapotranspiration estimates are computed using the Penman-Monteith equation. We aggregated daily potential evapotranspiration estimates to monthly sums. For both gridded datasets (GEAR and CHESS), grid cells were extracted corresponding to groundwater well locations. The 1 km^2 gridded precipitation and potential evapotranspiration sums were compared to monthly groundwater observations of the same location. This point-scale comparison relies on the assumption that the influence of precipitation is largest surrounding a groundwater monitoring site (Bloomfield et al., 2013; Bloomfield et al., 2015; Li et al., 2015; Kumar et al., 2016).

Precipitation estimates were converted into standardised precipitation indices (SPI) following the method of Mckee et al. (1993). A gamma distribution was fitted to precipitation estimates, but alternative distributions were also tested (Normal, Pearson III, and Logistic) (Stagge et al., 2015). Considering the use of SPI to account for delayed recharge, a large range of accumulation periods of precipitation (1 to 100 months) was calculated in order to find the optimal correlations between precipitation and groundwater time series.

For this particular use of the SPI, the 'best' fitting distribution varies (Svensson et al., 2017). Alternative distributions showed minimal differences from the gamma distribution in the computed correlations between standardised precipitation and groundwater time series, hence we decided to use the gamma distribution.

Groundwater level time series were obtained from the national groundwater database in the UK, which contains time series for both reference wells and regular monitoring wells. 209 wells (or sites) have been included in the analysis, of which 39 are reference sites and 170 regular monitoring sites. Reference sites were taken to represent near-natural conditions in the 30-year time period. These sites were selected from the Index and Observation wells listed in the UK Hydrometric Register (Marsh et al., 2008) and have previously been assessed by the British Geological Survey. Well descriptions indicate near-natural conditions or possible (intermittent) influence of groundwater abstraction. Wells selected for this study are categorised as near-natural reflecting regional variation in groundwater levels with minimal abstraction impacts. This selection of reference wells includes 30 wells in the Chalk and 9 wells in the Permo-Triassic sandstone. Regular monitoring sites are part of the monitoring network in the four water management units. Initially, 660 monitoring sites were considered for the regional groundwater drought analysis that were truncated to the 30-year analysis period and quality checked. Unrealistic observations were cross-validated with available meta-data, and if unexplained, removed from the dataset. Missing data were linearly interpolated from the last observation to the next observation in case of short sequences of missing data (less than 6 months) (Tallaksen et al., 2004; Thomas et al., 2016). Sites with records containing longer sequences of missing data were removed from the dataset prior to the analysis leaving a total of 170 (out of the original 660) groundwater level time series that were deemed of good quality, of which 38 were located in Lincolnshire, 45 in Chilterns, 36 in Midlands, and 51 in Shropshire.

All groundwater level time series were standardised into the Standardised Groundwater level Index (SGI) (Bloomfield et al., 2013), which is briefly explained here. Monthly groundwater observations were grouped for each calendar month and within each group observations were ranked and assigned a SGI value based on an inverse normal cumulative distribution of the data. No distribution was fitted, but SGI values were assigned to monthly observations accounting for seasonal variation within the calendar year. The resulting SGI time series represent extremely low to below-normal ($-3 < \text{SGI} < 0$) and above-normal to extremely high ($0 > \text{SGI} > 3$) monthly groundwater levels in the groundwater time series. Groundwater level observations are physically constrained by length of the screened interval of the borehole. Therefore, the lowest SGI value might indicate that groundwater levels fell below the borehole screen and highest SGI value can indicate groundwater levels reached the surface.

Qualitative information about groundwater use was provided for each water management unit by the national regulator (the Environment Agency (EA) in England). Detailed maps were made available regarding the purpose and recent (dated at 2015) licensed abstraction volumes (see Figure S1). In addition, reports describing the EA's regional groundwater resource models and location-specific groundwater studies were used as reference material to indicate changes in groundwater use (Table 3.1).

3.5.2 Methods

The developed methodological framework consists of two approaches to investigate the impact of groundwater use on groundwater droughts. The first approach uses a regional near-natural groundwater drought reference based on reference sites. SGI time series of reference sites are clustered to identify common spatial and temporal patterns in near-natural groundwater levels in the two aquifers. Reference sites were thereby taken to represent regional groundwater variation that is primarily driven by climate and hydrogeology. Then, monitoring wells in each of the four water management units were paired to these regionally-coincident clusters of reference wells (Figure 3.2) and human-influenced sites are identified using the correlation between SPI and SGI. Drought occurrence, duration, and magnitude in monitoring wells were compared with those in paired reference clusters to assess potential effects of abstraction on groundwater droughts. The second approach consisted of a groundwater trend test that quantified long-term trends as a consequence of continuous impact of groundwater use. The spatial distribution of identified trends was evaluated according to the location of annual abstraction licences, changes in water use, and hydrogeological features in the water management units.

Time series clustering

Three hierarchical clustering methods (single linkage, complete linkage, and Ward's minimum) were tested to find the most suitable and least biased approach for clustering SGI time series of the reference sites (Haaf et al., 2018). In each method, Euclidean distance was used as measure of similarity and cluster compositions that showed the least overlap between clusters were selected (Aghabozorgi et al., 2015). Criteria for selected clusters were set by previous studies (Chalk aquifer only) and known hydrogeological differences in the aquifers. For both aquifers, the minimum number of hydrograph clusters was sought that produced spatially-coherent clusters.

Correlation between SPI_Q-SGI

Under near-natural conditions, the optimum correlation between standardised precipitation and groundwater indices (SPI_Q-SGI) is generally high in unconfined aquifers (Bloomfield et al., 2013). Anomalies in precipitation propagate with a relatively constant delay in recharge to the groundwater, which is due to, subsurface controls on recharge, the antecedent condition of the land surface, and non-linear response of groundwater systems (Eltahir et al., 1999; Peters et al., 2006; Tallaksen et al., 2009). This constant delay is included in the calculated SPI_Q-SGI correlation by the optimal precipitation accumulation period that represents a long-term relationship for a certain site, as both the SPI and SGI were calculated for a continuous 30-year period including all seasons and both anomalously dry and wet periods.

The SPI_Q-SGI correlation can be reduced when groundwater level response becomes disconnected from driving precipitation under confined conditions (Bloomfield et al., 2015; Kumar et al., 2016; Lee et al., 2018) or when groundwater abstraction changes groundwater storage and levels independent from driving precipitation (Bloomfield et al., 2015; Lorenzo-Lacruz et al., 2017; Haas et al., 2017). In this study, the impact of confined conditions on reducing SPI_Q-SGI correlations is expected to be minimal, as only a small selection of Chalk sites are located in the semi-confined Chalk in South Lincolnshire (Table 3.1). On the other hand, the impact of dynamic groundwater use on SPI_Q-SGI correlations is expected to be significant. Long-term changes in groundwater use in the UK resulted in a spatially heterogeneous pattern of irregular, decreasing, or increasing influence of abstraction on groundwater storage. Groundwater use increased, for example, until the late 1980s and reduced afterwards with a large redistribution of where water is taken from to minimise the impacts on low flows (Ohdedar, 2017).

The presence or absence of human-influence on groundwater observations in the water management units was determined on the basis of the SPI_Q-SGI in each near-natural reference cluster. For each cluster, the lowest SPI_Q-SGI correlation was used as a threshold to differentiate long-term *influenced* from *uninfluenced* groundwater monitoring sites. Monitoring wells with high or higher SPI_Q-SGI correlations than the near-natural reference are regarded as (on average over the 30-year investigation period) uninfluenced and those with lower correlations as potentially human-influenced. An illustrated example is provided in Figure S2 showing SGI time series of a near-natural reference site and three groundwater monitoring sites. Statistical differences between the categorised uninfluenced and influenced sites were computed using a non-parametric Wilcox test.

Drought analysis

Groundwater droughts were defined using a threshold approach applied to SGI time series. Groundwater droughts are considered to occur when the SGI value is at or below -0.84, which corresponds to a 80^{th} percentile or a 'once every 5 year drought event' (Yevjevich, 1967; Tallaksen et al., 2004; Tallaksen et al., 2009). Drought characteristics were compared between near-natural reference clusters and monitoring sites focusing on drought occurrence, frequency, duration, and magnitude.

Trend test

The second approach consisted of a monotonic trend test applied to all monitoring sites given the previously identified trends in human-modified groundwater systems (Thomas et al., 2015; Sadri et al., 2016; Bhanja et al., 2017; Pathak et al., 2018). This trend test contributes to the first approach, as the SGI and SPI_Q-SGI correlation analysis do not specifically account for trends in groundwater time series that could result in significant trends going unnoticed. Hence, an additional trend test was introduced to compare trends in annual (averaged for each calendar year) groundwater levels to climate data (precipitation and evapotranspiration) that were extracted for grid cells corresponding to groundwater well locations from the GEAR and CHESS datasets (Tanguy et al., 2016; Robinson et al., 2016).

Trends were quantified by the trend Z value showing positive or negative deviations from the null hypothesis (no trend). Positive/negative Z values indicated increasing/decreasing trend directions. $|Z|$ values over $|2.56|$ ($\alpha = 0.01$) were considered significant.

Trends in groundwater level time series were tested using a modified Mann-Kendall trend test (Mann, 1945; Kendall, 1948), which includes a modification developed by Yue et al. (2004) to account for significant auto-correlation in the annual groundwater data (Hamed, 2008). Trends in climate time series were also calculated from annual data using a standard Mann-Kendall trend test.

3.6 Results

3.6.1 Near-natural groundwater reference clusters

The near-natural groundwater reference clusters, based on SGI clusters of the reference wells and the clustering criteria, were defined by Ward's minimum clustering technique showing the least overlap between clusters of the three tested clustering techniques (Figure S3). Eight clusters are identified, of which five clusters are located in the Chalk (C1-5) and three in the Permo-Triassic Sandstone (S1-3) (Figure 3.2). The spatial distribution of Chalk clusters (C1, C3, C4) is consistent with clusters identified by Marchant et al. (2018). Two additional clusters are identified, of which one is located in East Anglia (5 reference wells in C2) and one in South East England (2 wells in C5). The cluster dendrogram shows a small difference in similarity between C4 and C5, which is located close to the coastline (cluster dendrogram result not shown; difference between C4 and C5 is shown in Fig. S3). C1 and C3 are coincident with water management unit 1 and 2 respectively, and are used as near-natural reference for monitoring sites in those units. In the Permo-Triassic sandstone aquifer, only one spatially coherent cluster (S2) is found when all nine SGI time series are clustered (Figure 3.2). The cluster composition of the other two smaller clusters (S1 and S3) is not spatially coherent and there is no evidence of previous clustering studies available that can confirm these two clusters. Hence, only S2 is used as near-natural reference for monitoring sites in water management units 3 and 4.

The optimal SPI_Q-SGI correlations of near-natural wells are high on average (0.79) with a range of 0.66 to 0.89. These correlations are found using the optimal accumulation period, which accounts for delay in recharge that is different for each reference cluster. High SPI_Q-SGI correlations are found for both short and long accumulation periods and there was no systematic relationship between the SPI_Q-SGI correlation and the SPI accumulation period Q or SGI autocorrelation in the near-natural wells. C1 represents a relatively fast-responding section of the Chalk and has a short Q of 12.6±5.4 months. The Q of C2 and C3 is higher, respectively 18.2±4.3 and 24±8.6 months. This corresponds to the delay in groundwater recharge due to the Quaternary deposits present in these regions (Allen et al., 1997). In the South East, the Chalk is highly fractured, which is reflected by a short Q of 8±2.2 months for C4 and C5. In the Permo-Triassic sandstone, the Q of S2 is 35±4.5 months, which confirms a slow-responding groundwater system (Allen et al., 1997).

In the monitoring sites, the majority of the SPI_Q-SGI correlations are as high or higher than the minimum correlation of paired reference clusters. Hence, these monitoring sites are considered, on average, uninfluenced by abstraction. The percentage of uninfluenced sites varies between the water management units. The largest percentage is found in the Chilterns (71%), followed by the Midlands (63%), Shropshire (53%), and Lincolnshire (31%). Monitoring sites with a SPI_Q-SGI correlation below the minimum correlation of the paired reference cluster are treated as on average influenced by abstraction.

The found optimal precipitation accumulation periods within the management units is variable and appears to be in part a function of aquifer depth and the local nature of aquifer confinement (Figure S4). For example, shorter accumulation periods are found in shallow sections of the aquifer (East Shropshire and West Chilterns), and in outcrops (East Lincolnshire). Longer accumulation periods are found in deep sections of the Permo-Triassic aquifer (West Shropshire) and semi-confined sections of the Permo-Triassic (Midlands) and Chalk aquifer (East Chilterns, and South East Lincolnshire).

3.6.2 Groundwater droughts

Groundwater droughts observed in the reference clusters reflect both spatial and temporal variation due driving precipitation and hydrogeology setting. In general, the four UK-wide droughts (1988-1993, 1995-1998, 2003-2006, and 2010-2012) are reflected in near-natural groundwater time series. Spatial patterns in driving precipitation, however, result in variable groundwater drought occurrence (Figure 3.2). For example, in C1 groundwater levels are low in 2003-06, but not below the drought threshold. In C2, groundwater levels are slightly lower and a short drought event is observed in the SGI cluster mean. In C3-5 and S2, however, the 2003-06 drought event was a major drought event. Spatial variation in the hydrogeology also results in varying drought duration for the Chalk clusters. In central England, longer drought durations are found in clusters C2 and C3. This region is partly covered by Quaternary deposits that delays recharge. Shorter (and more frequent) events are observed in C4 and C5, which are located in highly fractured Chalk.

On a smaller scale in the water management units, average drought characteristics (duration in months, magnitude in accumulated SGI over the drought period, and frequency) for monitoring sites show differences due to abstraction influence, which we have classified in, on average, uninfluenced and influenced sites, see Table 3.2. Shorter and less intense, but more frequent drought events are observed in the influenced sites in Lincolnshire, Chilterns, and Shropshire. In these water management units, the difference in average drought duration and frequency between uninfluenced and influenced sites is significant. Droughts are observed twice as often in influenced compared to uninfluenced sites in Lincolnshire and Chilterns, although a smaller difference is found in Shropshire. The distribution of recorded

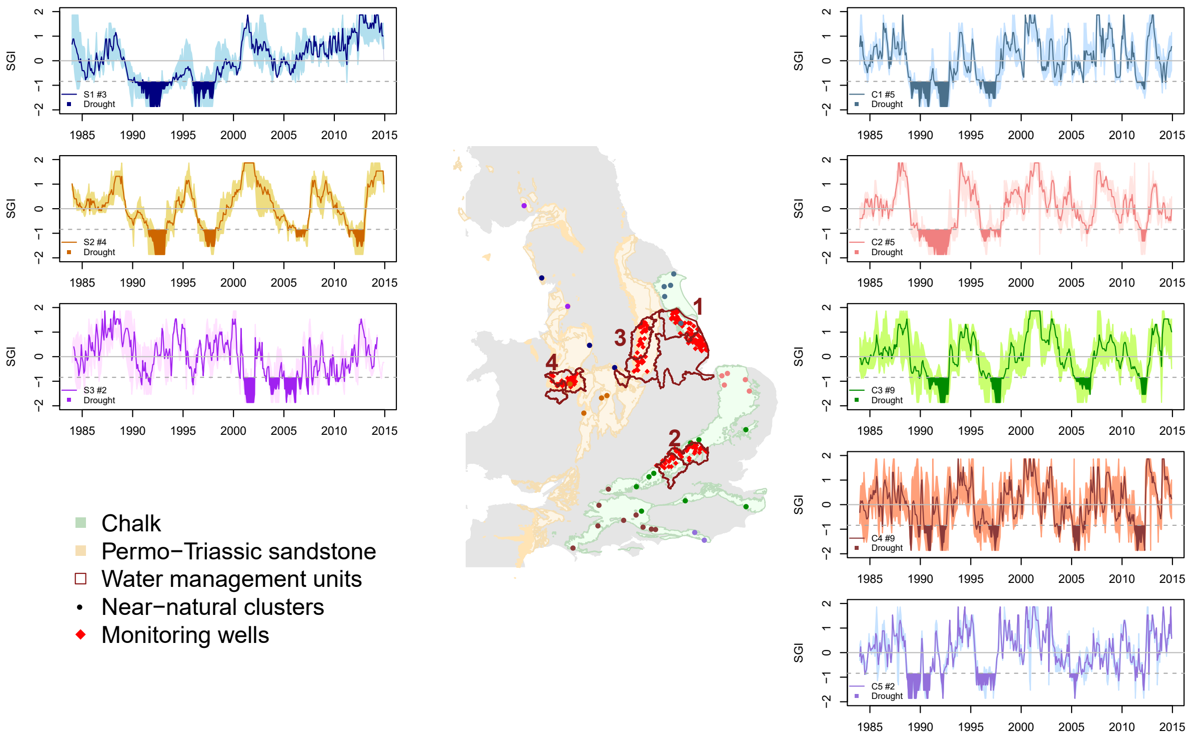


Figure 3.2: A total of eight clusters based on the 39 reference groundwater sites in the Permo-Triassic sandstone and Chalk aquifer are shown, representing long-term near-natural groundwater level variation. All time series are standardised for the 30-year time period (1984-2014). In the centre, locations of the reference wells are shown marked by the dots in different colours for all eight clusters. The four water management units are indicated in dark red (regular groundwater monitoring sites in red triangles). Three of these units coincide with reference clusters: 1: Lincolnshire (C1), 2: Chilterns (C3), and 4: Shropshire (S2). S2 is also used to compare water management unit 3 (Midlands) as this is the nearest reference cluster in the Permo-Triassic sandstone. In the panels left (Permo-Triassic sandstone) and right (Chalk), SGI time series are shown for each cluster, showing the cluster mean (thick line), the range of all reference wells in the cluster (shading) and reference droughts of the cluster mean (filled area).

Table 3.2: Average drought characteristics (duration, magnitude, and frequency) of all monitoring sites in the four water management units. 5^{th} - 95^{th} percentile of the drought characteristics are in parentheses. Distribution plots for all drought characteristics can be found in S5,S6,S7. The monitoring sites are separated using the lower limit of the cluster SPI_Q-SGI into on average *uninfluenced* and *influenced*. Differences between the two groups are tested for significance using a Wilcox test. Tests for which the p<0.05 are in **bold**.

	Uninfluenced wells (%)	Duration (in months)		Magnitude (from SGI)		Frequency	
		Uninfluenced Average	Influenced Average	Uninfluenced Average	Influenced Average	Uninfluenced Average	Influenced Average
1: Lincolnshire	31	**7.6 (1 - 28)**	**3.3 (1 - 12)**	-3.4 (-19 - -0.05)	-1.5 (-6.1 - -0.05)	**11.0 (4 - 17)**	**24.9 (12 - 36)**
2: Chilterns	71	**8.67 (1 - 24)**	**3.4 (1 - 11)**	**-3.9 (-15 - -0.05)**	**-1.54 (-6.5 - -0.05)**	**10.0 (5 - 18)**	**25.4 (9 - 34)**
3: Midlands	63	9.89 (1 - 36)	11.6 (1 - 45)	-4.5 (-22 - -0.05)	-5.3 (-26 - -0.05)	**9.5 (3 - 16)**	**9.0 (4 - 20)**
4: Shropshire	53	**6.8 (1 - 24)**	**5.0 (1 - 24)**	-3.1 (-14 - -0.05)	-2.3 (-12 - -0.05)	**11.9 (5 - 17)**	**15.7 (10 - 24)**

drought frequency (Figure S5) shows that the difference between on average uninfluenced and influenced sites is actually less pronounced in Lincolnshire and Shropshire. In the Midlands, average drought duration of influenced sites exceeds the duration in uninfluenced sites. Longer and more intense groundwater droughts occurred less often in influenced sites, which is in contrast with the other water management units. The distribution of recorded drought frequency (Figure S5) shows a majority of sites recording fewer droughts and some sites that record a higher frequency. On average, this results in a small difference between the influenced and uninfluenced sites.

Presented drought characteristics in Table 3.2 suggest that drought events vary significantly within and between water management units. These different drought events are shown in a combined time series plot (Figure 3.3) capturing reference droughts and droughts recorded in monitoring sites showing drought occurrence, duration, and magnitude. Monitoring sites are sorted based on their SPI_Q-SGI correlation (high to low). The cluster minimum SPI_Q-SGI correlation is indicated with a dashed line, i.e. 0.75 for Lincolnshire, 0.71 in the Chilterns, and 0.69 in the Midlands and Shropshire. Below this minimum correlation, drought occurrence in uninfluenced sites aligns mostly with that of droughts in the reference clusters. Observed droughts in influenced sites (those with SPI_Q-SGI correlations lower than the cluster minimum) are typically shorter, but drought events of a lower magnitude in Lincolnshire, Chilterns, and Shropshire. The distribution of drought duration in Figure S6 shows that the majority of these additional droughts is recorded in influenced sites compared to uninfluenced sites in Lincolnshire, Chilterns, and Shropshire (drought deficit distribution is shown in S7). Contrastingly, longer and more intense droughts are observed in all Midland sites in 1990-95. Droughts observed in influenced sites are also longer in 1984-1986, 1997-2001, and 2005-06 compared to the reference cluster and fewer droughts are observed in 2010-12.

The additional events in influenced sites coincide with low SGI values in the reference wells that sometimes occur prior to a long drought event. For example, additional droughts are observed in 1984, 1995-96, 2005-06, and 2014 in Lincolnshire, and in 1984-86, 2004, and 2009-10 in the Chilterns. In those periods, the reference cluster mean was below 0, but not below the drought threshold. In the case of 1995-96, 2004, and 2009-10, these additional drought events occurred prior to a long drought event. However, there was no consistent evidence found between the study areas in relation to the timing of these shorter drought events. In Lincolnshire, minor droughts occur more often during reference droughts compared to Chilterns and Shropshire, where more droughts are detected prior to reference droughts (Table S8). All minor droughts are shorter than the groundwater auto-correlation suggesting that these minor droughts are less likely to be related to propagated precipitation deficits and more likely to be related to groundwater abstraction.

Drought descriptions in the literature show an increase in water demand during the 1995-97, 2003-06 and 2010-12 drought (Walker et al., 1998; Marsh et al., 2013; Durant, 2015). For example, Durant (2015) found that during the 1988-93 drought event evapotranspiration was exceptionally high and groundwater use increased. Impacts were mostly felt in the Chalk, particularly in regions where groundwater is the principal source of water supply. An extreme rise in water use was also found during the 1995-1997 drought event putting strain on drinking water supply systems in North East England (Walker et al., 1998). Sections of the Permo-Triassic sandstone were amongst the worst affected prolonging drought conditions until 1998 (Durant, 2015). During the 2003-06 and 2010-12 droughts, a sudden increase in groundwater use was found that was attributed to dry weather and hot summers (Marsh et al., 2007; Marsh et al., 2013; Durant, 2015). Rey et al. (2017) reported low SPI_3 values in summer months for 1995, 1996, 2003-2006, and 2010-2011 highlighting exceptional dry weather that led to surface water use restrictions prior to droughts to maintain low flows. Consequently, reduced surface water abstractions were replaced by groundwater, for which use was rarely restricted (Rey et al., 2017) resulting in lowered groundwater levels and could also potentially aggravating groundwater droughts.

Over the whole investigation period, drought magnitude seems to be decreasing since the 1995-1997 drought event. Droughts observed in 2003-2006 and 2010-12 are shorter and of lower magnitude than the 1995-97 drought in most sites. This is seen most convincingly in Lincolnshire, Chilterns and the Midlands, where the magnitude of droughts decreases dramatically over the 30-year time period. In Shropshire, this tendency is less strong, as the 2010-12 drought was of a similar magnitude as the 1995-1997 drought.

3.6.3 Trends in groundwater

Significant trends in groundwater level have been detected in 38% of all monitoring sites in the water management units. Of these 38%, half of the trends are upward (positive) and the other half is downward (negative) trends (Figure 3.4). Overall, upward trends are dominating (61% of sites including significant and non-significant trends) indicating a sustained rise in the

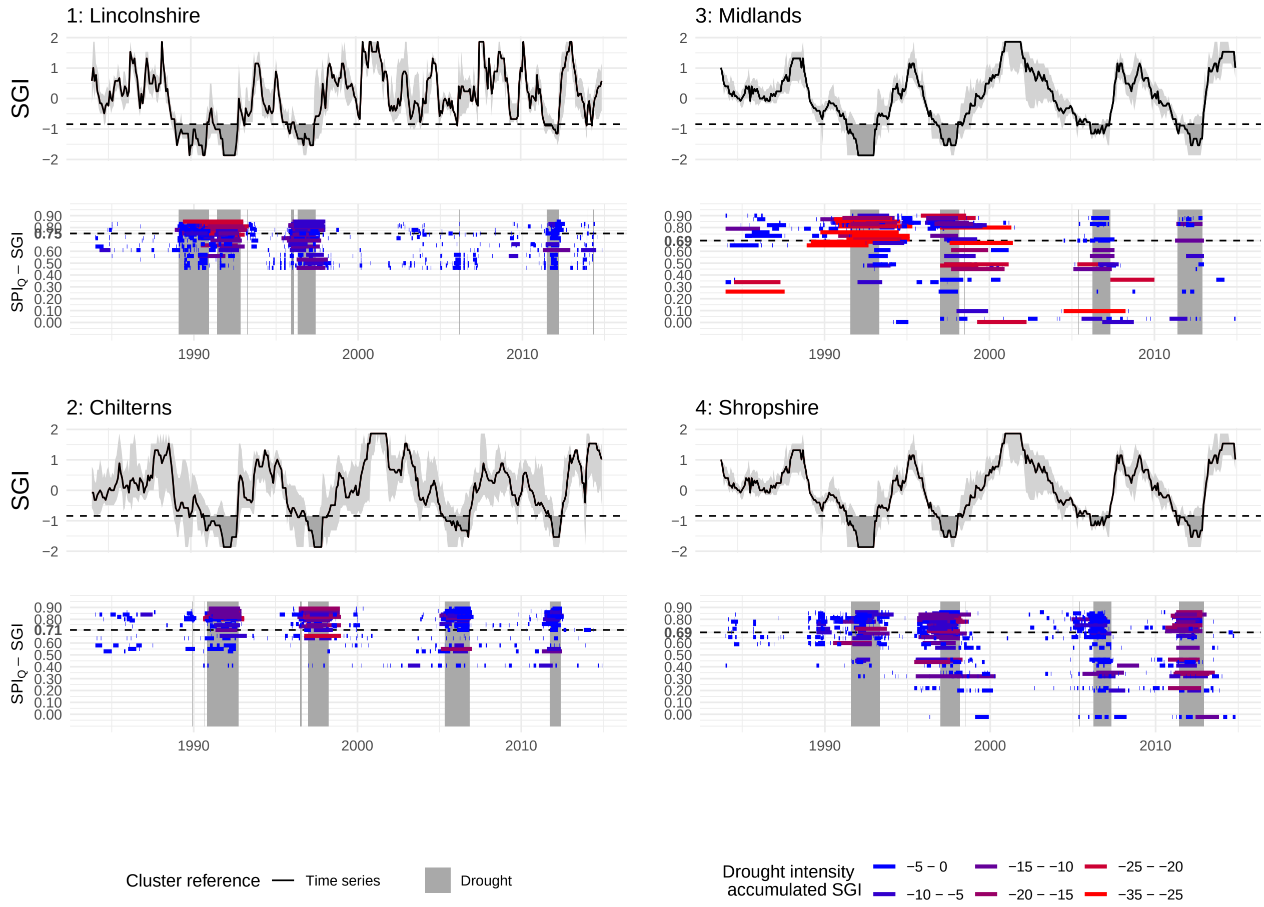


Figure 3.3: Drought occurrence, duration, and magnitude shown for all four water management units: 1: Lincolnshire, 2: Chilterns, 3: Midlands and 4: Shropshire. The top panel shows the SGI hydrograph of the reference cluster mean based on reference sites (see Figure 3.2 for the locations of these clusters). The range of reference clusters is coloured in grey. The dotted line represents the drought threshold for the cluster mean with shaded areas for the reference drought events. These reference drought events are also shown in long grey panels in the lower plot that shows the individual droughts as found in monitoring sites in each water management unit. The length of coloured bars indicates the drought duration and the colour represents drought magnitude of each drought in blue-red scale for accumulated SGI.

30-year groundwater level time series. Fewer (39% including significant and non-significant) downward trends are detected indicating sustained lowering of groundwater levels. The presence of these significant trends in groundwater is notable given the weak, non-significant, range of trend Z values in the 30-year precipitation and potential evapotranspiration data (P: Z = -0.75 - 1.53, PET: Z = 0 - 0.65).

The direction and spatial coherence of trends in groundwater show different patterns within the water management units (Figure 3.4). In the Chalk water management units, positive trends dominate. In Lincolnshire, 5 out of the total 25 positive trends are significant, compared to 3 out of 32 in Chilterns. There are fewer negative trends detected in both water management units, but more of these are significant, respectively 7 out of 13 in Lincolnshire and 4 out of 12 in Chilterns. In Lincolnshire, sites with a negative trend are, all but one, located in the semi-confined Chalk. This is in sharp contrast with the semi-confined Chalk in Chilterns, where mainly (significant) positive trends are found. In the Permo-Triassic sandstone water management units, more significant trends are detected compared to the Chalk (63% in Midlands and 43% in Shropshire). In the Midlands, more positive than negative trends are detected. In total, 17 out of 25 positive trends are significant, compared to 6 out of 11 significant negative trends. Negative trends are mainly found in the centre of the water management unit. Positive trends are found north and south of that. In Shropshire, more negative than positive trends are detected. 31 sites have a negative trend, of which 15 significant. These trends are mainly detected in the west of the water management unit. Positive trends are mainly located east in between two fault lines (Ollerton and Childs Ercall Fault; Voyce 2008). Seven of these positive trends (20 in total) are significant. In Fig. 3.4, the maximum licensed abstraction volumes are also shown. These licences show in which aquifer sections groundwater is primarily abstracted. However, without a record of the actual use of these licences or the change of licensed abstractions over time, it is impossible to directly relate detected trends to these abstraction locations.

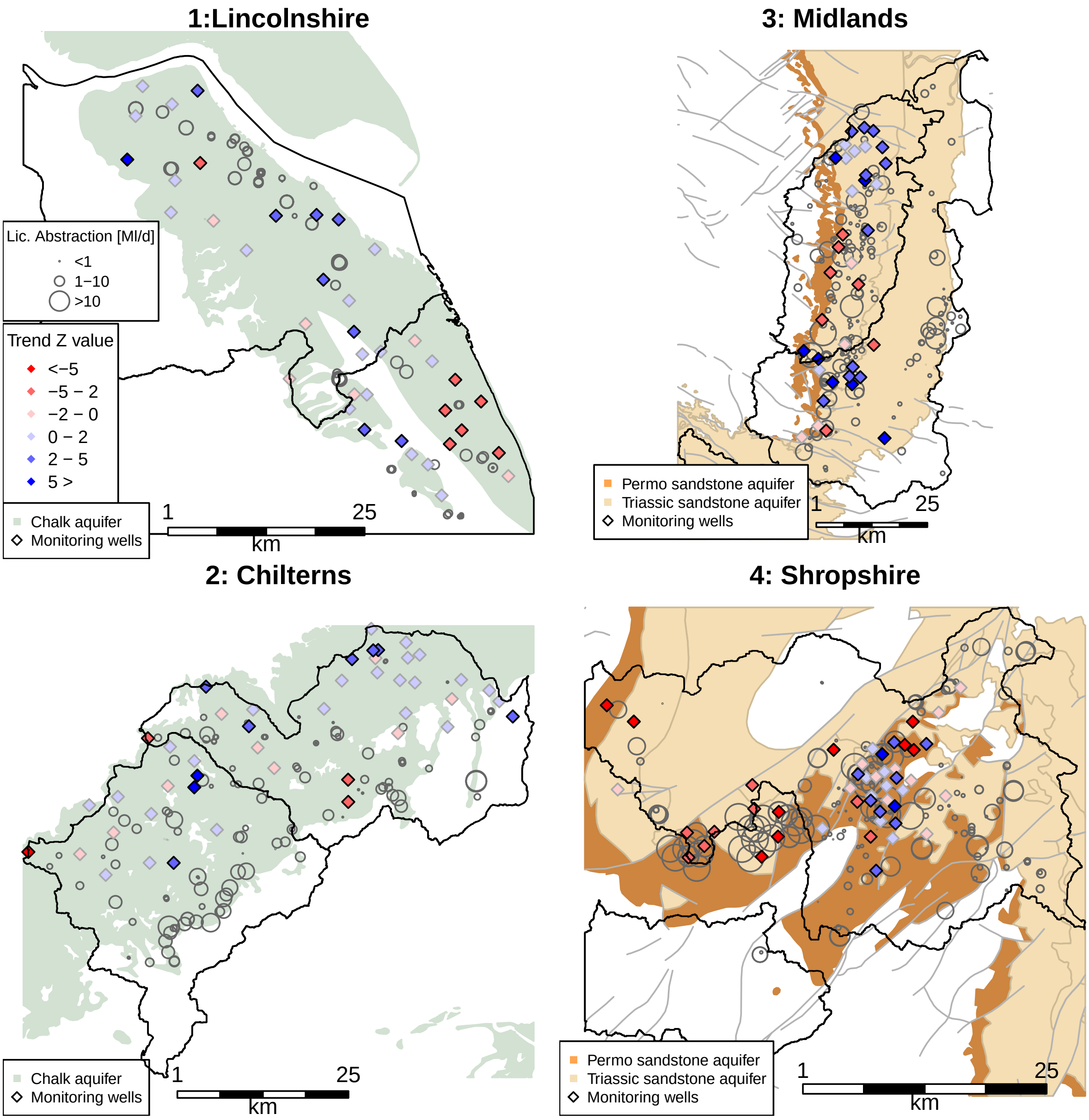


Figure 3.4: Trend values for monitoring wells in the four water management units (1: Lincolnshire, 2: Chilterns, 3: Midlands, 4: Shropshire). The red and blue diamonds indicate the positive or negative Z values for the Modified Mann-Kendall trend test for each monitoring well. Z values over |2.56| indicate a significant trend in the 30-year (1984-2014) groundwater level time series.

3.7 Discussion

Presented results of the UK case study show that groundwater droughts in the Chalk and Permo-Triassic sandstone aquifer are primarily driven by precipitation, and modified by the hydrogeology setting and groundwater use. The precipitation gradient was the primary driver for regional variation in near-natural groundwater droughts in 1989-1992 and 2003-06, which is confirmed by the work of Bryant et al. (1994) and Marsh et al. (2007). This explains the absence of a groundwater drought in 2003-06 in the northern Chalk (C1), compared to the southern Chalk (C2-C5). Regional variation of near-natural droughts within the different hydrogeological units was linked to the hydrogeological setting, as accumulation period varied in each reference cluster. These accumulation periods align with previous findings of Bloomfield et al. (2013). On a smaller scale, accumulation periods varied gradually within the water management units, as a function of aquifer depth and confinement of the aquifer, which was also found by Kumar et al. (2016), Van Loon et al. (2017), and Haas et al. (2017). The relation between accumulation period and groundwater drought duration, as observed in the reference clusters, corresponds to that of groundwater memory and drought duration for near-natural observations (Bloomfield et al., 2013).

Impact of groundwater use on groundwater droughts is detected in a subset of monitoring sites in all four water management units. This subset often represents a minority of monitoring sites. Two patterns are found that illustrate an asymmetric impact of water use on groundwater droughts. The first pattern (found in three water management units) is that of more, but shorter and less intense droughts that are primarily observed in the on average influenced sites compared to uninfluenced sites. The second pattern (found in one water management unit) shows the opposite impact with less, but longer groundwater droughts in on average influenced compared to uninfluenced sites. Both patterns are inferred as a direct consequence of groundwater use in the water management units.

The first pattern, apparent in Lincolnshire, Chilterns, and Shropshire, shows an increase in short drought events in influenced sites that sometimes occur before a major drought event or during unusual dry period that results in a rapid increase in both surface water and groundwater use (Walker et al., 1998; Marsh et al., 2013; Durant, 2015) and/or complementary groundwater use due to surface water use restrictions (Rey et al., 2017; Rio et al., 2018). We see the effect of this local increase in water use in our data in the temporarily lowered groundwater levels resulting in additional drought events. The majority of these events occur in influenced sites, but some of the (on average) uninfluenced sites also show minor droughts. Given the high correlation in these uninfluenced sites, the minor droughts seem not to disturb the long-term average correlation. The short duration and low intensity of these additional droughts suggests that local groundwater levels recover quickly. Whether groundwater was removed from groundwater storage or capture (impacting environmental flows) remains unknown (Konikow et al., 2014), although the short duration and rapid recovery suggest that an equilibrium was established soon after the abstractions. Regional groundwater model studies show that the annual average *actual* abstractions are smaller than modelled recharge for Lincolnshire, Chilterns, and Shropshire. The long-term ratio abstraction to recharge is 0.67 (Hutchinson et al., 2012), 0.5 (Environment Agency, 2010), 0.5 (Shepley et al., 2007) for the three water management units respectively. Even though these ratios are calculated using data from different regional groundwater models, the long-term balance between groundwater use and recharge is positive, which might be related to the overall reduced drought duration and magnitude observed in influenced sites.

The second pattern, apparent in the Midlands, shows intensified groundwater droughts that occur less often. Most of the intensified drought events are observed prior to 2001 with lengthened droughts in 1984-1986, 1990-95, 1997-2001. Lengthening of droughts is a common phenomenon in overused groundwater systems (Custodio, 2002). In the Midlands, prior to 2000, groundwater abstraction exceeded modelled recharge by 25% (Shepley et al., 2008). The over-abstraction resulted in lower stream flow in the area (Shepley et al., 2008) suggesting that water is removed from capture (Konikow et al., 2014). Reforms of water allocations in 2000 have reduced groundwater abstractions to meet the long-term water balance. These long-term changes in groundwater abstractions match with the majority of significant positive groundwater trends in the Midlands.

Long-term influence of groundwater use was inferred from identified trends in the groundwater level time series. Large spatial differences are found in the direction of groundwater trends in both aquifers, while trends in precipitation and potential evapotranspiration are negligible. Positive groundwater trends dominate in the water management units, which may be a result of the reduction of groundwater use since 1984 (start of the investigation period of this study). A gradual or immediate reduction in water use can restore the balance between groundwater use and recharge (Gleeson et al., 2010; Konikow, 2011), although it can take decades before an equilibrium is reached (Gleeson et al., 2012a). This slow rise or recovery to pre-development groundwater levels is not specifically included in the classification of influenced and uninfluenced monitoring sites, as a (slow) rise in groundwater level might not disturb the propagation of precipitation anomalies. SGI and SPI anomalies could in this case synchronise well resulting in a high linear correlation, while a long-term positive trend is observed as groundwater levels slowly recover. Over longer time periods, these rising groundwater levels could also buffer precipitation anomalies. In our results, groundwater droughts show an overall reduction in magnitude and duration from 1984 to 2014. Most intense droughts are found during in the first two decades (1984-2004) of the time period. Even though this coincides with a reduction of groundwater use, more research is required to distinguish climate-driven droughts from human-modified droughts.

A conceptual typology is presented in Figure 3.5 summarising near-natural drought, two types of human-modified droughts as found in the water management units, and an extreme condition of human-modified drought. Under near-natural conditions, groundwater droughts occur given the climate forcing and hydrogeological setting (upper panel in Figure 3.5). In human-modified environments, the impact of groundwater use on groundwater droughts is asymmetric. In regions where the annual average groundwater use is smaller than the annual average recharge, the frequency of groundwater droughts increases resulting in shorter events of a lower magnitude (second panel in Figure 3.5). This corresponds to the 'dynamic sustainable range' as presented in the conceptual model of Gleeson et al. (2020). In regions where the annual average groundwater use approaches annual average recharge, the opposite is found with less, but prolonged droughts of higher magnitude and duration (third panel in Figure 3.5) corresponding to strategic aquifer depletion, when meeting the dynamic sustainable range over a long time scale (Gleeson et al., 2020). The last panel shows extreme conditions of groundwater depletion, in which groundwater droughts are not recovering by the average annual recharge and groundwater levels tend to fall consistently. These extremes conditions are not identified in the UK, but the heavily intensified and lengthened droughts are found in California (He et al., 2017), Australia (Leblanc et al., 2009), Spain (Van Loon et al., 2013), Bangladesh (Mustafa et al., 2017) and India (Asoka et al., 2017).

Further research is required to analyse the modifying effects on droughts of a change in water use over time. In this study, we have investigated the overall long-term impact of groundwater use using monotonic trends in groundwater. However, a different methodology is required to evaluate the impact of new water regulations on groundwater droughts (Bhanja et al., 2017). For example, an observation-modelling or conceptual modelling approach can be used to differentiate pre- and post-regulation groundwater droughts (Van Loon et al., 2016c; Kakaei et al., 2019; Liu et al., 2016). This future modelling work could also provide context for long-term water management effects, natural variability, non-stationary effects of anthropogenic climate change (specifically warming) on changes in groundwater drought characteristics (Bloomfield et al., 2019).

Further applications of this study could be beneficial for water regulators and sci-

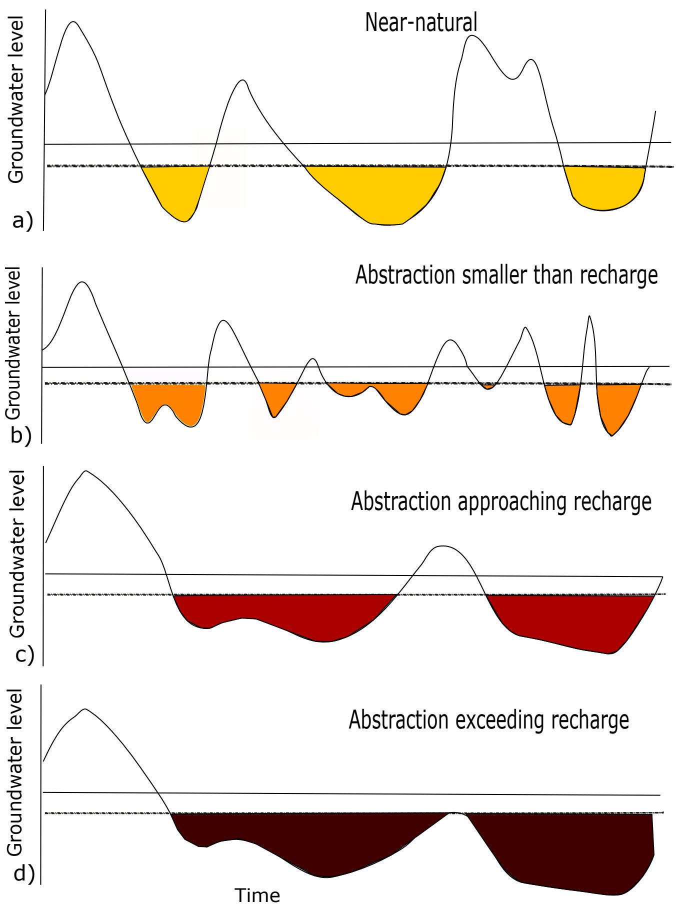


Figure 3.5: Conceptual figure summarising near-natural groundwater droughts (a) and three human-modified groundwater droughts with increasing intensity of impact of groundwater use. The top panel shows an example of near-natural groundwater droughts, followed by human-modified droughts when annual average abstractions are smaller than the annual average groundwater recharge (b) identified in the three water management units in the UK). Modified groundwater droughts when annual average abstractions approaches recharge (c) identified in one water management unit in the UK), and extreme groundwater drought conditions when average annual abstractions exceed recharge (d) not observed in the UK).

entists alike, as the presented conceptual typology can be used to investigate the impact of groundwater use without having to obtain time series of actual groundwater abstractions. The developed methodology shows how qualitative information on groundwater use and annual long-term averages aid to get a better understanding of asymmetric impact of groundwater use on groundwater droughts. Considering the large-scale modification of the hydrological cycle and the consequences for droughts (Van Loon et al., 2016a), it is important to further this approach and investigate the sustainable use of groundwater resources (Gleeson et al., 2020).

3.8 Conclusions

The impact of groundwater use on groundwater droughts is investigated based on a comparison of potentially influenced groundwater monitoring sites and near-natural reference sites in the UK. Results show that long-term groundwater use has an asymmetric impact on groundwater droughts for a subset of influenced groundwater monitoring sites in water management units in the UK. A conceptual typology summarises these different patterns in groundwater drought occurrence, duration, and magnitude. The first type (identified in three water management units) shows an increase in groundwater droughts with a low magnitude, of which the timing sometimes coincides with periods of a high water demand. This is found in three water management units where the long-term water balance is positive and annual average groundwater abstractions are less than groundwater recharge. The second type is marked by lengthened, more intense groundwater droughts. This is found in one water management unit where annual average groundwater abstractions temporarily exceeded recharge. The balance between long-term groundwater use and recharge seems to explain the asymmetric impact of groundwater use on groundwater droughts. However, more research is required to investigate the impact of changes in water use. During the period of investigation, regulated groundwater abstractions have reduced and our results show a majority of rising groundwater trends based on 30 years of data. Further research could potentially indicate how droughts are affected by these changes in water use.

In conclusion, this study presents a conceptual typology to analyse groundwater droughts under human-modified conditions. We found that human-modified droughts differ in frequency, duration, and magnitude depending on the long-term balance between groundwater use and recharge. This highlights the relation between short-term and long-term groundwater sustainability.

3.9 Chapter summary

In summary, this chapter presents a new framework based on statistical time series analysis to assess the impact of groundwater use on groundwater droughts. Moreover, in the assessed four case study areas an asymmetric impact of groundwater use on groundwater droughts was identified revealing the importance of the long-term balance between recharge and groundwater use. The summarising conceptual typology shows how groundwater droughts may be modified from a near-natural groundwater drought as a function of the long-term balance between recharge and groundwater use. These findings highlight not only the possibility of assessing human-influence on hydrological droughts using groundwater level observations, but also show that human-influence on groundwater droughts is a dynamic concept. Both short-term and long-term changes in groundwater use impact the long-term balance between groundwater recharge and water use that ultimately result in an asymmetric impact on hydrological droughts. Further implications of these findings are discussed in the Conclusion and outlook of the thesis (Chapter 7). Before that, human-influence on groundwater droughts is further investigated using this developed framework applied to a case study with enhanced recharge in the next chapters (Chapter 4 and 5) and the impact of groundwater use in combination with other drought mitigation strategies in Chapter 6.

Chapter Four

Exploring the long-term impact of Managed Aquifer Recharge in Southern California

Figure 4.1: An exploration for water in a dry landscape, illustration by Jos Zanders

4.1 Introduction

This chapter focuses on the second research aim investigating the impact of enhanced groundwater recharge or Managed Aquifer Recharge (MAR) on hydrological droughts. In this relatively short chapter, the presented methodology in Chapter 3 is applied to a different setting and different kind of human influence (see also Figure 1.1 and 2.1). The novelty of this chapter is the application of a regional groundwater analysis to a case study with large-scale enhanced recharge. In Southern California, large-scale MAR was first introduced in the 1960s and since more MAR facilities are operational. Despite the presence of multiple large-scale MAR facilities, the regional impact of MAR on groundwater storage remains unknown. This chapter explores regional and long-term impact of the MAR facilities. Chapter 5 continues this approach and discusses the impact of MAR on hydrological droughts and together the two chapters address the second research objective (see also Figure 2.1).

This chapter has been published in ISMAR10 conference proceedings (Wendt et al., 2019), for which the author contributions were the following: DW, Bridget Scanlon, and AVL conceived and designed the study. Bridget Scanlon contributed the data. DW performed the analysis and wrote the paper, supervised by AVL. All authors contributed to the manuscript that has been approved for publication in the conference proceedings series of ISMAR10.

4.2 Background

Continuous groundwater use can jeopardise groundwater sustainability, since groundwater abstractions might not be in balance with groundwater recharge (Gleeson et al., 2010; Famiglietti, 2014; Thomas et al., 2017a). A well-known example is the Central Valley in California, where the majority of groundwater basins is critically overexploited (Bertoldi et al., 1991; Faunt et al., 2009; Famiglietti et al., 2011; Faunt et al., 2016). Continuous groundwater abstractions exceed groundwater recharge, which results in falling groundwater levels and changes in regional groundwater flow in the Central Valley (Bertoldi et al., 1991; Faunt et al., 2009). Regional groundwater flow used to sustain large lakes (Kern and Tulare Lake) in the topographically-closed aquifer, but these lakes dried up in 1900 due to large-scale agricultural groundwater use (Preston, 1981; Bertoldi et al., 1991). Another permanent consequence of the sustained groundwater loss is subsidence in Southern California that reduces the long-term storage capacity of the aquifer (Faunt et al., 2009; Ojha et al., 2017).

Management techniques to increase groundwater recharge are reviewed as potential to reverse declining groundwater levels in Southern California (Scanlon et al., 2016). Managed Aquifer Recharge (MAR) was initiated in 1960 to meet the agricultural demand locally and reduce dependency of imported surface water (KCWA, 2010; Scanlon et al., 2012a). MAR projects were designed to overcome short dry periods and potentially secure water supply when applied continuously (KCWA, 2010; LTRID, 2017; Dillon et al., 2019). A local increase in groundwater storage is found by modelling studies that analysed one MAR project operating for 50 years (Scanlon et al., 2012a; Scanlon et al., 2016), although the combined influence of multiple MAR projects requires a new research approach.

4.3 Aim

This chapter aims to quantify the regional influence of continuously applied MAR in Southern California. The research focuses on one of the most critically over-drafted groundwater basin in the Central Valley: Tulare basin (Figure 4.2). MAR facilities have been recharging the groundwater since 1960s, and 8 facilities are operational since 1990 (see captions of Figure 4.2

for precise start and end data of obtained data from (Scanlon et al., 2016)). In addition to the MAR facilities, a dense monitoring network is present that is used to analyse groundwater level time series in Tulare basin.

4.4 Data and methods

4.4.1 Data

Long records of groundwater observations were obtained from the CASGEM groundwater dataset (CASGEM, 2017). Groundwater is recorded on biannual basis in over 12,100 wells (CASGEM, 2017). Wells with at least 35 years of data were selected (1980-2015). These time series were further screened for missing data, which were filled in case of minor gaps ($<$ 3 observations) (Tallaksen et al., 2004; Thomas et al., 2015). Time series with longer sequences of missing data were excluded, resulting in a selection of 149 wells (see Figure 4.2). Amongst the 149 wells, 20 wells were located inside MAR facility boundaries (Scanlon et al., 2012a). These 20 wells were therefore flagged as 'MAR observation wells' (marked with a ring in Figure 4.2) and used to analyse the direct influence of MAR (Scanlon et al., 2012a; Scanlon et al., 2016).

Precipitation data were obtained from the gridded Daymet dataset (Thornton et al., 2017). The 1km^2 grid cells were matched to groundwater well locations and precipitation data was extracted for all 149 wells. These precipitation time series were trimmed to meet the 35 year time frame (1980-2015).

Finally, we used reported annual recharged (infiltrated) and retrieved (extracted) volumes for 11 MAR facilities in Tulare basin. These volumes were converted to feet per year using the size of recharge basins at the time of infiltrating (KCWA, 2010). Data of MAR

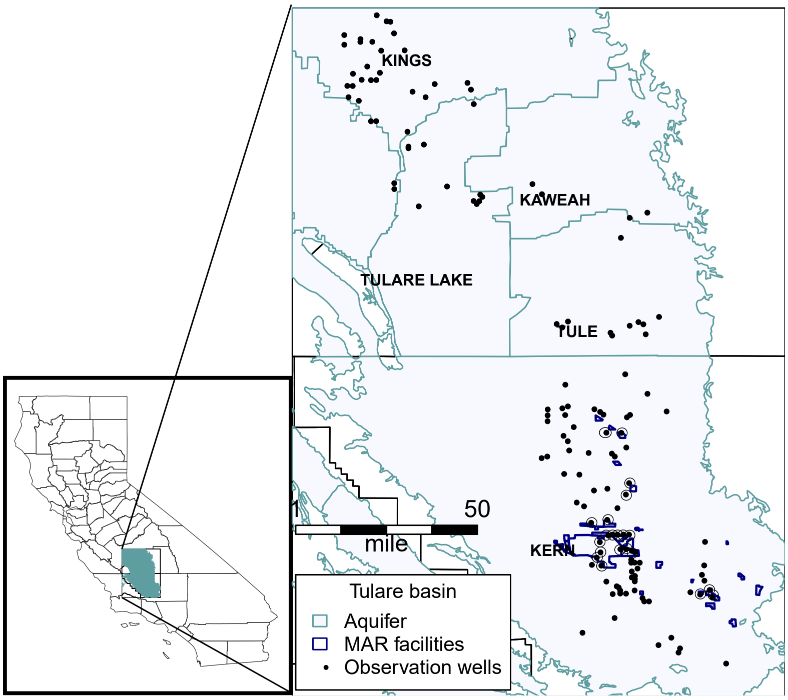


Figure 4.2: The Tulare Basin in Southern California that extends across counties: Kings, Kaweah, Tulare Lake, Tule, and Kern counties. The selected groundwater observation wells are indicated by the black dots, circled for the 'MAR observation wells'. MAR facility boundaries are indicated in blue. MAR infiltration data were obtained for Arvin-Edison (1966-2015) and Kern Water Bank (1968-2015), City of Bakersfield (1981-2010), Kern River Channel (1981-2010), City of Fresno (1985-2014), Berrenda Mesa (1983-2011), West Kern (1988-2010), Rosedale (1989-2011), Pioneer (1995-2011), Semitropic (2005-2010), and Waldron (1998-2007).

facilities was available for (almost) the whole 35 year (1980-2015) time period in the case of Arvin-Edison (1966-2015), Kern Water Bank (1968-2015), and City of Fresno (1985-2014). A shorter dataset was available for the other eight facilities: City of Bakersfield (1981-2010), Pioneer (1995-2011), Kern River Channel (1981-2010), West Kern (1988-2010), Semitropic (2005-2010), Berrenda Mesa (1983-2011), Rosedale (1989-2011), and Waldron (1998-2007)

4.4.2 Methods

The quality-checked groundwater level time series were converted into standardised groundwater indices (SGI) using the method of Bloomfield et al. (2013). The SGI values of 0 represent the long-term mean, groundwater levels above the long-term mean are positive and groundwater levels below the mean are negative. The SGI time series were compared to standardised precipitation indices (SPI). These SPI time series were calculated from the precipitation data using the method of Mckee et al. (1993).

Next, the SGI time series were clustered using two different unsupervised clustering techniques: kmeans and Ward's minimum. Kmeans is a partitioning clustering technique that minimizes the total distance between all objects into a number of clusters based on a common mean (linear discretization). Ward's minimum applies a quadratic reduction of distance between objects, and visualises this distance reduction in a dendrogram of all objects. Using both techniques on the same dataset gives a better indication of the stability of a certain cluster composition (Aghabozorgi et al., 2015; Jain, 2010). The optimal number of clusters for kmeans was determined by a numerical reduction of the sum of squared error between the clusters. These kmeans clusters were verified using Ward's minimum clusters. We chose the final clusters based on consistent results between the two clustering techniques (Jain, 2010; Haaf et al., 2018).

4.5 Results

The optimal number of kmeans clusters was 2, 7, 13. Out of these three options, most consistent results for both clustering techniques were obtained for seven clusters, as the composition of clusters was similar for 85% of wells. In Figure 4.3, the similarities are evident in the north of the basin (sub-basins Kings, Kaweah and Tulare Lake). Both cluster compositions allocated 45 wells in the same cluster (C1 in yellow). Another identical cluster is found in two southern sub-basins Tule and Kern (C6 in purple). Smaller variations are observed for clusters 3, 4, 5 and 7 for which a couple of wells differ between the two techniques (C3 in black, C4 in red, C5 in light blue, and C7 in blue). The largest variation between cluster groups is found in sub-basin Tule and Kern for cluster 2 (C2 in green).

The identified seven clusters represent the main groundwater level variation in Tulare basin (Ward's minimum clusters are shown in Figure 4.4). Time series of clusters C1, C2, and C5 show a gradual decline. This decline seems stronger in the cluster mean of C1 compared to C2 and C5. In C1, the decline starts in 1990 and ends in 2012, whereas the decline starts and ends later in C2 and C5 (2000-2015). The other four clusters show a contrasting pattern to the declining time series. The cluster mean of C3 and C6 rise from 1985 onwards, indicating a positive tendency in long-term groundwater level. C4 represents a pattern of both rising and falling SGI without a tendency for either positive or negative long-term groundwater level variation. The four remaining wells in C7 represent a distinct pattern that is found in one location only.

The majority of 'MAR observation wells' (16 out of 20) is included in C4, for which clustered SGI time series are relatively similar given the narrow range. Peaks in the clustered time series also synchronise with the peaks in total recharge volumes in 1998-99, 2005-06, and presumably in 2010-11, see Figure 4.5. Due to data limitations, recharge volumes were incomplete in 2010-2015. However, it is likely that the total recharged volume in 2010-11

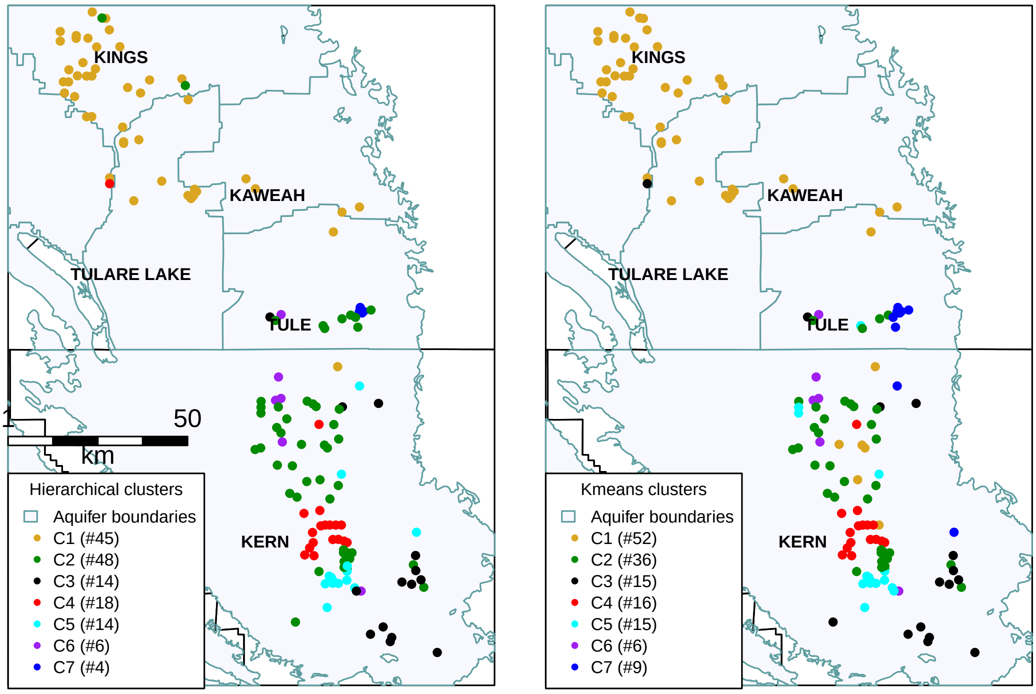


Figure 4.3: Cluster composition for 149 CASGEM wells in the Tulare Basin. Left, the clustering of 149 SGI time series using Ward's minimum is shown. On the right, the kmeans clustering shown for the same SGI time series.

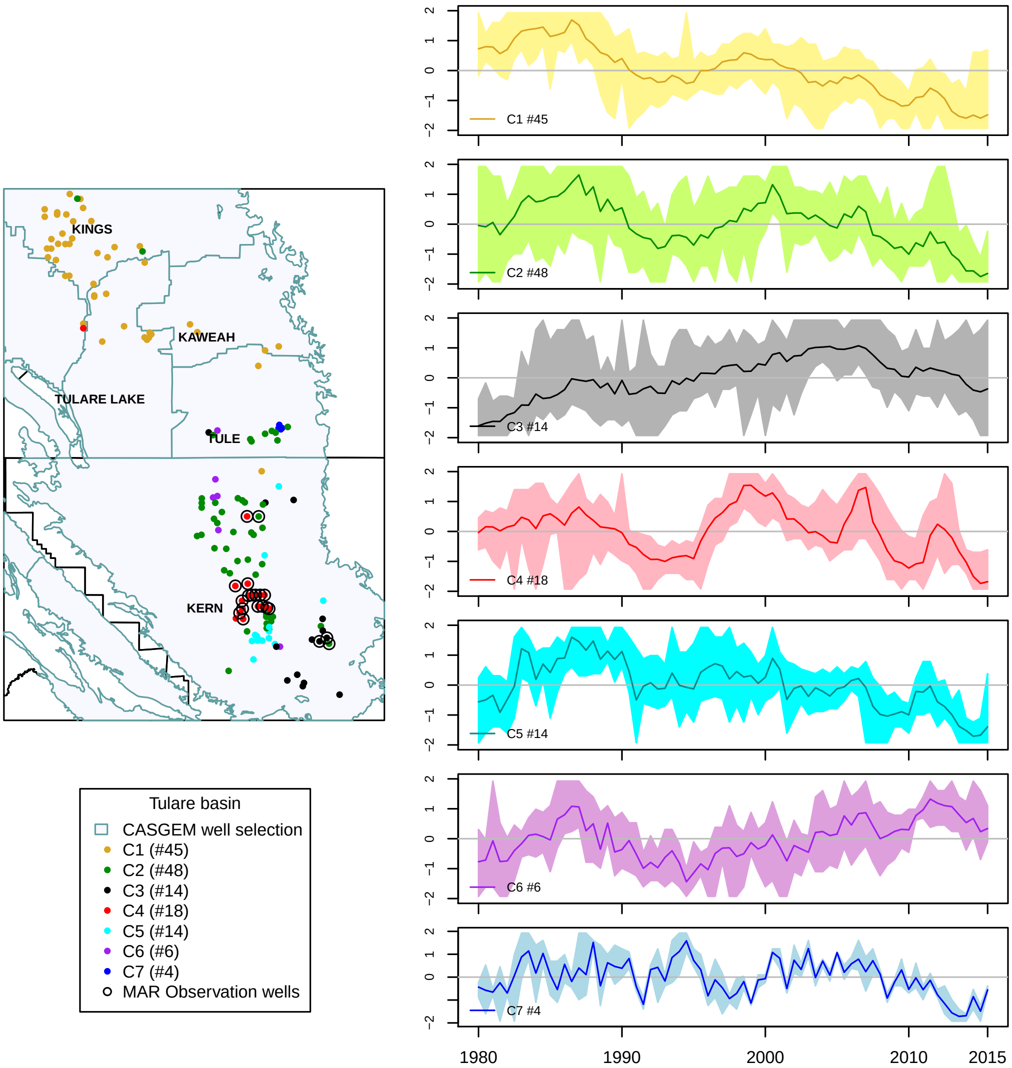


Figure 4.4: Spatial and temporal results of the Ward's minimum cluster analysis for 149 wells in Tulare basin. The map on the left shows the location of the seven clusters. On the right, the SGI time series are shown for each cluster. The cluster mean is indicated with a thick line and the range is represented by the shaded area.

is comparable to that of 2005-06. The middle panel of Figure 4.5 shows two example wells, representing C4 and C2. The SGI of C4 exceeds the SGI of C2 in 1997-2015. A remarkable result, as the precipitation was similar for the two example wells. The peaks in the SGI time series, representing C4, suggest that additional MAR recharge reflects in higher groundwater levels.

4.6 Discussion and conclusions

Three main patterns are identified in the clustered SGI time series. The first pattern is represented by three clusters that show a decline in groundwater level, mainly present in the north of Tulare basin (C1, C2 and C5). These clusters confirm the falling groundwater levels in the Central Valley due to overexploitation of groundwater (Faunt et al., 2016; Faunt et al., 2009; Thomas et al., 2017b). The second pattern is opposing the general trend, as SGI time series of C3 and C6 rise almost continuously in 1985-2015. The rising SGI time series confirms the results of modelling studies (Scanlon et al., 2012a; Scanlon et al., 2016), but the clusters have a larger spatial extent than previously assumed. The last pattern highlights gradual peaks and falls in the SGI time series (C4) that coincide with the recharge years of MAR facilities. The direct influence of MAR is evident when the SGI of C4 wells is compared to other wells nearby. From 1997 onwards the SGI in the MAR sites is consistently higher, which illustrates the direct and long-term influence of MAR on regional groundwater levels. This is also the case in C3, located in the southern tip of the aquifer. Groundwater used to accumulate here before flowing from Kern towards Tulare Lake (prior to 1900; Bertoldi et al. 1991) and C3 now shows an accumulation of groundwater level, as a consequence of continuously applied MAR.

The findings demonstrate the positive influence of continuously applied MAR on de-

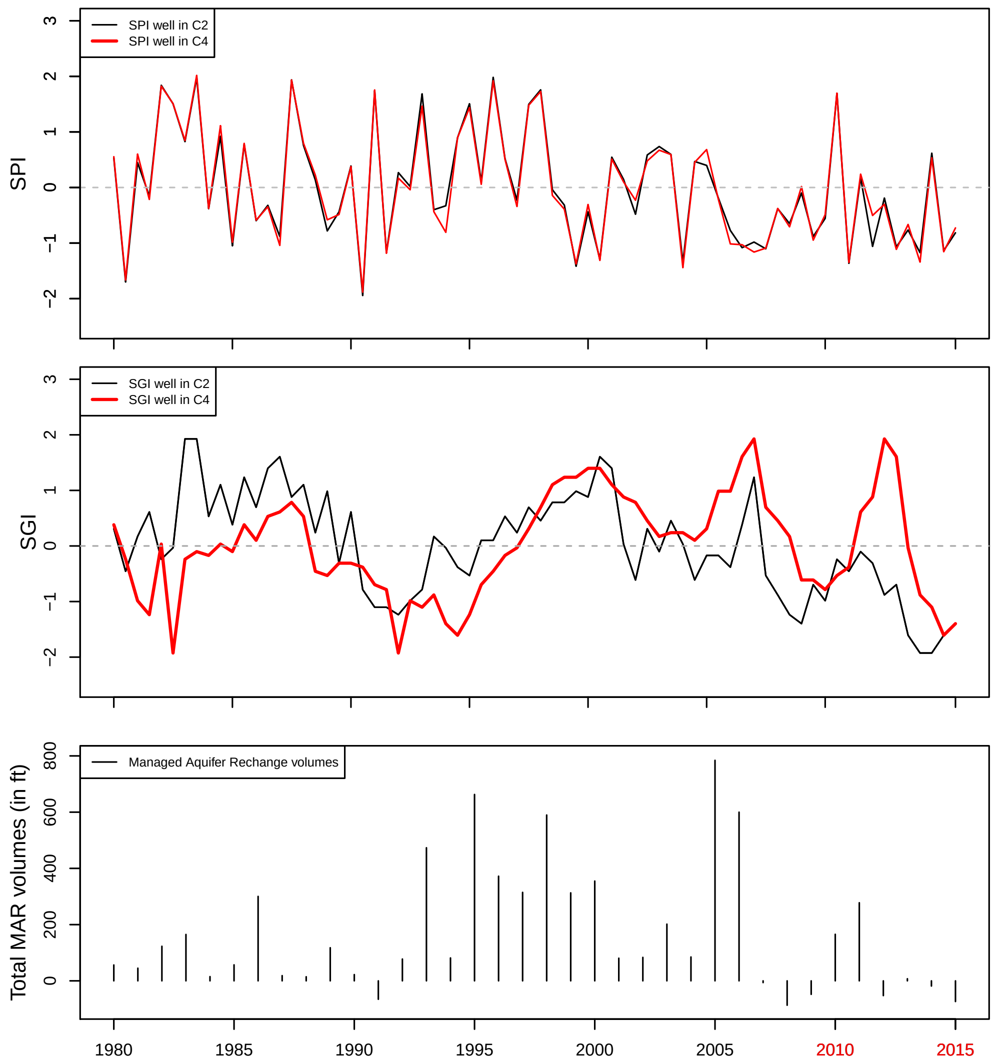


Figure 4.5: Two example wells representing clusters C2 and C4, of which the well in C4 is located within the boundaries of a MAR facility. In the top and middle panel, the SPI for both well locations and the SGI for both wells are shown in black (C2) and red (C4). The bottom panel shows the total recharged and retrieved MAR volumes. Limited data was available in 2010-2015 (therefore marked in red; see caption Figure 4.2).

clining groundwater levels. This emphasises the potential of active groundwater management in largely over-drafted aquifers, as Tulare groundwater basin is viewed as critically overexploited (Preston, 1981; Famiglietti et al., 2011; Thomas et al., 2017b). The positive influence of MAR on groundwater storage confirms the work of Thomas et al. (2015), who investigated groundwater trends in Coachella Valley. Even though groundwater trends are not investigated in this study, the clustered SGI time series show increased groundwater storage in relation to continuously applied MAR. MAR could thus contribute to sustainable groundwater use, even in largely over-drafted basins as the Tulare basin. However, more research is required to quantify the regional influence of MAR on declining groundwater storage and specifically during droughts.

4.7 Chapter summary

This chapter explores the regional and long-term impact of MAR on groundwater level storage in a highly-stressed aquifer in the Southern Central Valley. The presented findings show that statistical cluster analysis can be applied to explore long-term patterns in SGI time series. The identified patterns show the impact of MAR, mostly represented by the 'MAR observation wells' within the boundaries of the MAR facilities. In the last figure, the positive impact of MAR on groundwater storage is shown, representing two main cluster groups in the Southern Central Valley. Standardised groundwater levels rise for sites close to MAR facilities despite intensive groundwater use in the region. These initial findings are further explored in Chapter 5 that evaluates consequences for groundwater droughts and discuss the potential of MAR as a mitigation strategy given the regional rise in groundwater storage. Chapter 4 and 5 show thereby a successful application of the developed method in Chapter 3 in identifying human-influence and evaluate not only negative impact, but also positive impact of human influence on hydrological droughts.

Chapter Five

Managed Aquifer Recharge as a drought mitigation strategy in heavily-stressed aquifers

Figure 5.1: Ultimate drought mitigation by taxiing clouds to keep the grass green, illustration by Jos Zanders

5.1 Introduction

This chapter continues the investigation of long-term impact of Managed Aquifer Recharge (MAR) on groundwater storage in Chapter 4 aiming to meet the second research objective. This objective focuses on human-influence as enhanced recharge or MAR and assesses the impact of MAR on groundwater droughts. In the following chapter, identified regional groundwater patterns are further investigated, analysing long-term trends and drought characteristics. Given the highlighted potential of MAR in Chapter 4, this chapter also discusses implications of findings beyond the research aim by highlighting conditions to potential to scale-up current long-term MAR practices and encourage MAR as a drought mitigation strategy.

This chapter is published in Environmental Research letters (Wendt et al., 2021). For this publication, DW has conducted the research concept, statistical analysis, and submitted manuscript under supervision of AVL and DH. This manuscript was reviewed by AVL, BS, and DH, who also supervised the peer review process.

5.2 Background

Groundwater resources are increasingly pressured due to growing domestic, industrial, and agricultural water demand (Siebert et al., 2010; Döll et al., 2012). Overuse of groundwater resources can lead to heavily-stressed aquifers and severe groundwater depletion (Custodio, 2002; Gleeson et al., 2012b; Famiglietti, 2014) that can be aggravated following increased water use during meteorological drought events (Taylor et al., 2013; Russo et al., 2017), which are more likely to occur in near-future (Swain et al., 2018). Groundwater depletion rates have already increased globally (Konikow, 2011). Only few aquifers show decreasing groundwater depletion rates that are realised due to reduced withdrawals (mandatory or voluntarily), improved groundwater management, conjunctive use of surface water and groundwater, and enhanced groundwater recharge (Konikow, 2011; Scanlon et al., 2016; Dillon et al., 2019). These exceptional examples show the potential of mitigation strategies to ensure sustainable groundwater use and avoid maladaptation to meteorological droughts in heavily-stressed aquifers. Enhanced groundwater recharge can contribute to sustainable groundwater management and mitigate groundwater droughts, defined as a below-normal groundwater levels (Mishra et al., 2010). However, empirical evidence to support this hypothesis is difficult to obtain, because few regions globally have a long-term practice of reported Managed Aquifer Recharge (MAR) (Dillon et al., 2019). One of these regions is the Central Valley in California (USA) that has a long history of MAR and is classified as a heavily-stressed aquifer (DWR, 2016).

In the Central Valley, groundwater resources are heavily-stressed due to the extensive groundwater use to meet the high agricultural demand (Faunt et al., 2009; Scanlon et al., 2012b), which is likely to rise with an increased frequency of extreme meteorological droughts in near future (Swain et al., 2018; Alam et al., 2019). Current surface water imports from North California are insufficient to meet the agricultural water demand during meteorological droughts (Faunt et al., 2009; Li et al., 2018) exacerbating groundwater depletion with irreversible consequences (Faunt et al., 2016; Ojha et al., 2017). Without a change in its water management strategies, current groundwater depletion is likely to increase in the near-future (Alam et al., 2019), because existing drought mitigation strategies focus on maintaining agricultural production (Medellín-Azuara et al., 2015) resulting in a direct increase in groundwater use to complement the deficit in surface water (Christian-Smith et al., 2015) and an indirect increase due to a change in cropping pattern (Xiao et al., 2017; Li et al., 2018; Mall et al., 2019). Initiatives to increase drought resilience, such as MAR, receive increasing attention with the implementation of Sustainable Groundwater Management Act

(SGMA; SGMA 2014), although more evidence-based research is required to evaluate current impacts of MAR operations.

MAR, as a management strategy, is increasingly practised globally enhancing unmanaged surface water infiltration to benefit water quality and quantity (Dillon et al., 2019). Reported global MAR capacity is greatest in India (31%) and USA (26%) aiming to meet the extensive agricultural groundwater demand (Dillon et al., 2019). Most of India's MAR structures are, however, unreported and millions of structures are still in planning (Tushaar, 2009; Stefan et al., 2018). In the USA, and in particular in Arizona and California, large-scale surface water basins are in use since the 1960s to increase drought resilience of agricultural water users (Scanlon et al., 2012a; Megdal et al., 2014; Scanlon et al., 2016). On a smaller scale, MAR contributes significantly to sustainable groundwater use in many European countries and Australia. For example, Germany's MAR, representing 9% of global MAR capacity, has increased the resilience of urban water supply systems since 1870 (Sprenger et al., 2017). In Australia (4% of global MAR capacity), urban water supply was adapted to include MAR recharging groundwater in the aftermath of the Millennium Drought (Grant et al., 2013; Radcliffe, 2015). Moreover, national guidelines for applying MAR have been developed to aid safe development of MAR embedded in national water policies (Dillon et al., 2020). In contrast to the growth of MAR globally, few areas are monitored that limits the assessment of MAR impacts.

The long-term MAR practice in the USA is therefore an exceptional example, illustrated by the well-monitored and studied MAR facilities in California. Previous MAR studies focused on individual (Scanlon et al., 2012a) or multiple MAR facilities (Scanlon et al., 2016), temporal variability in groundwater levels (Thomas et al., 2015), and alternative strategies for enhanced recharge using agricultural fields for MAR (Ag-MAR; Dahlke et al. 2018b). Ag-MAR could expand current MAR infiltration surface basins (O'Geen et al., 2015; Maples et al., 2019), although currently, implementation of Ag-MAR is limited. Other studies focused on water availability using high magnitude stream flow (Flood-MAR) (Kocis et al., 2017) that could facilitate an expansion of MAR across the Central Valley (Alam et al., 2020). A limiting factor is, however, the required additional infrastructure for conveyance, storage, and recharging of high magnitude flows (Yang et al., 2019). Increased interest and highlighted potential of MAR contrast sharply with limited evidence-based research on spatio-temporal impact of existing MAR operations. Assessing existing MAR impacts would show how MAR contributes to sustainable groundwater use and that would be of interest for further expansion of MAR within SGMA.

5.3 Aim of the study

The aim of this study is to assess the impact of long-term MAR practices on groundwater droughts using a case study from the Central Valley Aquifer of California. To meet this aim, we focus on 1) spatial patterns in groundwater level time series, 2) short-term and long-term patterns in precipitation and groundwater level time series, and 3) groundwater drought characteristics. The novelty of this study lies in its analytical approach that infers long-term impact of MAR on groundwater droughts using long-term observational data of groundwater levels, precipitation, and MAR operations on a regional scale. This analytical approach differs from previous studies in the Central Valley, which used either groundwater models or water budgets to estimate impacts of actual or potential MAR sites (Scanlon et al., 2016; Xiao et al., 2017; Kourakos et al., 2019; Maples et al., 2019; Ghasemizade et al., 2019; Alam et al., 2020). Previously, this method has been applied to study groundwater droughts in near-natural settings (Bloomfield et al., 2013; Kumar et al., 2016; Haas et al., 2017), characterising of groundwater dynamics (Haaf et al., 2018; Heudorfer et al., 2019), and it was a starting point for modelling groundwater time series (Marchant et al., 2018) and investigating the asymmetric impact of groundwater use on groundwater droughts (Wendt et al., 2020). This study shows how a similar analytical approach is useful to infer MAR impacts.

5.4 Study area

The study area in the Central Valley in California is the Tulare Basin, which extends across five counties (Kings, Kaweah, Tulare Lake, Tule, and Kern; Figure 5.2). The Tulare Basin is currently over-drafted and represents critical groundwater conditions in Southern California (DWR, 2016). The area has a hot Mediterranean climate, which is dry with winter precipitation (including rain and snow in the mountains) that is the main source of groundwater recharge. Average annual precipitation is 152-254 mm, which is exceeded by reference evaporation of 1295-1422 mm. In addition to incoming precipitation, the landscape and streams also recharge the alluvial aquifer representing 36% of the modelled long-term water budget (Faunt et al., 2009). Outgoing components of the water budget are groundwater pumping (50%) and losses due to (in)elastic matrix storage, compression of specific yield, and groundwater flow leaving the Tulare Basin (14%; Faunt et al. 2009). The long-term modelled groundwater balance is thus strongly negative due to large-scale groundwater abstractions (Faunt et al., 2009; Alam et al., 2020)). These abstractions are currently not monitored or restricted, nor is the depth of abstractions reported, even though this might change with the implementation of SGMA (Thomas, 2019). Impact of MAR is currently not included in the groundwater model.

The Tulare Basin is set between two mountain ranges and is topographically confined by the Tehachapi Mountains in the south and the Sierra Nevada Mountains in the east (Faunt et al., 2009). From these mountain ranges, small streams fed by snow melt and run-off develop into rivers that recharge the layered alluvial fan aquifer in the valley. Discharge used to accumulate in the topographically-closed aquifer resulting in the second largest lake (Tulare Lake) in the U.S. until 1900, when it dried up due to intensification of groundwater use (Bertoldi et al., 1991). Regional groundwater flow and recharge in the area are still affected by lake bed sediments that consists of fine-grained material and (Corcoran) clays forming a confining layer in the alluvial aquifer. Unconfined aquifer layers define the first 900 m in the Tulare Basin and groundwater levels, when unaffected by groundwater abstractions, drain internally to Tulare Lake county (Faunt et al., 2009).

In addition to natural recharge, artificial recharge is provided by MAR facilities operating in conjunction with the State Water Project and Central Valley Project (USBR, 2019; California Department of Water Resources, 2020). These projects convey water from North California to the southern part of Central Valley since the 1960s (Kletzing, 1987; Scanlon et al., 2012a). To date, approximately 15 MAR facilities are in operation aiming to sustain agricultural water demand during dry years (KCWA, 2010). These facilities use infiltration basins to recharge a mixture of available surface water, storm run-off, and imported surface water. All facilities comply with SGMA and water is treated prior to infiltration to maintain high standards for water quality (SGMA, 2014; Kern County (CA), 2020).

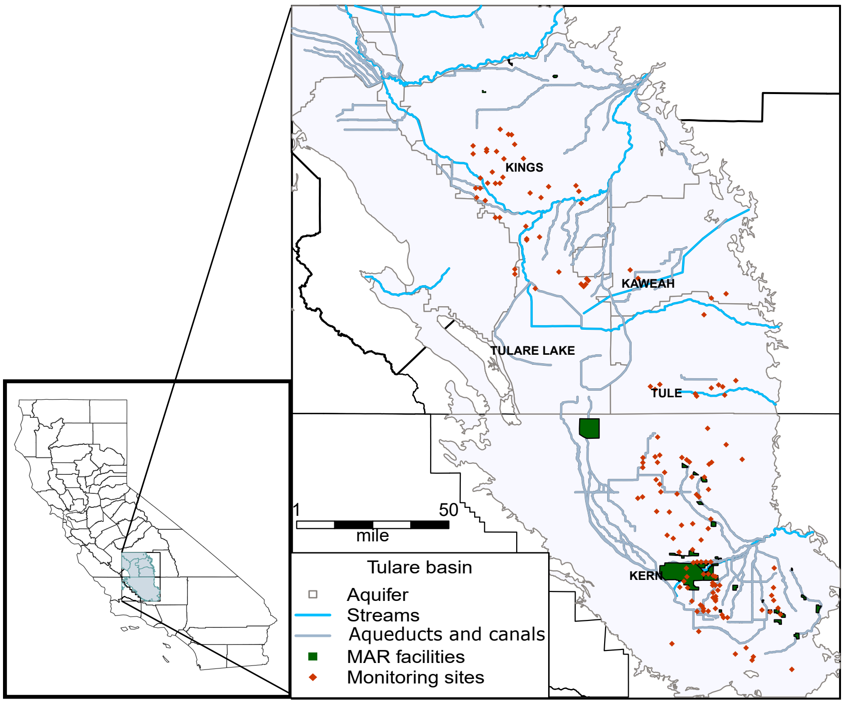


Figure 5.2: The Tulare Basin in Southern California that extends across counties: Kings, Kaweah, Tulare Lake, Tule, and Kern counties. Streams are shown in dark blue. Aqueducts and canals of the State Water Project and Central Valley Project are shown in light blue. MAR facilities are shown in green, data was obtained for Arvin-Edison (1966-2015) and Kern Water Bank (1968-2015), City of Bakersfield (1981-2010), Kern River Channel (1981-2010), City of Fresno (1985-2014), Berrenda Mesa (1983-2011), West Kern (1988-2010), Rosedale (1989-2011), Pioneer (1995-2011), Semitropic (2005-2010), and Waldron (1998-2007). Selected groundwater monitoring sites (149) are shown in red.

5.5 Data and Methods

The regional groundwater analysis is based on spatially-distributed precipitation, groundwater level, and operational MAR data in the Tulare Basin that cover a 35-year time period. The period of investigation started in 1980, when eight MAR facilities were (starting to be) operational, and ended in 2015 due to reduced availability of groundwater level observations after 2015. This 35-year period covers both extreme wet and dry periods including the exceptional drought in 2012-15 (DWR, 2016; Griffin et al., 2014; Robeson, 2015).

5.5.1 Data

Climate information was derived from two datasets with different spatial and temporal resolutions. The first dataset, the North American Drought Monitor (NADM), shows drought intensity and occurrence based on monthly standardised precipitation index (SPI) (Svoboda et al., 2002). NADM data are divided into climatological regions and San Joaquin basin that includes the Tulare Basin was used representing basin-wide monthly meteorological drought conditions (Lawrimore et al., 2002). These meteorological drought conditions are defined using the NADM threshold for moderate droughts ($SPI < -0.8$; Svoboda et al. 2002. For consistency, we applied the same (opposite) threshold ($SPI > 0.8$) for wet conditions. The second used dataset has a higher temporal and spatial resolution and consisted of gridded (1 km^2) daily precipitation estimates from the DAYMET database by Thornton et al. (2017), who spatially interpolated station measurements. This location-specific data were used to compare groundwater at a site with extracted grid cells of precipitation estimates. Extracted daily precipitation amounts were summed to 6-month totals to meet the biannual of groundwater time series and allow standardisation into SPI (Mckee et al., 1993; Wu et al., 2007).

Groundwater data were obtained from the CASGEM dataset managed by the Department of Water Resources (CASGEM, 2017) that contains about 12,100 groundwater monitoring sites (monitored biannually) in the Tulare Basin. Despite the high number of monitoring sites, few sites are monitored regularly, which is a key requirement to standardise groundwater levels in a regional comparison (Bloomfield et al., 2013). Therefore, time series were initially selected on the starting year (1980) and further screened for missing data, which were linearly interpolated in case of minor gaps ($\leq$ 3 observations; Thomas et al. 2017b; Tallaksen et al. 2004). This reduced the dataset from 12.128 sites to 3030 sites that starting monitoring in 1980, and finally to 149 sites that are regularly monitored. Regular groundwater monitoring was discontinued in 2015 for 39% of the selected wells, hence we set the time period to 1980-2015 to optimise the spatial representation of groundwater data. Final selection of sites consisted thus of 149 sites, of which 20 were located inside MAR facilities (Figure 5.2). These sites were flagged as 'MAR observation wells', as MAR impacts would first be observed in these sites (Scanlon et al., 2016).

The operational MAR data obtained from KCWA (2010) and Scanlon et al. (2016) contained detailed information regarding recharged (infiltrated) and retrieved (extracted) water volumes at MAR facilities. Reported annual volumes were obtained for 11 out of 15 MAR facilities. Annual volumes were converted to millimetres per year using the reported size of recharge basins at the time of infiltration (KCWA, 2010). Two MAR facilities out of eleven were in operation during the entire 35-year time period, other facilities partially covered the time period (see caption Figure 5.2) resulting in a variable temporal and spatial extend of the dataset. The total reported volume of MAR is 106.4 mm/y that is equivalent to 42-70% of the long-term precipitation (152-254 mm/y) in the Tulare Basin.

5.5.2 Methods

Regional patterns in groundwater level time series were investigated by clustered standardised time series. First, the standardised groundwater index (SGI) was calculated for all 149 groundwater level time series using the non-parametric approach of Bloomfield et al. (2013). Two clustering techniques (K-means and Ward's minimum) were applied to the SGI time series, applying both numerical and hierarchical reduction of similarity to reduce bias in the choice of clustering method (Haaf et al., 2018). Both methods resulted in similar regional patterns for 85% of the cluster composition, as shown in Figure 4.4 modified from Wendt et al. (2019). Only in Kern county, SGI clusters were slightly more spatially-coherent for Ward's minimum clustering (Wendt et al., 2019). Hence, these SGI clusters were used for further analysis.

Temporal patterns were analysed using the 35-year time series of groundwater levels and precipitation estimates for each site. The occurrence and strength of anomalies in time series were analysed for both short-term (in decades) and long-term (whole time series) patterns, following the same approach as Thomas et al. (2015). Short-term analysis consisted of SPI and SGI time series subdivided in three decades starting from 1980 (1980-89, 1990-99, and 2000-09) and a remainder of 5 years using the average of 10 years to evaluate climatic controls to groundwater variation (Thomas et al., 2015). Long-term temporal patterns were analysed using a monotonic Mann-Kendall trend test (Mann, 1945; Kendall, 1948) that was modified for serial correlated groundwater data Yue et al. (2002) and Hamed (2008). Biannual groundwater level observations were averaged for each calendar year to meet the requirements of the modified trend test. Trends in precipitation were tested using a standard Mann-Kendall trend test for annual precipitation totals. Trends were considered significant when the trend Z value was either < -2.56 or > 2.56 ($\alpha = 0.01$) and its strength was measured by the Sen slope of the (modified) Mann Kendal trend test.

Both meteorological and groundwater droughts were quantified in the drought analysis by applying the NADM threshold to SPI and SGI time series (SPI or SGI < -0.8). This threshold approach was used to calculate drought duration, length of time in which SPI or SGI time series were below the drought threshold, and magnitude, which is the accumulated SPI or SGI during a drought (Tallaksen et al., 2004; Mishra et al., 2010).

5.6 Results

The results consist of three subsections. First, spatial patterns in groundwater level time series are presented showing all SGI clusters and main regional patterns identified in the Tulare Basin. Second, short-term (decades) and long-term (35-year) patterns in precipitation and groundwater time series are shown, and lastly, groundwater drought characteristics are presented for the 35-year period and the 2012-15 meteorological drought event.

5.6.1 Spatial patterns in groundwater level time series

Three regional spatial patterns were found in the clustered SGI time series (Figure 5.3a and 5.3b). Six out of seven SGI clusters represent a spatially coherent group of groundwater monitoring sites (Figure 5.3a) that can be summarised in three main regional patterns showing a declining, variable, and rising SGI in the 35-year period (Figure 5.3b).

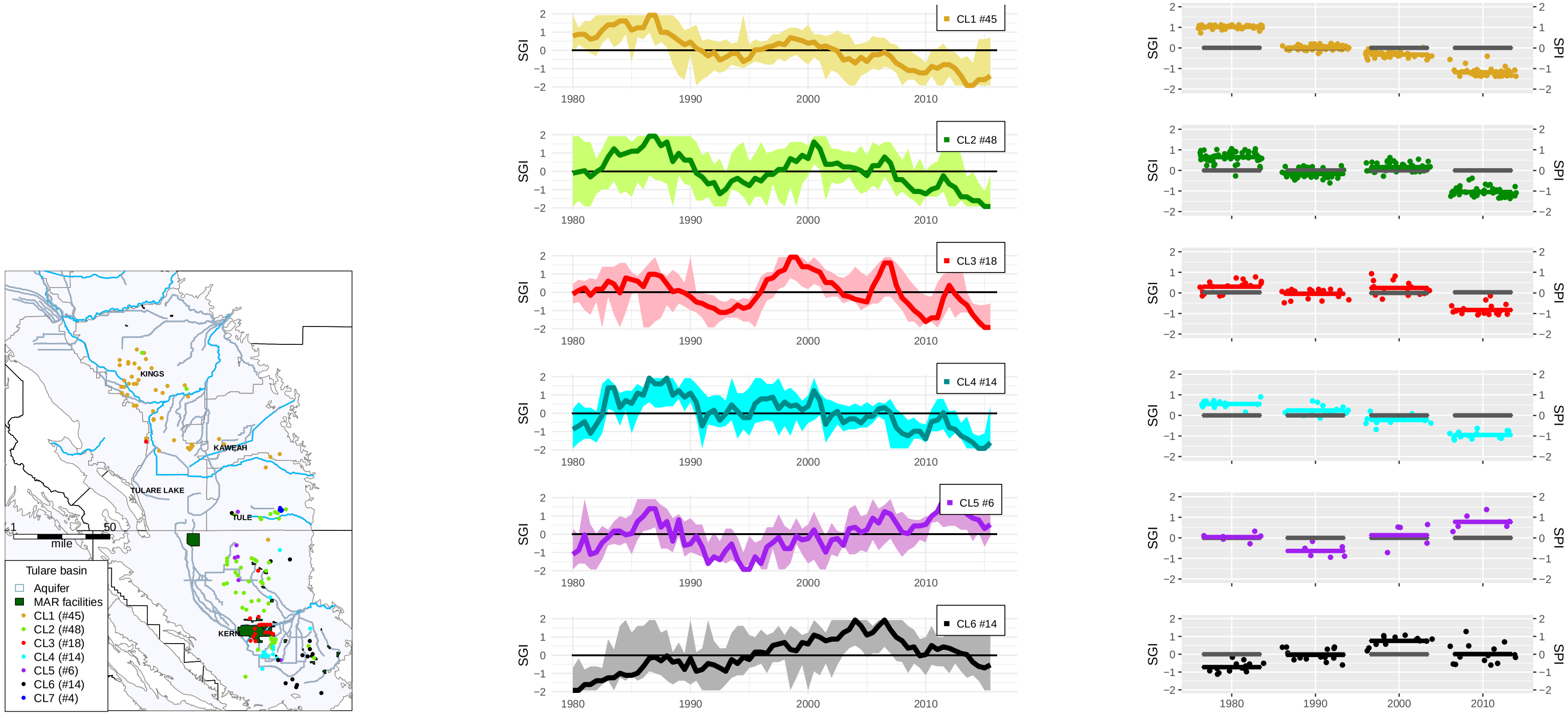
The first regional pattern (RP1) shows a decline in SGI over time (Figure 5.3b). RP1 is represented by cluster 1 (CL1) that consists of 31% of all monitoring sites in the northern counties of the Tulare Basin (Kings, Kaweah, and Tulare Lake counties). The cluster mean of CL1 shows a strong decline with below-average SGI (SGI < 0) since 2002.

The second regional pattern (RP2) shows periodic variation in SGI and is distinguished from the first by peaks in SGI in 2000-01, 2005-06, and 2011-12 (Figure 5.3b). During these periods, SGI rises to average or above-average conditions (SGI > 0). RP2 consists of clusters 2, 3, 4 (CL2, CL3, CL4) and represents 55% of all monitoring sites located mainly in Tule and Kern counties. RP2 also includes 16 of the 20 'MAR observation wells' grouped in CL3, which cluster mean is sharply rising and falling over time.

The third regional pattern (RP3) shows a consistent rise in SGI for most of the 35 years (Figure 5.3b). Clusters 5 and 6 (CL5 and CL6) represent RP3, located in Tule and Kern counties (14% of monitoring sites). The consistent rise in SGI contrasts with the declining SGI in RP1 for the same period. Not surprisingly, CL5 and CL6 are located in different aquifer sections. CL5 is a smaller cluster of six wells located along a line between Tule and northern Kern counties. CL6 is located in southern Kern county, which is the most southern and the lowest section of the Central Valley Aquifer.

5.6.2 Temporal patterns in precipitation and groundwater level time series

Contrasting temporal patterns are also found in short-term (decadal) SPI and SGI averages in the Tulare Basin (Figure 5.3c). Short-term SPI is above-average in the first decade (1980-89) and below-average in the second and third decade (1990-99 and 2000-09) for all clusters. The last 5 years (2010-2015) include an extremely wet period and an extreme meteorological drought resulting in, on average, normal conditions during the 5 years. SGI differs from this decadal SPI pattern (see Figure 5.3c). In CL1, moderately negative to strongly negative SGI are observed in 2000-2015 exceeding the SPI in this period. The SGI in CL2, CL3, and CL4 follow the SPI pattern relatively well, although the SGI declines in the last 5 years resulting in strongly negative SGI for both clusters. In CL5 and CL6, a rise in SGI is found that exceeds the SPI in the last 15 years (CL5) and in the second and third decade (CL6),



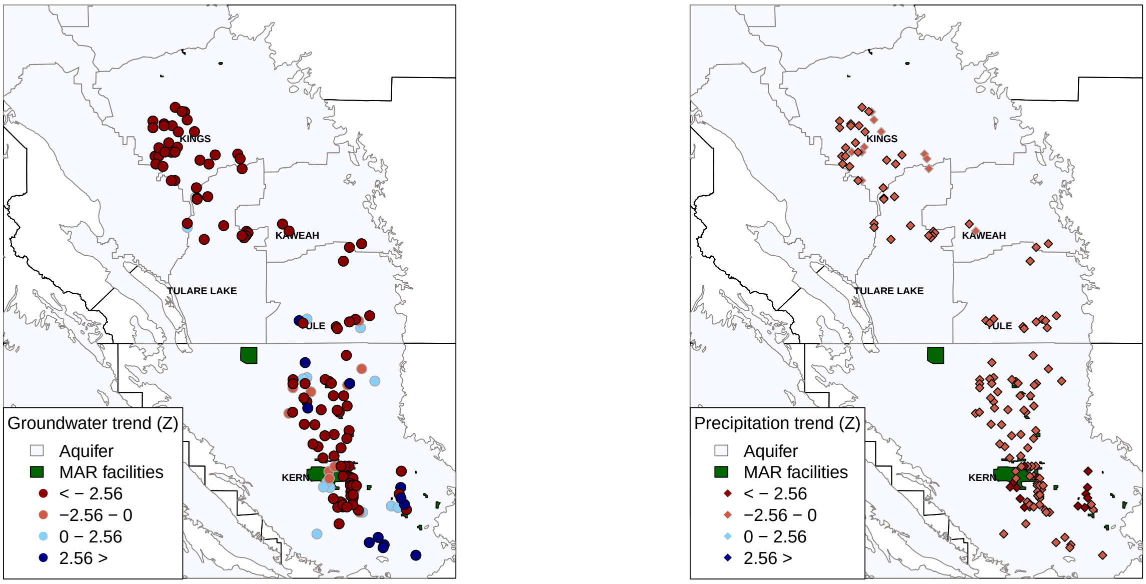
(a) (b) (c)

Figure 5.3: Regional patterns in 35-year SGI time series in the Tulare basin. Left (a) shows the spatial distribution of 7 hierarchical clusters (Ward's minimum). Both clustering methods are shown in Figure 4.3. Six out of seven clusters represent a regional pattern and are further analysed. The centre figure (b) shows clustered SGI time series of these six regional clusters. For each cluster, the cluster mean (thick line) and the range (minimum and maximum) in SGI are shown in the six panels. Colours are matching the map 2(a). On the right (c), the average cluster SPI (grey) and SGI (coloured) is plotted for each decade (horizontal bars and individual points for groundwater sites). Decades are divided into 1980-89, 1990-99, 2000-09, and the 5 remaining years (2010-15).

but declines to below-average conditions in 2010-2015. This decline is thus reflected in all but one cluster and shows average groundwater conditions during extreme meteorological drought in 2012-15, impacting most groundwater monitoring sites in the Tulare Basin.

Long-term (35-year) temporal patterns in groundwater level time series show both negative and positive trends that are distributed unevenly in the Tulare Basin. Significant negative trends are primarily found in northern counties (Kings, Kaweah, and Tulare Lake) compared to moderately negative, neutral, and positive trends in the southern counties (Tule and Kern; Figure 5.4a). Significant positive trends are detected for 12 sites suggesting groundwater levels have risen consistently. This is remarkable considering negative precipitation trends (Figure 5.4b) and the considerable groundwater abstraction in the Tulare Basin.

The strength of identified trends reflect the long-term regional spatial patterns (RP1-3; Figure 5.5). Significant negative trends have a linear decrease in groundwater level exceeding of, on average, 0.79 m/y with extreme outliers in RP1 (CL1). Sites in RP2 (CL2-4) decrease less per year compared to RP1, but average trend Z values remain significant for CL2 and CL4. CL3 marks a transition from negative to positive trends. This cluster includes most 'MAR observation wells' and represents sites located in the vicinity of four large MAR facilities (Kern Water Bank, City of Bakersfield, Kern River Channel, and Pioneer) suggesting that long-term MAR impact contributes to these moderately and significant positive trends. RP3 (CL5 and CL6) consists of mainly positive trends, increasing on average 0.2 m/y, which are found close to the Arvin Edinson MAR facility (CL6).



(a) Groundwater trends

(b) Precipitation trends

Figure 5.4: Groundwater (dots) and precipitation (diamonds) trends based on 35-year (1980-2015) annual time series for 145 groundwater monitoring locations in the Tulare Basin. Trend Z values show significant trends $Z < -2.56$ or $Z > 2.56$ ($\alpha = 0.01$) in brighter colours. The MAR facilities are shown in green.

5.6.3 Groundwater drought characteristics

Groundwater drought characteristics are also summarised by RP1-3 and show three different patterns in the Tulare Basin (RP1-3; Figure 5.6). In RP1 (CL1), groundwater drought (shaded) occurred after a series of meteorological droughts (light red surfaces) in 2007-09. This groundwater drought did not recover until 2015 despite the above-normal precipitation conditions in 2010 and 2011 (light blue surfaces). Consequently, two meteorological droughts in 2007-09 and 2012-15 were combined into one multi-year groundwater drought.

In RP2 (CL2-4), groundwater droughts occurred more often and recovered during above-normal precipitation conditions. SGI values in RP2 recovered more quickly compared

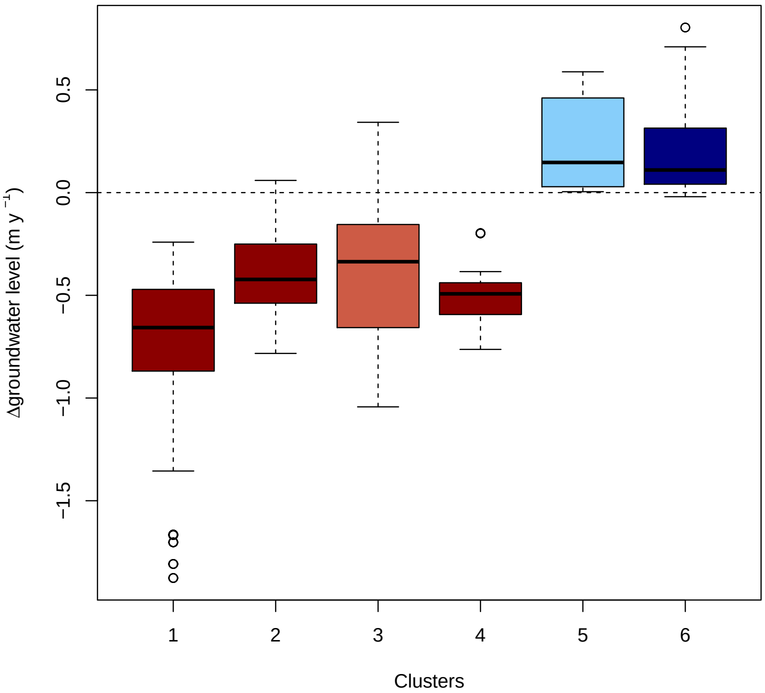


Figure 5.5: Annual in/decrease of groundwater levels for identified six groundwater clusters. Colours are matched to Z value of the cluster mean following the legend of Figure 5.4a. Darkest colours show significant trends, brightest colour show non-significant trends. For location of clusters, see Figure 5.3.

to CL1 resulting in a (brief) periods of above-normal SGI between drought events. Drought recovery is highest for sites in CL3 that includes most 'MAR monitoring wells'. The sharp rise in SGI could be due to a combination of above-normal precipitation and additional recharge supplied by MAR facilities, which recharge most water during above-normal precipitation conditions (see bottom panel in Figure 5.6). The synchronised rising and falling SGI in CL2-4 suggests that most groundwater monitoring sites reflect this combined effect in Tule and Kern counties.

The last regional pattern (RP3; based on CL5 and CL6) shows a rise in SGI resulting in entirely different groundwater drought characteristics. Groundwater droughts are observed at the start of the investigation period in 1991-96 (CL5) and 1980-85 (CL6). During meteorological droughts in 2007-09 and 2012-15, SGI declined gradually for both clusters, but the NADM threshold was not exceeded resulting in alleviated groundwater droughts compared to the other regional patterns.

The increment of MAR volumes since 1993 coincides with short-term increases in SGI in RP2 and long-term increasing SGI in RP3 resulting in different groundwater droughts. This is remarkable, as precipitation trends are decreasing in Tule and Kern counties (Figure 5.4b). Most MAR volumes were recharged during periods of above-normal precipitation resulting in large MAR contributions in addition to the natural recharge. However, actual recharged volumes remain uncertain as documented volumes did not cover the complete 35-year period and might be higher than shown in Figure 5.6.

In general, the groundwater drought duration in RP2 and RP3 halved compared to RP1 and drought magnitude reduced (Figure 5.7). Average drought durations in RP2 and RP3 were both around a year, compared to two years for RP1. Average drought magnitude was close to -1.2 compared to -2.1 for RP1. The maximum drought duration was slightly shorter for RP3 and a lot shorter for most events in RP2. Maximum drought magnitude also decreased, although high outliers are still observed in RP2 and RP3.

Most severe groundwater droughts events (measured in drought magnitude) occurred at different times in the three regional patterns. In RP1, most severe droughts occurred before and during the extreme meteorological drought in 2012-15. This contrasts with RP2 and RP3, where most severe drought events occurred in the period 1980-00. This is remarkable, as driving meteorological droughts in 1980-00 were less severe than the 2012-15 drought (Robeson, 2015).

The extreme meteorological drought in 2012-15 had also a mixed impact in the Tulare

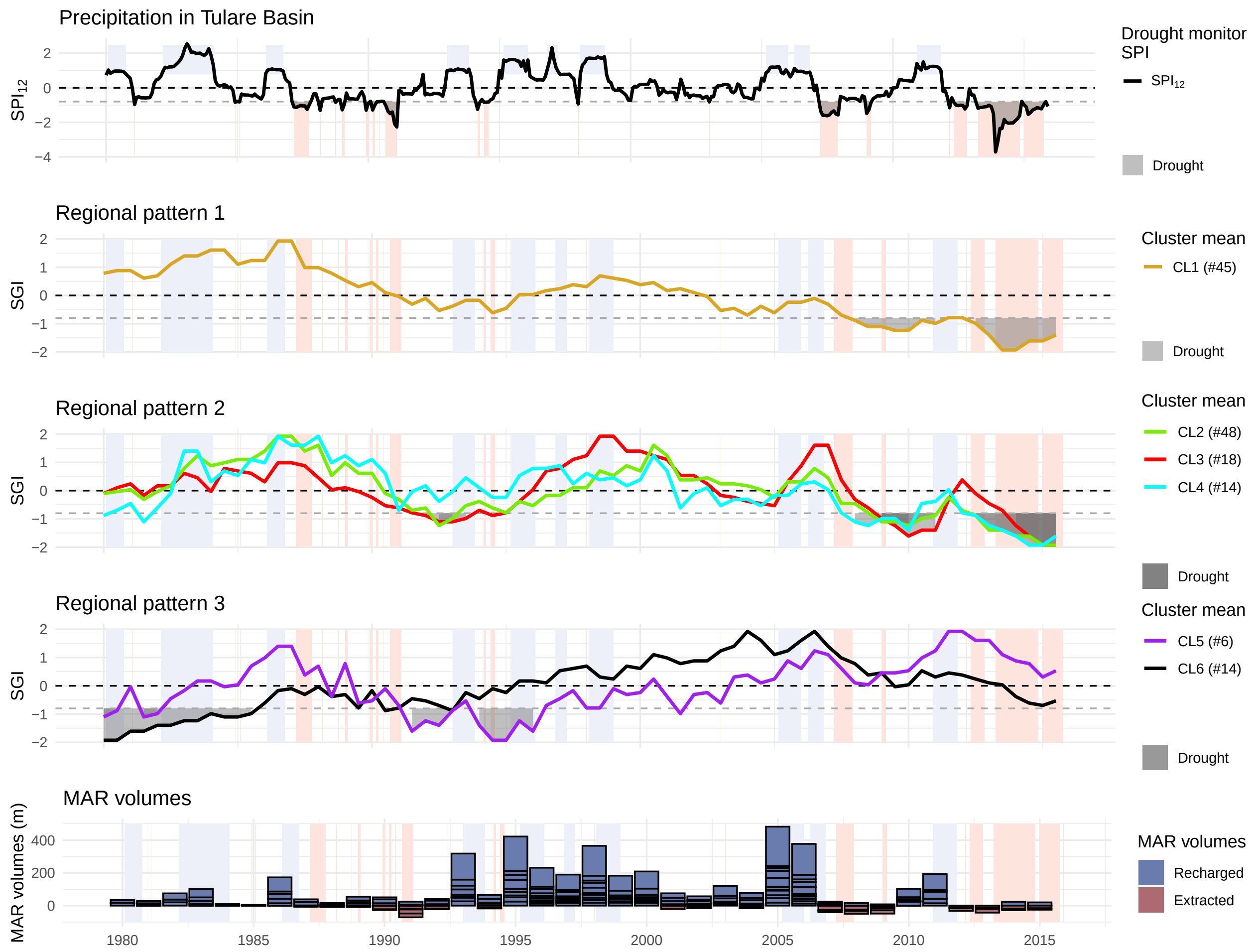


Figure 5.6: Groundwater droughts are shown for the identified three regional patterns in the cluster analysis. In the first panel, standardised precipitation (SPI_{12}) is shown based on Drought Monitor data for San Joaquin basin (includes the Tulare Basin) (Svoboda et al., 2002). Meteorological droughts (below-average precipitation $SPI_{12} < -0.8$) are shaded and shown as light red surfaces in the other panels. Similarly, above-average precipitation ($SPI_{12} > 0.8$) are marked by light blue surfaces. The three regional patterns are shown in panel 2-4 with cluster means in matching colours according to Figure 5.3. Groundwater drought events are shaded. The fifth panel shows recharged (blue) and extracted (red) MAR volumes of 11 MAR facilities. The stacked bar plot visualises recharged or extracted volumes (in m) in each year, reported by individual facilities. Most reports (9 out of 11) did not contain most up-to-date MAR volumes and were updated until 2010 (see caption of Figure 5.2). It is therefore plausible that more water was recharged during 2010-15 than shown here.

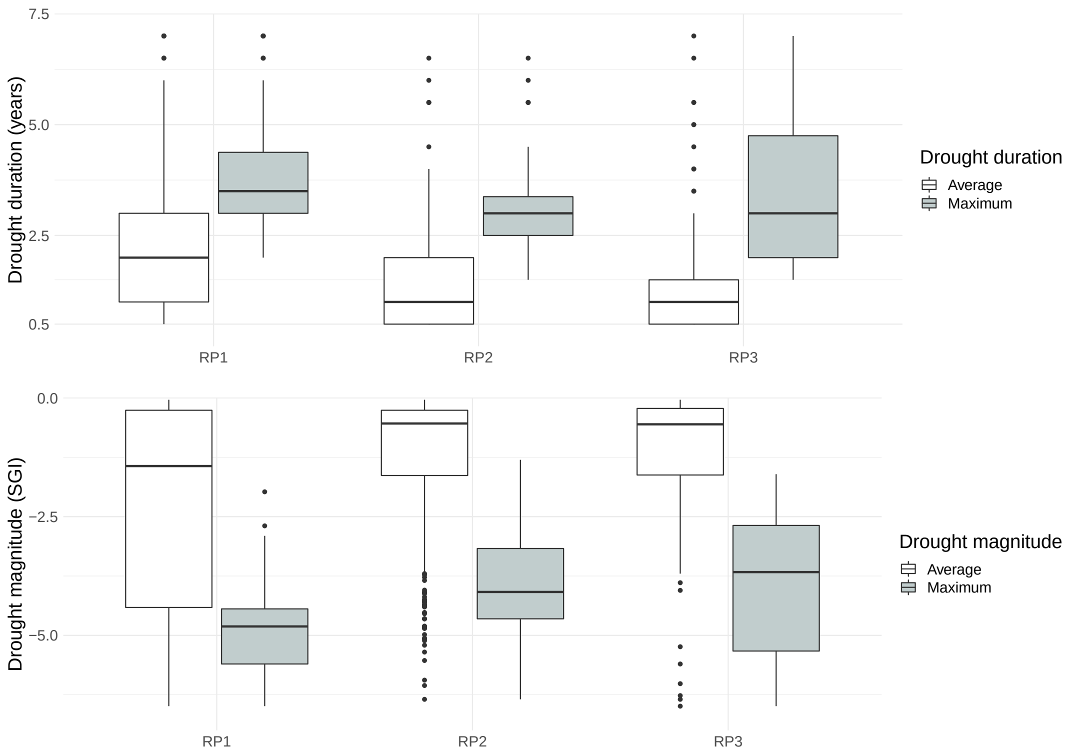


Figure 5.7: Maximum groundwater drought duration (top panel) and magnitude (bottom panel) for the 35-year period (1980-2015), as observed in the three regional patterns. Groundwater drought duration is measured in years. Groundwater drought magnitude is measured in accumulated SGI over the drought period.

Basin (Figure 5.8). In RP1, groundwater droughts were severe and lasted 3.3 years on average. Drought duration in RP1 covered the entire meteorological drought and possibly longer, as the drought continues beyond the analysis period. Groundwater droughts in RP2 and RP3 started later and lasted 2.4 years on average, which is significantly (p=4.6E-6) shorter. The later start resulted in lower drought magnitude (-0.8 less on average), which is a significantly (p=7.3E-3) different compared to RP1. Largest reductions and absent droughts are observed in the vicinity of MAR facilities or within MAR facility boundaries, where above-average antecedent conditions prevented SGI values from crossing below the drought threshold.

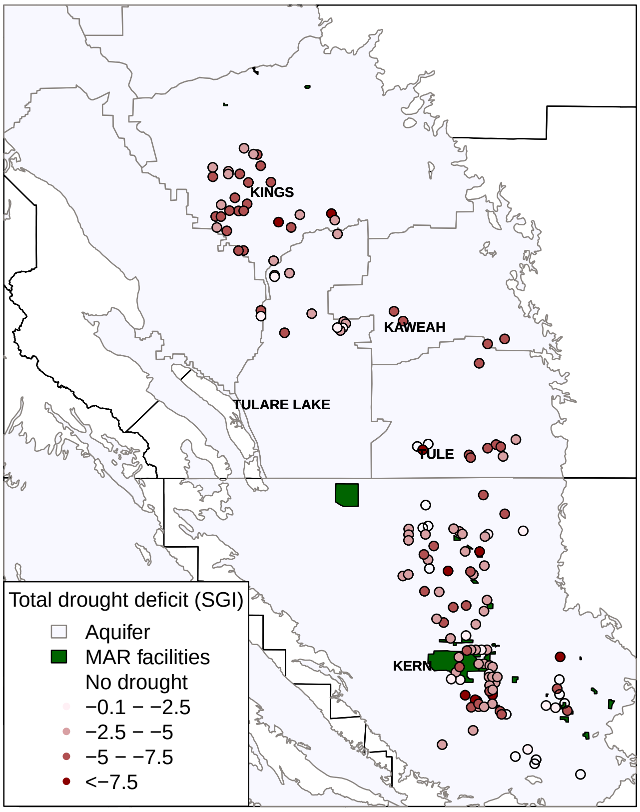


Figure 5.8: Groundwater drought magnitude (measured in cumulative SGI) observed in groundwater monitoring sites in the Tulare Basin during the meteorological drought in 2012-15. MAR facilities are indicated in green.

5.7 Discussion

In the Tulare Basin, groundwater drought occurrence, duration, and magnitude change from north to south according to three regional patterns in long-term groundwater level variations. The first regional pattern (North Tulare Basin: Kings, Kaweah, and Tulare Lake counties) shows a long-term decline in groundwater levels, which resulted in extended groundwater droughts, as deficits in groundwater storage were not replenished despite above-average precipitation. The second regional pattern (South Tulare Basin: Tule and Kern counties) shows rising groundwater levels during periods of above-normal precipitation resulting in shorter droughts and rapid drought recovery. Long-term trends are moderately negative, neutral or even positive. The third regional pattern is found in a smaller southern section of South Tulare Basin. Here, groundwater levels rose consistently from 1995 onwards. Significant positive trends suggest an increase in groundwater storage over the past 35 years that alleviated droughts in 2012-2015.

5.7.1 Regional patterns in groundwater level variations

The long-term decline in groundwater levels in the first regional pattern has been related to the continuous overuse of groundwater (Faunt et al., 2009; Famiglietti et al., 2011; Thomas et al., 2017b; Scanlon et al., 2012b). Faunt et al. (2009) found an additional non-linear increase of groundwater abstractions during dry years that explains the discrepancy between precipitation and groundwater anomalies in the short-term (decadal) SPI and SGI comparison (Figure 5.3c). The natural drought propagation was altered, as groundwater conditions remained below-normal despite periods of above-normal precipitation resulting in an extended groundwater drought in 2007-15 presumably driven by long-term overuse of groundwater.

Regional short-term MAR impacts in the Tulare Basin are seen in the second regional pattern, representing a gradual change from declining to rising groundwater levels. Since the 1960s, groundwater has been recharged in MAR facilities aiming to overcome short dry periods showing temporary rising groundwater levels for single sites due to MAR recharge (KCWA, 2010; Scanlon et al., 2016). This is confirmed by clusters in Tule and Kern counties showing rising SGI following above-normal precipitation and MAR recharge. The amplified periodic rise in groundwater levels was also noted by Xiao et al. (2017). However, our results suggest that regional MAR impact is larger than previously assumed. Short-term MAR impacts are observed for the majority of sites in Tule and Kern counties and were not, or less strongly, observed in other counties. Moreover, groundwater deficits were quicker replenished in Tule and Kern counties. This rapid drought recovery is largest in the vicinity of MAR facilities and synchronises with recharged MAR volumes. As a result of regional short-term MAR impact, groundwater droughts reduced significantly in duration and magnitude.

The long-term rise in groundwater levels, found in the third regional pattern, shows that groundwater storage is (slowly) increasing despite a negative precipitation trend. Observed rising groundwater levels are probably due to a combination of long-term MAR practice and regional hydrogeological conditions. In this region, groundwater storage (natural and artificial) accumulates resulting from the dominant North-South regional groundwater flow and topographic confinement of the Central Valley Aquifer (Faunt et al., 2009, p.49). Previous studies indicate a steady increase in groundwater as a consequence of MAR practices in the Central Valley (Faunt et al., 2009; Scanlon et al., 2012a; Scanlon et al., 2016; Thomas, 2019). A similar, local increase in groundwater storage due to MAR impact was found in Coachella Valley in California (Thomas et al., 2015). However, findings of this study show a larger extent of the long-term rising groundwater levels in particular in aquifer sections where groundwater storage naturally accumulates. This accumulation of groundwater storage results in alleviated groundwater droughts in Kern and Tule counties during the last extreme drought in 2012-15. This illustrates the potential of MAR as a measure to enhance drought resilience (Scanlon et al., 2016) that is also effective on a regional scale. The regional increase in drought resilience was also found by Thomas (2019), who analysed observed and remotely-sensed groundwater anomalies.

5.7.2 Implications for management

The short-term and long-term MAR impacts highlight the contribution of MAR in a heavily-stressed aquifer to sustainable groundwater management. However, increasing groundwater recharge using MAR is only a partial solution (Dillon et al., 2012). Sustainable use of groundwater implies that groundwater use is in balance with (natural and artificial) recharge. Monitoring groundwater levels, MAR volumes, and groundwater abstractions would enable water managers to evaluate sustainability of abstractions, as measurable objectives are essential for sustainable groundwater management (Gleeson et al., 2012b; Thomas, 2019) that would also inform water managers whether groundwater is abstracted from deeper confined layers (non-renewable) or shallower unconfined (renewable) sections of the aquifer. This information is crucial to assess contribution of MAR to sustainable groundwater management, as MAR in (semi-)confined aquifers requires a different technique compared to unconfined aquifers (Bouwer, 2002). Unconfined aquifers can be recharged with enhanced surface water infiltration, such as Flood-MAR and Ag-MAR that can result in a short-term increase (Kocis et al., 2017; Dahlke et al., 2018b; Ghasemizade et al., 2019) and a long-term rise in unconfined groundwater storage (Niswonger et al., 2017; Gailey et al., 2019). MAR in semi-confined aquifer sections would only be impacted if lateral spread of additional recharge allows seepage (i.e. preferential path ways) to deeper sections of the aquifer (Faunt et al., 2009). The value of MAR to sustainable groundwater management depends thus partly on the type of groundwater use and MAR contribution for which regular monitoring can be used to ensure sustainability objectives are met.

Encouraging MAR in heavily-stressed aquifers requires not only available water to infiltrate and potential to store water safely in the aquifer, but also careful implementation of MAR practices (Dillon et al., 2019). The growth in MAR in the past 60 years suggests that MAR is going to play an important role in groundwater management (Dillon et al., 2019). Although this should also be accompanied by a policy framework to ensure its correct implementation and safe development of MAR. Australia (only representing 4% of global MAR capacity) is the first by having a risked-based MAR guidelines in place since 2009 (Dillon et al., 2020). Less strict guidelines are found in India (30% of global MAR capacity; Dillon et al. 2019. In Europe, EU member states are encouraged to develop their own policies resulting in varying practices and applications (Sprenger et al., 2017; Capone et al., 2015). In the US, legislation is in place to secure the water quality of infiltrated water and guidelines on safe implementation, but MAR should be further included in water policies before encouraging further expansions (i.e. Flood-MAR, Ag-MAR) (Kiparsky et al., 2017). Potential MAR capacity to store water may exceed surface reservoir capacity in many US states (Scanlon et al., 2016; Maples et al., 2019) and additional funding could, for example, facilitate additional infrastructure to capture high magnitude flows (Kocis et al., 2017) increasing the water availability for MAR (Dahlke et al., 2018b; Alam et al., 2020). Despite some state funding being available, water demand still exceeds the planned capacity (Rohde et al., 2014). Using high magnitude flows would, however, also require additional water treatment to avoid deterioration of groundwater quality (Dillon, 2005; Yang et al., 2019), which highlights the importance of careful implementation of MAR practices.

5.8 Conclusions

The impact of long-term MAR on groundwater droughts has been identified using an analytical regional groundwater analysis applied to groundwater observations in the Central Valley of California. Presented results show that regional MAR impact is larger than previously estimated confirming the importance of MAR in heavily-stressed aquifers. Groundwater droughts are reduced and even alleviated in aquifer sections as a result of short-term and long-term impacts of MAR. Short-term MAR impacts result in rapid groundwater drought recovery and thereby reduced groundwater drought duration and magnitude. Long-term MAR impacts are reflected in neutral and positive groundwater trends in the Central Valley. Despite a negative trend in long-term precipitation, groundwater trends are neutral and even significantly positive in the vicinity of MAR facilities located in the most southern, topographically confined, section of the Central Valley Aquifer. The consistent increase in groundwater levels resulted in alleviated groundwater droughts during the extreme meteorological drought in 2012-15 showing the potential of MAR as regional drought mitigation strategy.

Neutral and positive trends in groundwater level data show that groundwater levels were maintained thanks to long-term (35-year) MAR practices despite a long-term reduction in precipitation and continuous use of groundwater. The transition from negative trends in the North to neutral and positive trends in the South stresses the significant contribution of long-term MAR practices to sustainable groundwater use in heavily-stressed aquifers. However, this success highly depends on water availability, capacity and infrastructure to store water, and careful MAR implementation. Institutional support and guidance for a safe implementation are required to ensure longevity of MAR facilities and their success as a drought mitigation strategy.

Further research on MAR impacts and sustainable groundwater management in California could address the largely unknown groundwater use, which could not be included in this study due to unknown groundwater abstractions. Enhanced monitoring of the Californian groundwater resource might be encouraged with the implementation of SGMA and wider inclusion of MAR within the new water policies is recommended. Advancing techniques to fill in missing groundwater level observations in a human-modified are also recommended, as this limited the spatial coverage of the current analysis.

Future applications of the presented analytical method could aid to assess impact of individual MAR facilities or to identify MAR facilities of unknown performance. For example, groundwater monitoring sites located within MAR facility boundaries were primarily found in one cluster (CL3) showing that short-term MAR impact can be identified regionally without documented MAR recharge, which opens the door for advanced analytical methods focusing on quantification of groundwater level dynamics (Heudorfer et al., 2019) that could isolate short-term MAR impacts. In conclusion, we presented a versatile method that enables researchers to evaluate short-term and long-term MAR impacts on groundwater droughts and thereby, we have shown that MAR can be used as a regional drought mitigation strategy in heavily-stressed aquifers.

5.9 Chapter summary

This chapter continues the assessment of the impact of Managed Aquifer Recharge on hydrological droughts based on findings of Chapter 4. Regional groundwater patterns have been further investigated marking a change in observed groundwater drought characteristics in sites close to MAR facilities and in the southern section of the Central Valley Aquifer. Groundwater droughts are shorter and even alleviated in some sections. These shorter droughts are thanks to the sharply rising limbs in groundwater levels that synchronise with recharged volumes in MAR facilities. The rise in groundwater level is evaluated as short-term MAR impact. Long-term MAR impact is observed in the transition in identified long-term positive groundwater trends despite a negative precipitation trend. Groundwater trends in other sections of the Central Valley follow the (amplified) negative precipitation trend. The promising positive impact of MAR on groundwater droughts is, however, conditional as long-term MAR practises require sufficient imported water to infiltrate, infrastructure to store and distribute water, and sufficient guidance on MAR practises to ensure maintenance of both water quantity and quality. The exemplar case study in California shows the potential for other regions that have a long-term MAR practise, although to ensure longevity of MAR practises and their success as drought mitigation strategy careful implementation and groundwater management is recommended. In summary, this chapter shows the potential of MAR as a drought mitigation strategy in a heavily-stressed aquifer and highlights the success of reduced and alleviated droughts on the careful long-term MAR practise. Since implementation of MAR is conditional in terms of suitable hydrogeological conditions, available water, infrastructure, implementation, and institutional support, MAR is excluded from the idealised socio-hydrological modelling in Chapter 6. This is because drought mitigation strategies scenarios are intended to represent often applied mitigation strategies in various hydrogeological conditions as reported in the case study. However, it is possible to extend groundwater models or more conceptual models with MAR, as suggested in Chapter 7.

Chapter Six

Modelling strategies to manage and mitigate hydrological droughts

Figure 6.1: Discussing options to save water, as part of the drought policy. Illustration by Jos Zanders

6.1 Introduction

This chapter introduces a developed socio-hydrological model that is used to investigate the impact of drought management strategies on hydrological droughts aiming to meet the third research objective (see also Figure 2.1). In this research objective, human influence on hydrological droughts is evaluated as a range of different management strategies that may be in place during a drought, i.e. changes in reservoir regulation, integration of surface water and groundwater, and in/decreased surface water and groundwater abstractions. This chapter addresses the third research objective by different modelled drought mitigation strategies using the developed socio-hydrological model. This model represents an idealised catchment with a soil moisture balance, surface water storage, and different options for groundwater storage properties in the groundwater module. Modelled drought management strategies have impact on both surface water and groundwater demand and supply and consequences for hydrological droughts are evaluated for the different scenarios, showing strengths and weaknesses of strategies depending on a range of hydrogeological conditions.

This chapter was initiated during a international workshop of the ‘Drought in the Anthropocene’ IAHS working group. Initial ideas and modelling concept were conducted together with Margaret Garcia (Arizona State University), Benedikt Heudorfer (UDATA GmbH), and AVL. Development of the model, scenario development, and testing of drought management strategies was undertaken by DW supervised by AV, JB, and DH. DW also acknowledges the helpful discussions with Kerstin Stahl (University of Freiburg), Chris Jackson (British Geological Survey), Mike Jones (Thames Water), and Natalie Kieboom (Environment Agency).

6.2 Background

Groundwater plays a key role during droughts by sustaining natural and anthropogenic water demand (Graaf et al., 2019; Siebert et al., 2010; Döll et al., 2012). Meteorological droughts, defined as periods of sustained dry weather (Mishra et al., 2010), reduce water availability in soil moisture, surface water, and groundwater. Due to the natural delay in groundwater recharge, it may take weeks, months or even years before a precipitation deficit propagate through the hydrological cycle, resulting in a groundwater drought, defined as a deficit in groundwater level (Yevjevich, 1967; Tallaksen et al., 2004). This results in a longer availability of groundwater, which is therefore often used to complement surface water during droughts (Taylor et al., 2013; Cuthbert et al., 2019). Increased groundwater use may result in aggravated streamflow droughts, a deficit in discharge or reservoir storage (Mishra et al., 2010; Wada et al., 2013; Wanders et al., 2015). Overexploitation of groundwater, periodically during droughts or permanently, may lead to depletion of groundwater systems and reduced drought resilience (Custodio, 2002; Custodio et al., 2019). Given the importance of groundwater availability during droughts, there is a need for long-term drought management plans that include groundwater use and management (Aeschbach-Hertig et al., 2012; Gleeson et al., 2020). The question is, however, how groundwater can be managed best (White et al., 2019; Jakeman et al., 2016) and whether sustainable water management can meet both environmental and anthropogenic water demand during droughts.

Drought policies are designed to guide and structure drought response ultimately creating a drought resilient society (Wilhite et al., 2014). National drought policies vary in their structure, focus on (different) water users, and implementation. Key elements are 1) a drought definition, 2) monitoring of water resources and drought impacts, 3) risk management, 4) (early) warning systems, 5) interventions or drought management strategies, 6) recovery and evaluation of drought events (Wilhite et al., 2014; De Stefano et al., 2015a;

Urquijo et al., 2017). Studies aiming to compare drought policies address these facets often in a qualitative manner, for example when comparing Australia and the US (White et al., 2001; Botterill et al., 2012), different US states (Fu et al., 2013), and European countries (De Stefano et al., 2015a; Urquijo et al., 2017; Özerol, 2019). However, few of these drought policies are assessed in terms of their effectiveness (Urquijo et al., 2017; Wilhite et al., 2014). In Europe, drought polices or drought management plans are evaluated as part of the Water Framework Directive (abbreviated as WFD, Directive 2000) and member states are encouraged to move from crisis management towards proactive management of droughts (Howarth, 2018). However, implemented drought policies vary (De Stefano et al., 2015a; Urquijo et al., 2017) and there is currently no consistent methodology to assess drought policies with respect to their impact on water resources or hydrological droughts.

Studies investigating feedback processes between drought policies and water resources often use socio-hydrological models to capture both hydrological and anthropogenic responses in time (Sivapalan et al., 2012; Di Baldassarre et al., 2015). Some studies address one specific measure of a drought policy, for example focusing on environmental flow requirements (Klaar et al., 2014), groundwater use (Apruv et al., 2017; Martínez-Santos et al., 2008), restrictions on water use (White et al., 2019), conjunctive use of water resources (Huggins et al., 2018), management regulations of reservoir storage (Di Baldassarre et al., 2018; Garcia et al., 2020; Dobson et al., 2020), and awareness of water shortage during a drought (Garcia et al., 2016; Gonzales et al., 2017). Jaeger et al. (2019) were the first to model a set of drought policy measures. They tested separately and combined drought measures and showed that reservoir regulations and timely interventions have a large impact on streamflow droughts. Alternative water sources, such as groundwater, were not considered. Given the importance of and increasing dependency on groundwater during drought (Aeschbach-Hertig et al., 2012; Taylor et al., 2013; Cuthbert et al., 2019), there is a need to model drought policies that apply to both surface water and groundwater.

6.3 Aim of the study

This study aims to assess the impact of drought policies on hydrological droughts and water resources for a range of hydrogeological conditions. For this, we used a lumped socio-hydrological model to simulate drought management strategies that apply to both surface water and groundwater. The socio-hydrological model represents an idealised (simplified) hydrological system that includes water storage in a reservoir and groundwater system and water use from surface water and groundwater. This model is used to evaluate separate and combined drought management strategies that alter water use, the source of water supply, and the amount of imported surface water. Drought management strategies are tested for a range of hydrogeological conditions (high, medium, and low groundwater storage systems) to assess their impact in different conditions. Results are discussed in terms of the relative influence of drought management strategies (either separately or combined) on hydrological droughts and water resource availability. In the sensitivity analysis (included in the result section), model parameters are tested and discussed in further sections.

6.4 Case study

England is the used case study in this Chapter considering the publicly available information on surface water and groundwater allocations during normal and drought conditions. Since 2003, water allocations are based on a catchment water balance approach as WFD standards were integrated in national water policies (Environment Agency, 2016; Howarth, 2018). Drinking water supply is the largest water user, comprising 55% of water use on average and up to 90% in some densely populated regions (data from 2000-2015, presented in S8; Agency 2019a). Drinking water supply is privatised since 1989 and 18 drinking water companies are currently in charge of providing drinking water in England (Ohdedar, 2017; Ofwat, 2020). Thirteen drinking water companies rely on both surface water and groundwater and those were used in this study to inform baseline conditions and drought management scenarios (see Table S19). The source of water supply varies for the selected companies given regional variability of surface water and groundwater. For example, companies with access to principal aquifers might depend more on groundwater compared to companies with access to shallow, less productive aquifers (Table S19). Considering the variation in surface water and groundwater use and importance of groundwater during droughts, a range of hydrogeological conditions was modelled using three different groundwater storage options in the groundwater module, as described in Stoelzle et al. (2015). In addition to locally available water, water transfers between drinking water companies overcome seasonal or annual shortages that occasionally represent a large proportion of regional water use (Table S19; Dobson et al. 2020; Agency 2019b). These transfers also ease pressure on water resources and act as emergency supply during droughts (Dobson et al., 2020). Pressure on water resources in the case study is considerable. During normal conditions on average 88.5% of allocated water is used and this can increase during periods of high water demand or droughts (S19; Agency 2019b). Not surprisingly, drought management plans are mandatory for drinking water companies to guide their drought response. These plans are publicly available and often updated. Most recent plans published by the thirteen drinking water companies have been used in this study (see S18 for references to regional drought management plans).

Drought management plans in the UK consist of five main components: 1) drought definition, 2) warning system based on drought trigger levels, 3) demand management, 4) supply management, 5) evaluation of drought events (summarised in Table 6.1; references in S18). Drought definitions and trigger levels are used to distinguish minor from severe drought events and activate different drought management strategies with increasing severity (Table 6.1). Drought trigger levels are often based on deficits in seasonal precipitation or the total precipitation in winter months (also called dry winters in drought management plans) that is the main groundwater recharge period in the UK. Water levels in rivers, reservoirs, and (key) groundwater boreholes are also used as drought triggers when flow or storage levels are falling low. Drought plans list various demand-related and supply-related drought management strategies that are activated in stages (see Table 6.1 for the variety of implemented strategies). The most commonly applied strategies were implemented in the model, if the model setup allowed it, using the average effect of these measures reported by drinking water companies.

6.5 Data and Model structure

The developed socio-hydrological model consists of a water balance model driven by climate data and a water demand model based on the regionally-averaged water resource management plans. The temporal resolution is daily and the water balance model is driven by climate data. Input climate data were selected to include the four most recent national hydrological drought events (Barker et al., 2019), resulting in a period of investigation from 1980 to 2017.

6.5.1 Data

Climate data to drive the idealised socio-hydrological model should ideally represent average climate conditions in England providing an estimate for precipitation (P) and reference potential evapotranspiration (PET). Therefore, a regionally-weighted precipitation product was selected to represent average precipitation conditions (at a daily time scale) (Alexander

[1]Water use efficiency is included with hose pipe bans in first drought stage.

[2]Temporary use bans are sometimes only implemented during 'moderate droughts'. Reductions in demand are here taken as documented reductions as a result of drought policies in place.

[3]Not all public drinking water companies provided an estimate of demand reductions with rota cuts.

Table 6.1: Recent drought management plans of 13 drinking water companies with staged drought management strategies according to drought trigger levels (see S18 for references to the drought plans). Average drought trigger levels are shown (range in parenthesis) based on 11 drought plans with trigger levels under 100 years for initial drought stages. Demand management and water supply strategies are shown per drought stage with model implementations (*4th* and *7th* column respectively). Modelled impact on water resources is based on the average of reported effect of strategies by the drinking water companies. The range of reported effect is in parenthesis and the number of reports is in squared brackets. Surface water and groundwater are abbreviated as SW and GW respectively for readability.

Drought trigger level	**Demand management plans**	**Applied in drought plans** (#)	**Modelled as**	**Supply management plans**	**Applied in drought plans** (#)	**Modelled as**
Mild drought (1 in 8.5 year [5-20])	Promote water use efficiency	13	Demand reduces[1]	Maximise GW licence	3	GW use increases 4% (2-6% [3])
	Leak reduction	13	-	Import of SW	10	Water is imported when storage falls below 25%
	Water metering	6	-	Conjunctive use of SW & GW	6	Flexible use of SW & GW
	Temporary use ban[2] (non-essential)	13	Demand reduces 5% (0-15% [13])	Maximise SW licence	6	SW use increases 6% (1-9% [6])
Moderate drought (1 in 22.5 year [10-80])	Reduce pressure on water network	7	-	Deepening boreholes	4	-
				River augmentation	8	-
	Temporary use ban[3] (Commercial)	12	Demand reduces 12% (1-33% [12])	Reduce water export	9	-
				Artificial recharge schemes	1	-
				Reduction of ecological minimum flow	8	Ecological minimum flow not maintained
				Maximise GW licence	9	GW use increases 7% (1-13% [9])
				Maximise SW licence	10	SW use increases 14% (1-98% [10])
Severe drought (1 in 69 year [20-100])	Phase winter & summer water use	4	-	Installation of additional GW wells	6	-
	Rota cuts	8	Demand reduces 36% (30-40% [3[4]])	Reuse sewage water	5	-
				Maximise GW licence	10	GW use increases 12% (1-49% [10])
				Maximise SW licence	9	SW use increases 10% (2-26% [9])

et al., 2001). In the absence of a regional product for PET, we selected a centroid location to obtain a representative point location in England and extracted daily time series from the (gridded) CHESS dataset (Robinson et al., 2016).

Baseline conditions for water demand were taken from water resource management plans that document long-term (2000-2015) water demand and water availability for normal year (Agency, 2019b). These documented volumes were converted into a percentage (water demand divided by available water) representing water allocation per drinking water company (see Table S19). The average water allocation in percentage was 88.5%, implying that on average 88.5% of available water is used for drinking water. This average was based on water allocation for the selected drinking water companies had a narrow range of 82% - 95% (Table S19). The average water allocation was used in the baseline and drought management strategy scenarios. In the sensitivity analysis, water allocated was in/decreased with 5% (to 93.5% and 83.5% respectively). Proportional use of surface water and groundwater ranges widely within England (15-88% and 10-84% for surface water and groundwater use, respectively). Water demand is satisfied for on average 44.6% (standard deviation: 23.1%) surface water and 48.5% (standard deviation: 24.1%) groundwater. The remaining water demand (6.9%) was provided by imported water representing water transfers between companies. Considering the large range of surface water and groundwater use between the companies, alternative proportions of surface water and groundwater use were briefly tested in the baseline result section. Tested alternative proportions were taken as the mean plus standard deviation resulting in 67.7% (surface water) and 25.4% (groundwater) when using primarily surface water. When using primarily groundwater, proportions of 72.6% (groundwater) and 20.5% (surface water) are used. The share of imported water remained constant.

Drought management strategies were based on regionally-averaged drought management plans (Table 6.1) that were activated based on drought trigger levels (first column). Trigger levels were averaged, although extremely long return periods (100-150 year) for initial drought stages were excluded from this average. Nearly all drinking water companies relate these trigger levels to precipitation, discharge, reservoir and groundwater levels. In this study, modelled trigger levels relate to precipitation (using monthly SPI) and modelled discharge and groundwater level time series. This means that if either surface water or groundwater falls below the trigger level, for example,in a 1 in 8.5 year drought event, the first category of drought management strategies is activated. Different trigger levels are applied to reservoir storage levels. These reservoir trigger levels vary, but the range is similar for droughts with increasing severity. Reservoir trigger levels in the first drought category typically start from 80% to 60% of reservoir storage, second category from 60% to 30%, and the last from 30% to 12% (see individual drought management plans, reference in S18). Therefore, reservoir trigger levels of 75%, 50%, and 25% were modelled based to activate drought management strategies for surface water.

Due to the lumped model setup, only a selection of the listed management strategies could be modelled. For example, strategies aimed at spatially-distributed water resources, such as (urban) waste water reuse and river augmentation could not be simulated. Selected strategies were first tested separately resulting in the following four scenarios (Table 6.2). The first scenario focuses on water supply and includes an increase in water use for both surface water and groundwater. The percentage increase represents the average of the reported range that are described in Table 6.1 in column 7 for each drought stage. The second scenario focused on restricting water demand and reduces surface water and groundwater demand with the average percentage (range is presented in Table 6.1 column 4). The third scenario is conjunctive water use that integrates surface water and groundwater use. Depending on the (highest) available storage, either surface water or groundwater is used to meet the total daily water demand. The fourth scenario maintains the ecological flow and is also known as 'hands off flow'. Groundwater use is restricted when baseflow falls below the seasonal ecological minimum flow threshold (80^{th} percentage). In addition to the four separate scenarios, two combined scenarios were modelled to investigate the combined effect of drought mitigation strategies with either conjunctive use (scenario 'combined 1-2-3'), or maintaining the ecological flow (scenario 'combined 1-2-4').

Table 6.2: Detailed description of the four separate drought management strategies. Note that staged drought management strategies under the first and second scenario (1: Water supply and 2: Restricted use) are activated by drought trigger levels. The third and fourth scenario are active throughout the modelling period (1985-2017). Modelled scenario rules are based on (averaged) documented drought management strategies and reported impact of these (see Table 6.1 for details).

	1: Water supply	2: Restricted use	3: Conjunctive use	4: Maintaining ecological flow
Mild drought	+ 6% surface water use + 4% groundwater use	Water demand -5%	Integrated storage use	No groundwater use, when baseflow falls below ecological minimum flow
Moderate drought	+ 14% surface water use + 7% groundwater use	Water demand -12%		
Severe drought	+ 10% surface water use + 12% groundwater use	Water demand -36%		
Applicable at all times:	Surface water import when reservoir levels fall below 25%			

6.5.2 Model structure

The socio-hydrological model consists of a lumped water balance model, as previously described in Van Lanen et al. 2013. From this water balance model, the linear groundwater was extended and available surface water (in the surface water reservoir) and groundwater were used to meet the water demand (Figure 6.2). Climate data is used as input for the soil moisture balance, generating runoff and groundwater recharge that are routed further to the surface water and groundwater module, respectively. Based on the 37-year time period (1980-2017) of the input climate data, a 5-year spin-off period was excluded for the drought mitigation scenarios. This spin-off period includes water use, but no drought management strategies. Drought characteristics of baseflow and groundwater storage were calculated applying a threshold of the lowest 80^{th} percentile of the baseline run, corresponding to a 'once every 5 year drought' (Yevjevich, 1967; Tallaksen et al., 2004; Mishra et al., 2010). This baseline threshold was also used for the drought management scenarios.

For simulating soil moisture, a medium soil (light silty loam soil: Soil II) is modelled, generating daily balance (Equation 6.1, Van Lanen et al. 2013). The daily soil moisture (SS for daily time steps $_t$) determined the actual evapotranspiration (ETa) that was calculated from PET. ETa was taken equal to PET when SS_t is between field capacity and critical soil moisture content (well-watered grass would in this case transpire at the potential rate), ETa was reduced for drier soils with a factor $\frac{SS_t - SS_{WP}}{SS_{CR} - SS_{WP}}$, and below wilting point ETa was assumed to be zero (Van Lanen et al., 2013). Overland flow or runoff (Qr) occurs when the soil reaches field capacity (168.9 mm) and when it is raining on very dry soil (below critical moisture content of 95.2 mm). Groundwater recharge (Rch) is calculated from the daily soil moisture content depending on the soil moisture retention shape parameter and the unsaturated hydraulic conductivity (Equation 6.3). Long-term annual average runoff and groundwater recharge generated by the soil moisture balance define the total available

$$SS_t = SS_{t-1} + P_t - ETa_t - Qr_t - Rch_t \tag{6.1}$$

Equation 6.1: Soil moisture balance (SS) driven by precipitation (P) and actual evapotranspiration (ETa), generating runoff (Qr) and recharge (Rch). The long-term annual average runoff and recharge defined the total available water for water use.

$$Qr_t \begin{cases} SS_t - SS_{FC} & \text{if } SS_t \geq SS_{FC} \\ 0 & \text{if } SS_{CR} < SS_t < SS_{FC} \\ \frac{1}{2}P & \text{if } SS_t \leq SS_{CR} \text{ \& P} > 2 \text{ mm/d} \end{cases} \tag{6.2}$$

Equation 6.2: Runoff (Qr) for overland flow conditions (SS exceeds field capacity or is too dry). Generated runoff is routed to the surface water reservoir and available for surface water use from the surface water reservoir.

water for anthropogenic water use. Allocated water is taken as a fraction (88.5%) of the total available water and divided equally over the days of the year (Table S19).

The second model component is a surface water reservoir that stores generated runoff and baseflow. Stored water is used to meet the surface water demand (44.6% of allocated water) and therefore impacted by drought management strategies (illustrated by the yellow box in Figure 6.2). Reservoir storage can be complemented with imported surface water when storage declines. In the baseline scenario, surface water is only imported when storage is insufficient to meet the surface water demand. During droughts, water is regularly transferred from one region to another to overcome shortages in reservoir storage (see Table 6.1; also described in Dobson et al. 2020). Modelled reservoir storage levels are refilled with imported surface water (Qimp) when storage declines below 25% in drought management scenarios. In the model, Qimp is unlimited and additional to the water balance. Maximum reservoir storage is set to one year of winter recharge, defined as the long-term total precipitation in

$$Rch_t = \begin{cases} 0 & \text{if } SS_t \geq SS_{FC} \\ \left(\frac{SS_t - SS_{CR}}{SS_{FC} - SS_{CR}}\right)^b k_{FC} & \text{if } SS_{CR} < SS_t < SS_{FC} \\ 0 & \text{otherwise } SS_t \leq SS_{CR} \end{cases} \tag{6.3}$$

Equation 6.3: Recharge (Rch) defined as a downward flux from the soil to groundwater is calculated by a power function with a shape parameter (b = 3; average conditions Seibert 2000) and unsaturated hydraulic conductivity at field capacity of a light silty loam soil (Soil II: 22.3 mm/day Van Lanen et al. 2013 and Tanji et al. 2002). Generated recharge is routed to the groundwater module.

the period December to February. Excess reservoir storage (Qout) leaves the model and is not used to meet surface water demand.

The groundwater module consists of one module with three different options for hydrogeological conditions. The three options represent baseflow generation for different aquifer structures with high, medium, and low groundwater storage (based on the karstic, porous, and fractured aquifers in Stoelzle et al. 2015). All options are tested for baseline conditions and drought management scenarios. The high storage system is modelled with a non-linear power law (Equation 6.4). The medium storage system is computed by a linear storage reservoir with additional by-pass component (Equation 6.5) and the low storage system is represented by two parallel linear storage reservoirs (Equation 6.6). Groundwater use (Agw) was taken from the daily groundwater storage balance resulting in different time series for baseflow and groundwater storage. From the generated baseflow (Qb), the ecological minimum flow (Qeco) is first taken to allocate water for the environmental water demand. Qeco is calculated as the 80^{th} percentile of the baseline time series. The remainder of baseflow is routed to the surface water reservoir. This implies that on days when baseflow is less than Qeco, no baseflow is routed to the surface water reservoir and all available water is allocated for environmental water demand. Maintaining environmental flow is only applied in some drought management scenarios, in which groundwater use is restricted when flows fall below the 80*th* percentile.

Groundwater storage-outflow parameters for the high, medium, and low groundwater storage systems were based on primary aquifers in the UK (Allen et al., 1997) and alternative parameters were tested in the sensitivity analysis (Table 6.3). The values for groundwater storage are effectively determining discharge outflow (baseflow) and also are called groundwater storage-outflow parameters (s in days^{-1}). In addition to s, the response time (in days) of groundwater storage systems is also shown in Table 6.3, as this is a more intuitive unit. If groundwater storage is depleted, additional groundwater storage (GSimp) is imported to meet the groundwater demand. Similar to imported surface water, as additional groundwater is unlimited and additional to the water balance. In reality, additional groundwater would come from other aquifer sections.

In the sensitivity analysis, alternative groundwater storage parameters were tested that may in/decrease storage in the baseline and potentially alter the impact of drought management scenarios. To evaluate the relative sensitivity of storage-outflow parameters and scenarios, new drought thresholds were calculated taking the 80^{th} percentile of each baseline run with an alternative groundwater storage-outflow parameters. Similar to the main analysis, impact of drought management strategies is taking from this baseline and drought threshold (with alternative storage parameter).

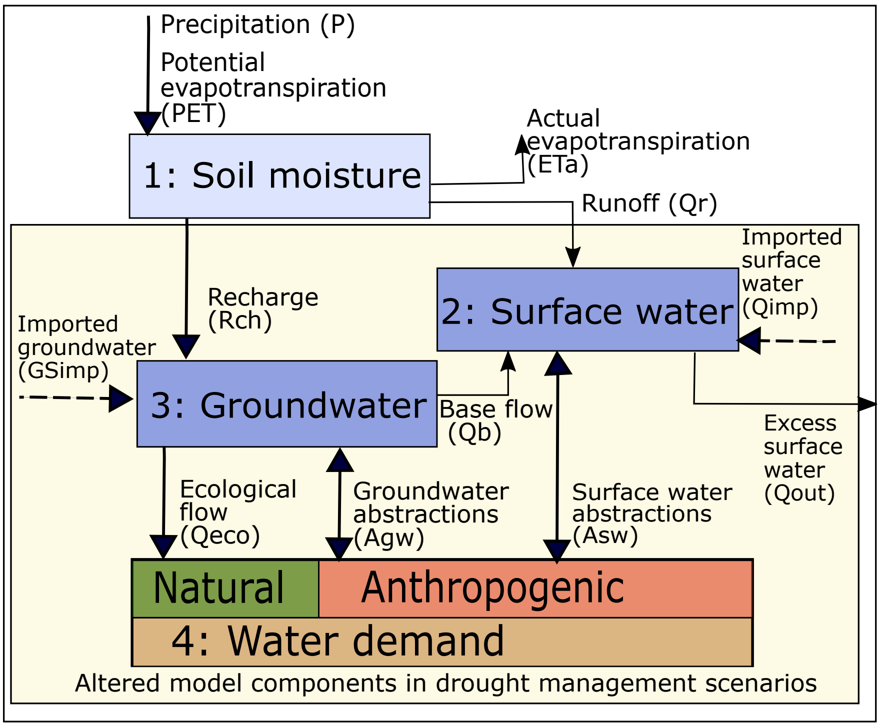


Figure 6.2: Socio-hydrological model setup that consists of a soil moisture balance (1) driven by precipitation (P) and potential evapotranspiration (PET),a surface water reservoir (2) that stores generated runoff (Qr), and a groundwater module (3) driven by groundwater recharge (Rch). From generated baseflow, the natural water demand (ecological flow requirements: Qeco) is met first before routing remaining baseflow (Qb) to the surface water reservoir. Anthropogenic water demand is taken from the surface water reservoir and groundwater storage (Asw and Agw, respectively). When surface reservoir and groundwater storage are unable to meet water demand, additional water is imported in the model. For the surface water reservoir, this represents surface water import (Qimp) by water transfers. Additional groundwater is also imported and considered as an external groundwater source (GSimp). Drought management strategies apply to the surface water reservoir, groundwater module, and water demand (illustrated by the yellow box).

$$\text{High groundwater storage aquifer} = \begin{cases} Qb_t = sGS_t^B \\ GS_t = GS_{t-1} + Rch_t - Qb_t - Agw_t \end{cases} \tag{6.4}$$

Equation 6.4: Baseflow (Qb) and groundwater storage (GS) for the high storage system represented by a non-linear power law. B is taken as 0.5 based on the normal range is 0.3 - 1 from Stoelzle et al. 2015). Table 6.3 shows the range and modelled groundwater storage-outflow (s) values for high groundwater storage aquifers.

$$\text{Medium groundwater storage aquifer} = \begin{cases} Qb_t = sGS_t + DRch_t \\ GS_t = GS_{t-1} + (1 - D)Rch_t - Qb_t - Agw_t \end{cases} \tag{6.5}$$

Equation 6.5: Baseflow (Qb) and groundwater storage (GS) for medium storage system represented by a linear storage reservoir with additional by-pass component (D). D is taken as 0.1 based on the range of 0.07 to 0.12, as tested in Stoelzle et al. 2015). Table 6.3 shows the range and modelled groundwater storage-outflow (s) values for medium groundwater storage aquifers.

Table 6.3: Groundwater storage-outflow s values for the three groundwater options in the groundwater module. The first row shows s values used by Stoelzle et al. (2015), the second row shows representative s values for England based on Allen et al. (1997), and the third row presents the modelled s values for the three groundwater options. Baseflow and groundwater storage are calculated with these s values in Equations 6.4-6.6. In the sensitivity analysis, a range of s values was calculated (last row). For the low storage system, only s_1 was changed in the sensitivity analysis. The response time (in days) is shown for the modelled s values in parenthesis.

	High storage system (s in days^{-1})	**Medium storage system (s in days^{-1})**	**Low storage system (s in days^{-1})**
s values as modelled by Stoelzle et al. (2014)	0.008-0.025	0.001-0.01	s_1 : 0.004-0.011 s_2 : 0.05-0.25
Representative s values for England by Allen et al. (1997)	0.009-0.04	0.0008-0.004	0.002-0.02
Modelled (mean) s values	0.02 (50 days)	0.004 (250 days)	s_1 : 0.005 (200 days) s_2 : 0.1 (10 days)
Alternative s values in sensitivity analysis	0.01 (100 days) 0.0133 (75 days) 0.03 (33 days)	0.001 (1000 days) 0.002 (500 days) 0.01 (100 days)	0.002 (500 days) 0.00285 (350 days) 0.01 (100 days)

$$\text{Low groundwater storage aquifer} = \begin{cases} Qb_t = s_1 GS1_t + s_2 GS2_t \\ GS1_t = GS1_{t-1} + \frac{1}{2}Rch_t - s_1 GS1_t - \frac{1}{2}Agw_t \\ GS2_t = GS2_{t-1} + \frac{1}{2}Rch_t - s_2 GS2_t - \frac{1}{2}Agw_t \end{cases} \tag{6.6}$$

Equation 6.6: Baseflow (Qb) and groundwater storage (GS) for low storage system represented by a two parallel linear storage reservoirs. Total groundwater storage is a sum of both parallel linear storage buckets for which recharge and water demand is equally divided. Table 6.3 shows the range and modelled groundwater storage-outflow (s_1 and s_2) values for low groundwater storage aquifers.

6.6 Results

The results are presented in four sections starting with baseline conditions for the three modelled hydrogeological conditions. In section 6.6.2, drought management strategies are presented, followed by the hydrological droughts analysis for these strategies. The sensitivity analysis is presented last.

6.6.1 Baseline

In the baseline scenario, the soil moisture shows inter-annual variations, but no systematic wetting or drying, as the total water balance is close to zero (18mm) for 37 years (see Figure S9). Periods of below-normal precipitation resulting in reduced groundwater recharge and runoff are visible in spring 1989, 1991-1992, 1996-1997, 2003-2004, 2005-2006, 2010-2012, and June 2017. These periods are colour-coded according to drought definitions in Table 6.1 in Figure 6.3. Periods of above-normal precipitation are noted in 1991, 2001 and 2012 resulting in a saturated soil with excess runoff generation instead of recharge.

Surface water availability in the baseline follows the inter-annual variability in runoff and baseflow that is generated by the groundwater modules (Figure 6.3). Surface water demand (44.6% of allocated water) is taken from stored runoff and baseflow in the surface water reservoir. A small percentage (6.9%) is always imported, representing water transfers between drinking water companies. In the high groundwater storage system, surface water availability is lowest (mean: 16%, range: 0-89%) and groundwater availability is high. Surface water availability is much higher in the medium and low groundwater storage systems with on average 36% and 66% reservoir storage, respectively. In the low groundwater storage system, low reservoir storage levels occur during mild droughts only. When surface water availability is insufficient to meet the daily demand, additional surface water is imported. This additional import represents 15%, 9%, and 7% of the total water demand for the high, medium, and low groundwater storage systems, respectively (Figure S11, high and low groundwater storage systems in Figure 6.4). These percentages of imported surface water thus suggest that surface water availability is sometimes insufficient to meet the surface water demand.

Groundwater availability is largest in the high groundwater storage system and smaller for the other two catchments (medium and low groundwater storage systems; Figure 6.3). Groundwater in the high storage system buffers more mild droughts compared to the other two systems, for which groundwater storage depletes rapidly in summer months. The overall low groundwater storage in these systems results in lower baseflow and ecological flows. Compared to scenarios without water use (see Figure S10), groundwater storage and baseflow are much lower, showing the pressure on groundwater systems given current water demand. Additional groundwater import represents a relatively small proportion (1%) in the high groundwater storage system compared to the medium and low systems (11% and 17% respectively; see Figure S11, high and low storage systems in Figure 6.4).

When changing the relatively even proportion of surface water and groundwater,

Figure 6.3: First panel shows the standardised Precipitation Index (SPI) for regionally averaged *monthly* precipitation. Drought severity is indicated in three colours according to three drought stages in drought management plans (Table 6.1). Other three panels show *daily* baseline conditions for surface water availability (reservoir storage) and groundwater availability for high (green), medium (gold), and low (blue) groundwater storage systems. In the baseline, reservoir storage is a function of runoff, baseflow (minus ecological flow) and surface water demand (44.6% of available water). Groundwater storage is a function of stored groundwater recharge and abstracted water demand (48.5% of allocated water). The remainder water demand 6.9% is always imported, representing the water transfers between drinking water companies S19. Note that y-axes are different for the 3 systems. Reservoir capacity is constant and defined as the total long-term winter precipitation (see 2.2 Model structure).

using the mean and standard deviation from Table S19, the amount of imported water can be reduced depending on the storage capacity. In the medium and low groundwater storage systems, using primarily surface water (67.7%) results in a slight increase of imported surface water and a reduction of imported groundwater use compared to the baseline (Figure S11). This is in sharp contrast to the high groundwater storage system, for which primarily surface water use implies a steep rise in imported surface water. The surface water reservoir is insufficient to meet the surface water demand and over 25% of surface water demand is imported. When using primarily groundwater (72.6%), surface water import reduces to the set 6.9%, but imported groundwater increases from 1% in the baseline to 18% in the high groundwater storage system. In the medium and low storage systems, imported groundwater increases even more up to 30% and 32%, respectively. These alternative proportions of water use show that the amount of imported water reduces when optimising water storage and use of both water resources. This was further tested in the conjunctive use drought management scenario.

6.6.2 Drought management scenarios

Out of the four drought management strategies, conjunctive use of surface water and groundwater has the largest impact on surface water and groundwater availability (Figure 6.5; only the low groundwater storage system is shown as results are very similar). In this scenario, surface water and groundwater use are integrated. Using either surface water or groundwater depends on the relative availability of the resource resulting in flexible water use depending on the relative storage levels. In the low groundwater storage system, conjunctive water use results in an increase in groundwater storage and baseflow. In this case, locally available surface water is used more intensively representing 65.6% of total water demand (Figure 6.4). Groundwater use decreases to 17% resulting in a 50% increase in baseflow compared

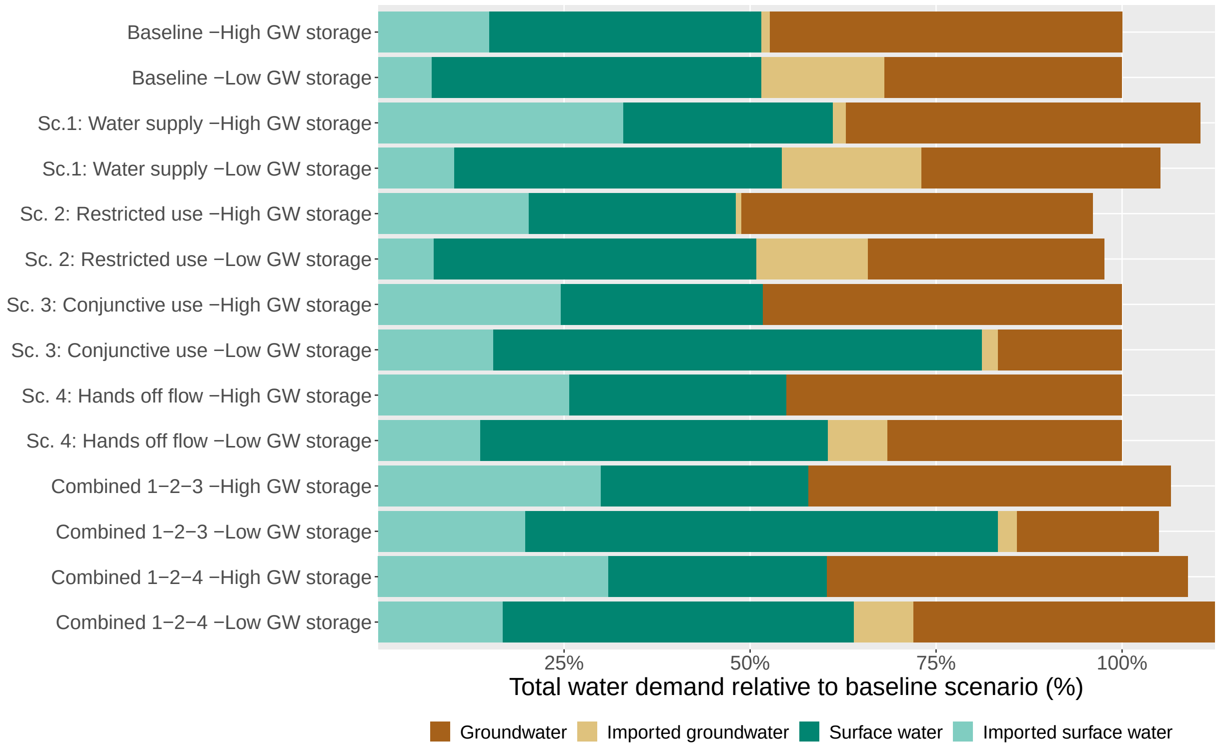


Figure 6.4: Total water demand for baseline (rows 1 & 2), separate drought management scenarios (rows 3-10), and combined scenarios (11-14) in the high and low groundwater storage systems. Names of both groundwater storage systems are abbreviated as 'High/Low GW storage' for readability. Total water demand is met by a combination of surface water (imported and locally available) and groundwater (imported and locally available) and percentages are relative to baseline conditions. Note that total water demand in scenarios can be different to baseline conditions due to the drought management strategies.

to the baseline. In the high groundwater storage system, surface water and groundwater use changes mainly in timing and show a minimal change in proportional surface water and groundwater use compared to the baseline (Figure 6.4). Baseflow remains high, similar to the baseline, although groundwater storage reduces slightly (Figure 6.5). Additional groundwater import reduces to a minimum in both systems, although this comes at the expense of imported surface water, which increases to 24.5% and 15.5% in the high and low groundwater storage systems respectively (Figure 6.4).

Second to the conjunctive use scenario, hands off flow (4^{th} scenario) also has a substantial impact on the high groundwater storage system resulting in higher groundwater storage and baseflow (on average 14%; groundwater time series shown in Figure 6.5). Key difference with baseline conditions is the restriction on groundwater use to maintain minimum flows (not used to meet anthropogenic water demand). The restrictive use of groundwater results in a continuous increase in groundwater storage in the high storage system, compared to periodic increases in storage in the low storage system. These periodic increases in storage result in a minimal increase in baseflow (on average 1%) suggesting that this scenario has much less impact in the low groundwater storage system. With restricted groundwater use, surface water use increases to meet the water demand. In the low storage system, the use of locally available surface water increases with 2.2%, but most surface water is imported (additional 6.5%). In the high storage system, no locally available surface water is available and the increased surface water use is primarily imported (additional 10.7%; Figure 6.4).

The first and second scenarios (increased water supply and restrictive use) result in periodic in/decreases during meteorological droughts (Figure 6.5). Increasing water supply during droughts (1^{st} scenario) results in storage deficits that often recover after drought periods. A reduction in water demand (2^{nd} scenario) shows a similar, but opposite, pattern with an increase in groundwater storage during most severe meteorological droughts resulting from the severe restrictions on water use. Compared to the baseline, water restrictions

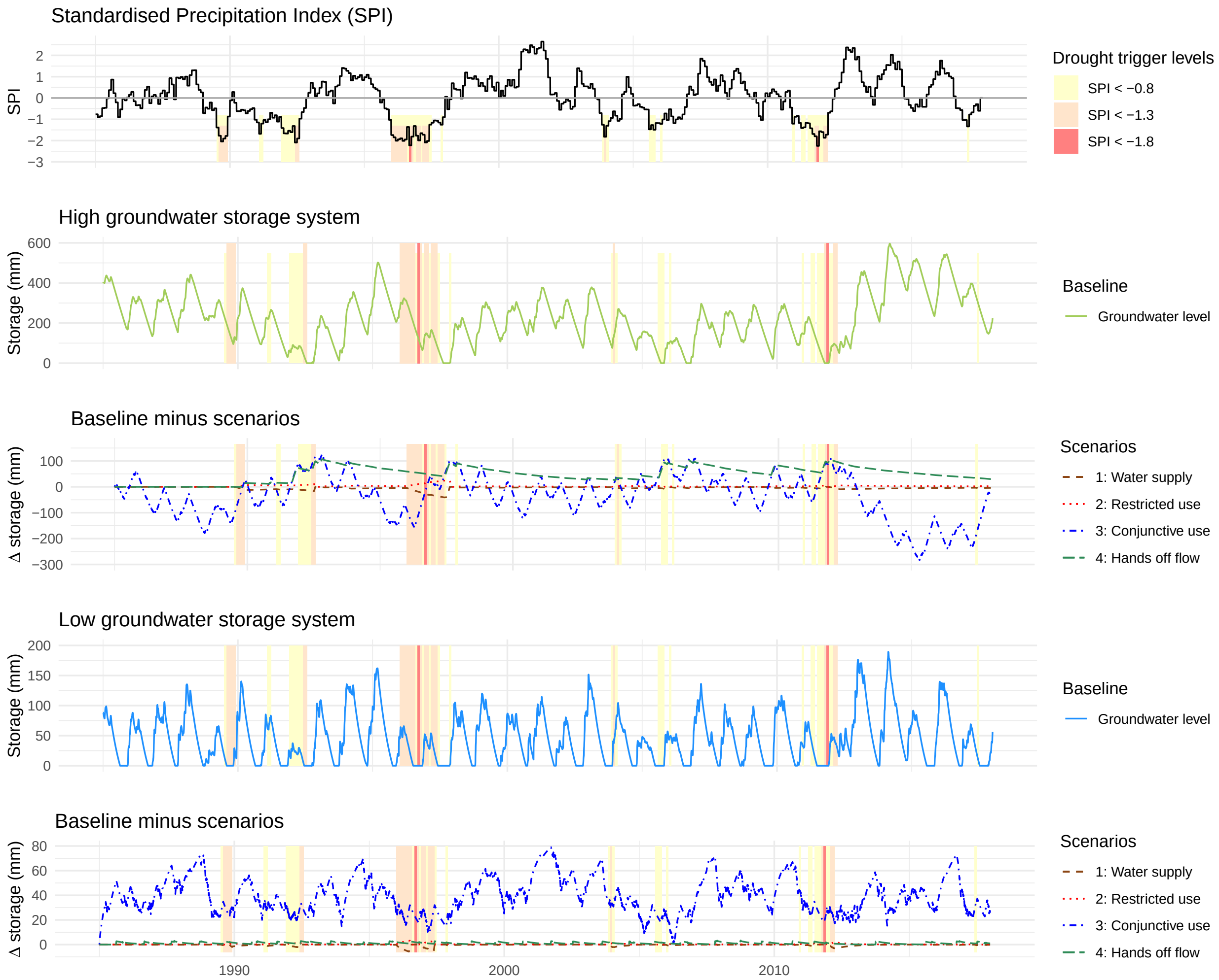


Figure 6.5: Impact on groundwater storage by four separate drought management scenarios. Coloured surfaces match the increasing severity of meteorological droughts (related to trigger levels, see Table 6.1). Baseline conditions for high and low groundwater storage systems are shown in the first and third panel. Second and fourth panel show the impact of drought management strategies in these systems (baseline minus scenario). The four separate drought management strategies represent 1) increased water use from both surface water and groundwater (1: Water supply), 2) restricted water (2: Restricted use), 3) integrated use of surface water and groundwater (3: Conjunctive use), 4) maintaining the ecological flow by reducing groundwater abstractions (4: Hands off flow). For details see Table 6.3.

reduce the overall water demand slightly for high and low storage system (96% and 98%, respectively). The impact of increased water use is larger, as the total water demand exceeds the baseline due to increased surface water import (111% and 105%, respectively).

The two combined drought management scenarios show an overall increase in baseflow and groundwater storage. Baseflow increases when hands off flow is combined with scenarios 1 and 2 (combined 1-2-4 scenario), particularly for the high groundwater storage system (14% and 1% for high and low system respectively). Combining conjunctive use with scenarios 1 and 2 (combined 1-2-3 scenario) results in a slight reduction in groundwater storage for the high storage system (-8%), but baseflow increases 42% on average in the low storage system. Both combined scenarios show that total water use is comparable to baseline conditions (Figure 6.4), implying that the increase in water use of the first scenario is in balance with the decrease in water use of the second scenario. The use of imported groundwater reduces in both combined scenarios compared to the baseline, but the dependency on imported surface water increases, which is related to import of surface water when reservoir levels fall below 25% (Table 6.1). This is because, surface water availability decreases rapidly during meteorological droughts resulting in activating the reservoir trigger levels and consequently importing surface water to complement reservoir storage (reservoir level time series in Figure S12).

6.6.3 Impact on hydrological droughts

In the baseline, there is a large difference in hydrological drought characteristics between the two groundwater storage systems (Table 6.4). In the high groundwater storage system, baseline conditions show longer baseflow and groundwater droughts compared to the low storage system. Baseflow and groundwater droughts are on average 333 and 344 days (approximately 11 months). In the low groundwater storage system, hydrological droughts are remarkably intense for their short duration (66 and 88 days for baseflow and groundwater, or 2-3 months). Both baseflow and groundwater time series are flashy, with a high baseflow component in winter and rapidly declining flows in summer months (Figure 6.3). This difference results in the high drought intensities compared to those of steady, but lower baseflow in the high groundwater storage system. In the high storage system, groundwater droughts are more intense on average, which is not surprising given the large buffer. This buffer in the high groundwater storage system results in slower drought propagation with consequently more intense hydrological droughts that occur less frequently buffering meteorological droughts. The low groundwater storage system is on the other end of the spectrum with low storage that depleted rapidly resulting in double the amount of groundwater droughts compared to meteorological droughts. Baseline hydrological droughts are thus different in both systems given the contrasting slow/fast response to recharge, baseflow variation, and groundwater storage. The impact of drought management strategies (separately or combined) is remarkably different for the two groundwater storage systems.

In the combined scenario including conjunctive use (combined 1-2-3), groundwater droughts are shorter in both systems compared to baseline conditions (Table 6.4). Drought intensity reduces in the high groundwater storage system, compared to a slight increase in baseflow droughts in the low storage system. Drought frequencies of both baseflow and groundwater show a sharp contrast between the two systems, as drought frequency increases from 7 events to 24 and 23 for baseflow and groundwater in the high storage system, compared to a reduction in the low storage system. Groundwater time series in the low storage system in Figure 6.6 show that short groundwater droughts are alleviated in 1985, 1988-1989,1991, 1995-1996, 2001, 2003, 2009, 2011 and 2016-2017. Remaining events are of a shorter duration and reduced severity. However, in the high storage system, groundwater droughts also occur without initial precipitation deficits, which might be related to the altered surface water and groundwater abstractions, as there are no meteorological droughts observed in 1988,

Table 6.4: Hydrological drought duration, maximum intensity, and drought frequency for the high and low groundwater storage systems. Mean hydrological (baseflow and groundwater) droughts are presented with standard deviation for baseline, combined 1-2-3, and combined 1-2-4 scenarios. See Table 6.2 for specific modelling rules in the two combined scenarios. Groundwater storage time series and groundwater droughts are shown in Figure 6.6.

		Drought duration (in days)		Maximum drought intensity (in mm)		Drought frequency (count of events)	
		Baseflow	Groundwater	Baseflow	Groundwater	Baseflow	Groundwater
High groundwater storage system	Baseline scenario	333 ±150	344 ±127	-0.16 ±0.07	-96.2 ±44.3	7	7
	Combined 1-2-3 scenario	145 ±73	152 ±71	-0.04 ±0.02	-51.7 ±21.7	24	23
	Combined 1-2-4 scenario	165 ±75	166 ±75	-0.04 ±0.02	-45.1 ±20.7	6	6
Low groundwater storage system	Baseline scenario	66 ±33	88 ±64	-0.31 ±0.2	-16.0 ±11.2	25	20
	Combined 1-2-3 scenario	58 ±16	62 ±8	-0.38 ±0.2	-14.3 ±2.9	8	5
	Combined 1-2-4 scenario	67 ±28	92 ±60	-0.32 ±0.21	-18.2 ±11.2	20	15

1992-1993, 1999-2000, 2002, 2008, 2009, and 2015-2016.

The combined scenario including hands off flow (combined 1-2-4) also shows mixed impacts on hydrological droughts in the two systems. In the high groundwater storage system, drought severity and duration reduces on average compared to baseline conditions (Table 6.4). Time series show alleviated groundwater droughts in 1993 and 2009. In the low storage system, however, the impact of the 1-2-4 combined scenario is much less. Drought duration and intensity reduces slightly and droughts are alleviated in 1996-1998, 2006, and 2011. This is not surprising seeing the overall low ecological minimum flow and therefore limited impact on restricted groundwater use.

6.6.4 Sensitivity analysis

Groundwater storage-outflow parameters

The tested different groundwater storage-outflow parameters are based on (mean) aquifer characteristics in England (Allen et al., 1997) and the range of groundwater storage-outflow coefficients presented by Stoelzle et al. 2015 (parameters are shown in Table 6.3). These tests show that groundwater storage in the high groundwater storage system increases more compared to the low groundwater storage system (Figure S13). This increase in storage has only small consequences for hydrological droughts (groundwater droughts shown in Figure 6.7), as drought duration and intensity increase slightly for each drought event. In the low groundwater system, larger differences in hydrological drought duration are found, as maximum duration increases from 137 days (baseflow) and 237 days (groundwater), to 273 and 455 days, respectively. The droughts in the low groundwater system also increase slightly in severity.

When running the drought management strategies (combined scenarios only) the

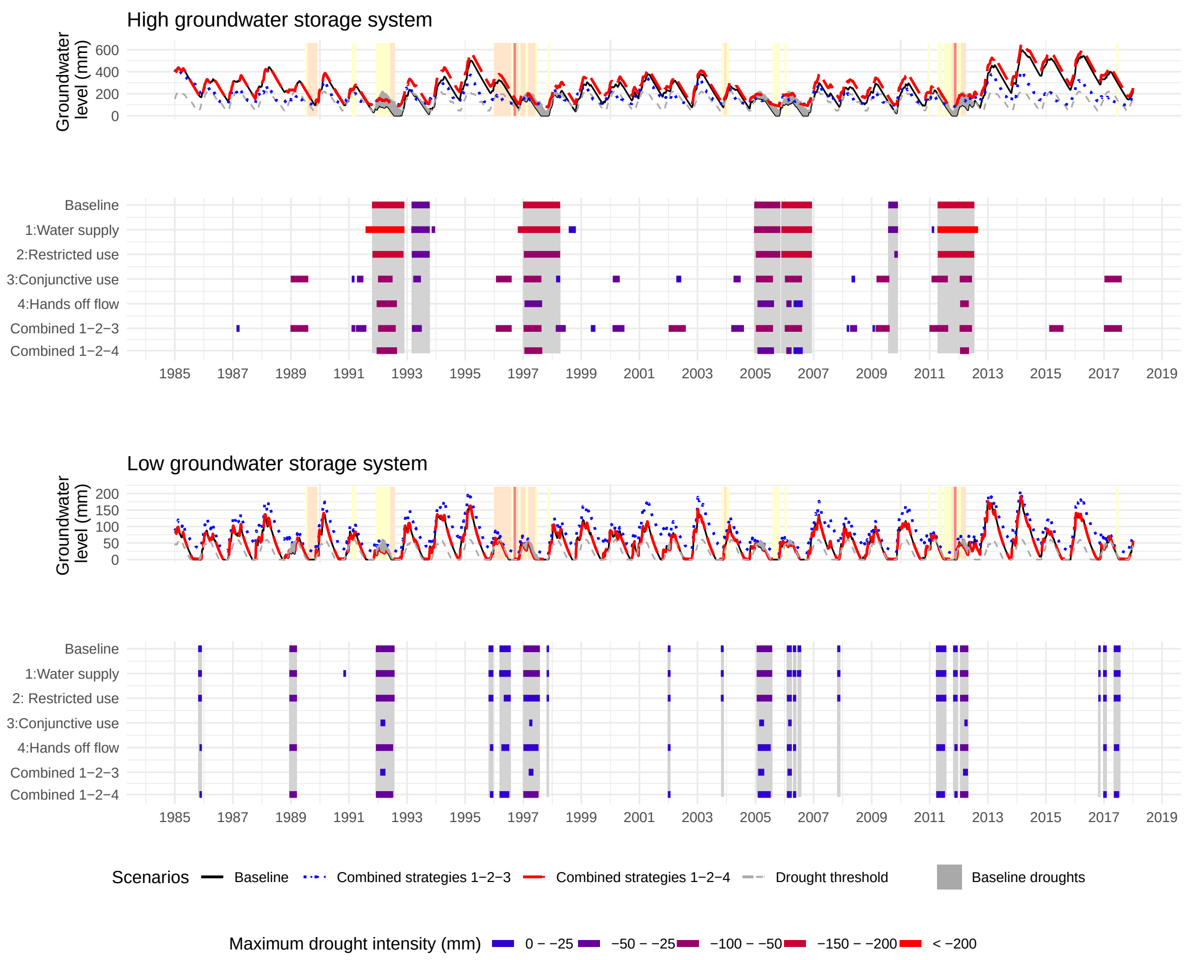


Figure 6.6: Hydrological droughts shown for the baseline scenario and the six tested drought management scenarios (four separate scenarios and two combined scenarios). In the first and third panel, time series of groundwater level variation in the two groundwater storage systems (high and low) are shown for both baseline (black) and combined scenarios (combined 1-2-3 in dotted blue and combined 1-2-4 in striped red). Baseline drought events are marked in grey following the drought threshold (grey striped). Coloured surfaces indicate mild, moderate, and severe meteorological droughts (measured in SPI) following definitions in Table 6.1 and colour scale of Figure 6.3. In the second and fourth panel, groundwater drought occurrence and maximum intensity is shown for drought management scenarios for both catchments. Note that the coloured maximum drought intensity scale is the same for both catchments with red being the most severe and blue representing least intense droughts.

model with these different groundwater storage-outflow parameters in the two groundwater storage systems, the overall hydrological drought intensity and duration reduce for most scenarios (see Figure S14). The combined scenario 1-2-4 (including maintaining the ecological minimum flow) reduces hydrological drought duration for all groundwater storage-outflow parameters, even for high storage parameters in the two different groundwater storage systems (Figure S14). The combined scenario 1-2-3 (including conjunctive use) results in longer droughts, but less severe droughts, particularly for increased storage parameters. In the high groundwater system, groundwater drought duration increases dramatically with the highest groundwater storage parameters, as groundwater storage declines in this scenario and falls below the drought threshold resulting in a depleted system with exceptionally long drought.

Altered water allocation

Altering the water allocation with 5% shows the significant pressure on water resources resulting in lengthened droughts in the high groundwater storage system and significant imports of surface water. When increasing the water allocation (from 88.5% to 93.5%), hydrological drought duration in the high groundwater storage system increases to 866 and 867 days for baseflow and groundwater respectively (groundwater in Figure 6.7). Hydrological drought duration nearly doubles compared to hydrological drought duration in baseline conditions (Table 6.4). Increasing the water allocation results also in additional shorter events that increase the drought frequency. Reducing water allocation with 5% results in fewer severe droughts with a maximum of 453 and 456 days for baseflow and groundwater drought duration, respectively. This drought alleviation would, however, require a permanent cut in water consumption. This is, in addition to the existing water restrictions during drought only. In the low groundwater storage system, in/decreasing the water allocation has less direct impact on hydrological droughts, as drought duration and severity are similar to the baseline. However, in this system additional water use is compensated by an increase in imported groundwater and surface water.

An increase in imported surface water and groundwater is also found in the combined drought management scenarios. Both combined drought scenarios reduce hydrological droughts successfully (S15), although this comes at the cost of increased surface water and groundwater imports. For example, increased water allocation (93.5%) in the high groundwater storage system with the combined 1-2-4 scenario reduces maximum hydrological drought duration from 866 and 867 days to 308 and 309 days for baseflow and groundwater, respectively (S15). This drought alleviation comes with an increase of imported surface water representing 30% of the total increased water demand. Reduced water allocation (83.5%) results in shorter droughts of maximum 218 days with slightly less surface water import (27% of total water demand). These increased percentages of imported surface water show the pressure on water resources and the true cost to reducing hydrological droughts in combined drought management scenarios.

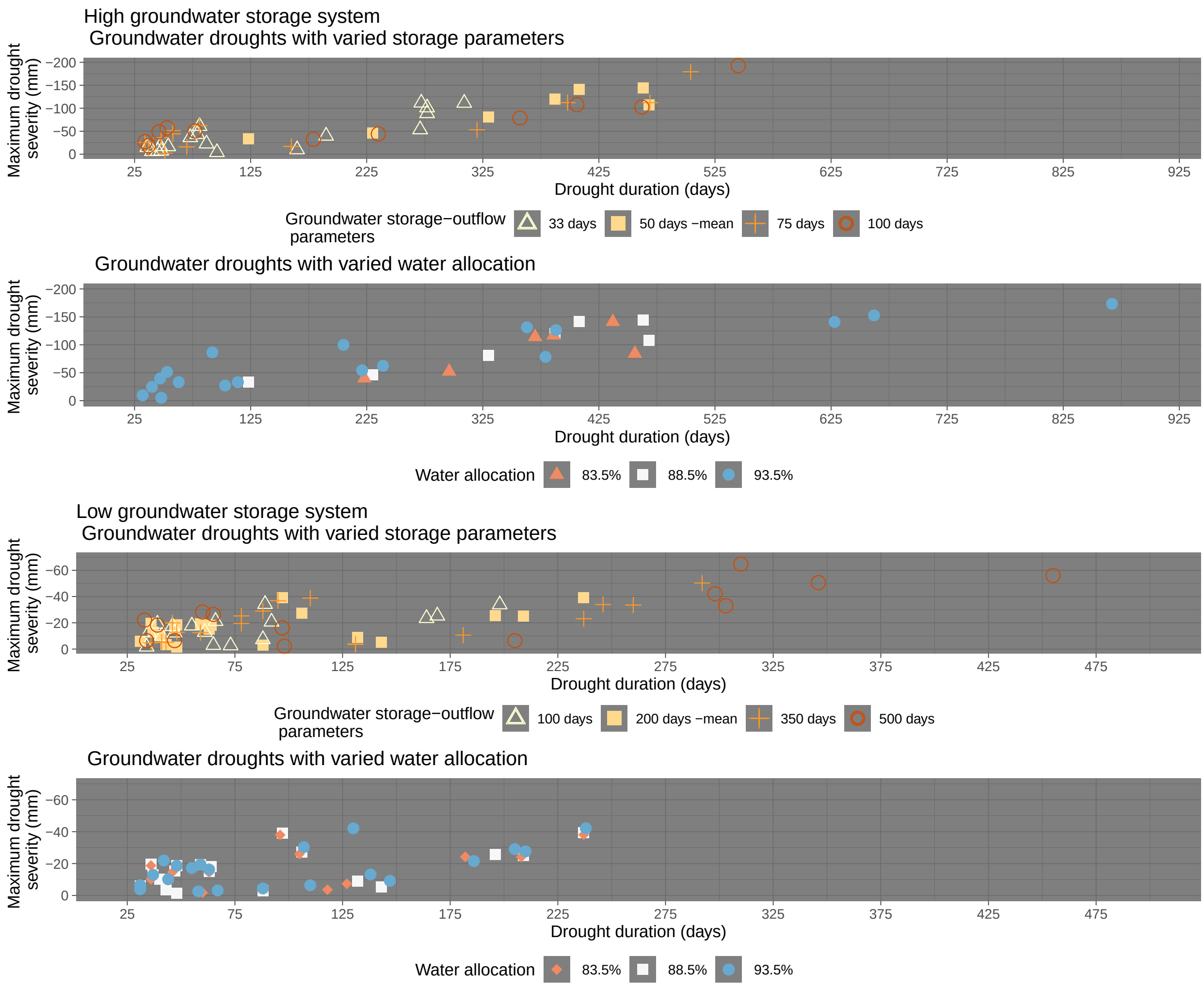


Figure 6.7: Impact of in/decrease modelled storage-outflow parameters and in/decreased water allocation on groundwater drought characteristics (drought duration and maximum intensity). The range and reference for tested groundwater storage-outflow parameters can be found in Table 6.3. The range of documented water allocation of the selected drinking water companies can be found in S19. The first two panels show drought characteristics of the high groundwater storage system. The second two panels represents drought characteristics for the low groundwater storage system. Drought impacts following mean values for storage-outflow parameters and water allocation are shown in squares (all panels).

6.7 Discussion

6.7.1 Model

The impact of drought management strategies on hydrological droughts was investigated using a socio-hydrological model for a range of hydrogeological conditions. Comparing different drought management strategies in a quantitative manner complements qualitative comparisons of previous studies (White et al., 2001; Wilhite et al., 2014; Urquijo et al., 2017). Some of the tested strategies have been assessed separately, as studies focused on either water demand (Low et al., 2015; Maggioni, 2015; Gonzales et al., 2017; Hayden et al., 2019), adaptive water management (Thomas, 2019; White et al., 2019), or conjunctive use combined with managed aquifer recharge to increase drought resilience (Scanlon et al., 2016; Alam et al., 2020). Jaeger et al. (2019) and Dobson et al. (2020) show that combined drought policy interventions mitigated streamflow droughts by altering reservoir storage regulations and transfers. Results in this study also show mitigated baseflow droughts in separately and combined scenarios, but important differences are found between the tested hydrogeological conditions. When integrating both surface water and groundwater storage by applying conjunctive use in a low groundwater storage system, baseflow increases and hydrological droughts reduce. This comes, however, at the cost of additional surface water import that fulfills storage deficits in groundwater. In high groundwater storage systems, restrictive groundwater use during low flow periods showed to be most effective in reducing hydrological droughts, but also comes with additional import of surface water.

The tested hydrogeological conditions show a positive relation between drought duration and groundwater-outflow storage properties confirming earlier studies in natural settings using a virtual model (Van Lanen et al., 2013; Van Loon et al., 2014) and a spatially-distributed model (Carlier et al., 2019). Findings in the sensitivity analysis show that this is true for both high and low storage systems. Hydrological droughts in the high groundwater storage system are longer and have a longer drought recovery. In the low groundwater storage system, mostly short, climate-controlled droughts are observed that was also found by Stoelzle et al. (2015). Both baseflow and groundwater droughts have a short response time and limited lengthening of hydrological droughts even when the pressure on water resources increases. These findings match observations made across English aquifers that are characterised by a low or high groundwater storage (Bloomfield et al., 2013; Bloomfield et al., 2015).

6.7.2 Impact of drought management strategies on hydrological droughts

Out of the four separate drought management strategies conjunctive use is most effective in easing pressure on water resources resulting in reduced hydrological droughts, increased baseflow, and groundwater storage, particularly in the low groundwater storage system. Integrating both water resources has been found invaluable as management strategy with increased drought resilience as ultimate result (Scanlon et al., 2016; Noorduijn et al., 2019; Holley et al., 2016). Conjunctive use does not create water, but optimises storage use, particularly in catchments with large surface water storage (Bredehoeft, 2011). Flexible use of surface water and groundwater aligns the timing problem between water use and availability (Taylor et al., 2013; Cuthbert et al., 2019). It should be noted that conjunctive use could also alter the river regime, resulting in adverse impacts on ecohydrology (Rolls et al., 2012). In the high groundwater storage system, conjunctive use has mixed results as groundwater storage reduces, resulting in frequent, but less intense hydrological droughts. This was also found by Shepley et al. (2009), who found that groundwater levels fell due to increased groundwater use in an English conjunctive use system. Optimising the timing of surface water and groundwater use is key for a successful conjunctive system, although the required flexibility might have practical limitations for water managers (Bredehoeft, 2011). For example, water use licences are often set to a specific water source and re-allocation of water licences can be difficult, which limits implementation of conjunctive use (Holley et al., 2016; Noorduijn et al., 2019). A degree of flexibility can be achieved when water management units are large enough to contain multiple source-specific licences (Shepley et al., 2009; Fowler et al., 2007; Thorne et al., 2003). Current practises show promising results for current and future water use (Fowler et al., 2007), although detailed (water management specific) modelling is required to investigate the potential for specific water management units in England.

Maintaining the ecological minimum flows is also very effective in mitigating droughts, particularly in the high groundwater storage system. This confirms earlier findings focusing on the protection of ecosystems using trigger level regulations (Werner et al., 2011; Noorduijn et al., 2019). Crucial to the success of both is the integration of surface water and groundwater use to maintain low flows (Howarth, 2018). However, results show that impact of hands off flow relies on the defined trigger level (defined ecological minimum flow) and baseflow component. When increasing storage-outflow parameters in the sensitivity analysis and thereby increasing the baseflow component, impact of the hands off flow scenario increases. Defining the ecological flow correctly is key, as protecting the minimum flow might not preserve natural (undisturbed) river flows per se (Howarth, 2018).

Combined drought management strategies show primarily the impact of conjunctive use and hands off flow in both systems. The impact of drought mitigation scenarios 1 and 2 (increased water supply and water conservation) is mostly noticeable during extreme drought conditions when water demand reduces more than groundwater use increases. Water demand reduces with 36% in most extreme drought conditions, which is similar to extreme water reductions realised in Melbourne during the Millenium Drought (Low et al., 2015), but not as low as water restrictions enforced in some parts of Cape Town during the Day Zero crisis (Rodina, 2019; Garcia et al., 2020).

When introducing a permanent increase in water use (+5%), the effect on water resources is evident as hydrological droughts increase disproportionally in duration and additional imported surface water is required to meet the water demand. Reducing the water allocation (-5%) results in shorter hydrological droughts and less water import, but realising a permanent reduction in water demand can come at high costs for both providers and users, and might not always be successful (Low et al., 2015; Gonzales et al., 2017; Muller, 2018; Caball et al., 2019; Simpson et al., 2019). Generating more awareness and reducing water use prior to the actual water shortage might also result in better adaptive management of water resources (Garcia et al., 2016; Noorduijn et al., 2019; Garcia et al., 2020; Thomann et al., 2020), but practical constrains restrict the application of adaptive water management in many regions (Thomann et al., 2020) that are yet to be investigated in England.

6.7.3 Model limitations

Limitations of the model are related to the overall drawbacks of using a lumped and idealised groundwater storage modelling approach. The regionally-averaged model input for both climate time series and water management means that model outcomes are generic and broadly representative for water resource availability in an English setting. Model outcomes would require different climate input data and additional information regarding local water resource and drought management to specify the impact of tested strategies on hydrological droughts in a specific water management region. However, the versatile model setup shows for which tested storage properties drought management strategies are effective. For example, conjunctive use of water resources and combined drought management strategies are effective at reducing hydrological droughts in all systems. This is in contrast to the impact of a hands off flow strategy, which depends on the baseflow component. Crucially, hydrological droughts aggravate when the ecological minimum flow is neglected and groundwater use reduces the environmental flow (Gleeson et al., 2018; Graaf et al., 2019). These crucial sensitivities to different groundwater-outflow parameters show the value of conceptual, idealised socio-hydrological modelling, which outcomes could be used in the discussion regarding the protection of groundwater dependant ecosystems and the status of protected water bodies (Ohdedar, 2017; Howarth, 2018).

Spatially-distributed model structures would have allowed testing of a wider range of drought management strategies, as not all documented strategies can be modelled with a lumped model structure. Out of the listed strategies (Table 6.1), four drought scenarios were tested in this study. Other measures, such as river augmentation, reduction of pressure on the water network, and reuse of urban wastewater could not be modelled and would benefit from a distributed model setup similar to the work of Dobson et al. (2020). A spatially-distributed setup could also enhance teh current analysis, as spatial impact of increased abstractions to the stream could not be included (Gleeson et al., 2018). However, conceptual understanding and impact of drought management strategies can be further explored using a lumped conceptual model, as presented in this study. For example, the current methodology could be improved by applying dynamic water use or increased awareness of water stress that would advance the currently implemented static water use (Garcia et al., 2016). It would also be useful to test the impact of drought management plans with projected groundwater recharge scenarios (Mansour et al., 2018) or benchmark and extreme drought conditions (Stoelzle et al., 2014; Hellwig et al., 2020). Further along these lines could be an application to different climates in order to highlight strengths and weaknesses of drought management strategies impact on hydrological droughts in different climates.

6.8 Conclusion

The presented idealised socio-hydrological model shows the impact of water use and drought management strategies on hydrological droughts. The idealised socio-hydrological model was used to highlight sensitivities to drought management strategies in high and low groundwater storage systems. Three systems were modelled, representing low, medium, and high groundwater storage. Results show different drought characteristics related to the modelled groundwater storage-outflow parameters. In the low groundwater storage system, drought occurred frequently and were mostly climate-driven, although amplified by water use. External water imports were necessary to meet water demand periodically and these were only reduced when managing surface water and groundwater in conjunction. The high groundwater storage system shows larger inter-annual storage resulting in fewer, but more intense hydrological droughts amplified by water use.

Introducing drought management strategies relieved both baseflow and groundwater droughts in nearly all scenarios, mostly in those including conjunctive use and maintaining the ecological minimum flow by restricting groundwater use. Integrating the use of water resources resulted in optimal use of stored surface water and the delayed response of groundwater storage. Hydrological droughts were reduced and sometimes alleviated completely in the low and high groundwater storage systems. These findings encourage further exploration of conjunctive use as a drought mitigation strategy. The impact of restricted groundwater use to maintain ecological minimum flows (hands off flow) depends on the baseflow component. Combined scenario including hands off flow show that hydrological droughts are effectively reduced under a range of storage-outflow parameters and even when increasing pressure on water resources. The considerable pressure on water resources is evident when increased even further, resulting in a disproportional increase in hydrological drought duration and imported surface water. This increase shows delicate the pressure on water resources in the case study's water management.

The novelty of this study is the assessment of the impact of drought management strategies on hydrological droughts. Results show how strategies as conjunctive use and maintaining ecological flows reduce and alleviate hydrological droughts and reduce the dependency on imported water. The low sensitivity of some drought management strategies to different hydrogeological conditions highlights the wide applicability of results and give confidence in the tested separate and combined scenarios. The presented findings encourage further exploration of the implementation of drought management strategies in, for example, other climates or under more extreme droughts. This could advance our understanding of the robustness of current drought management strategies. Further broader extensions could also explore the effect of different timing implemented drought management strategies or in/decrease the severity of implemented strategies. The presented coupled water balance model shows thus the relative impact of drought management strategies given dominant storage characteristics on hydrological droughts and water resources. This relative impact and highlighted sensitivity contributes to a better understanding drought management and could therefore contribute to more sustainable water management.

6.9 Chapter summary

In summary, this chapter presents a developed socio-hydrological model to investigate the impact of drought management strategies on hydrological droughts. Using a lumped idealised socio-hydrological model, water use of both surface and groundwater was simulated in three different hydrogeological conditions. Different scenarios were designed to represent the regionally-averaged drought management plans, and investigate their relative impact compared to baseline conditions for the three hydrogeological conditions. Results show that drought management strategies are sensitive to primary groundwater storage properties and overall water allocation. Integrating surface water and groundwater use was found particularly effective in reducing and alleviating hydrological droughts in low groundwater storage systems. In high groundwater storage systems, restricting groundwater use was found more effective to maintain environmental flows and thereby reduce and alleviate hydrological droughts. Both separate and combined drought management strategies show a considerable proportion of imported surface water that is necessary to sustain surface water demand. The use of external water (imported in the model) increases when the water allocation increases, showing the considerable pressure on water resources with disproportional consequences for hydrological droughts. Even though the idealised conceptual model is limited in its representation of water management regions, model outcomes indicate important sensitivities of drought management strategies to hydrogeological conditions. The impact of modelled drought management strategies on hydrological droughts shows the potential to reduce and alleviate hydrological droughts, although this may be associated with an increased import of water to meet the water demand. Further recommendations on the modelling and possible future applications are provided in Chapter 7, in which all result chapters are concluded.

Chapter Seven

Conclusions and outlook

The main aim of this thesis was to advance knowledge on hydrological droughts, and particularly groundwater droughts in human-modified environments. Each presented results chapter contributed to advancing knowledge of a specific aspect of human-influence showing how the impact of human-influence on hydrological drought characteristics. These different aspects corresponded to the three research objectives addressing the impact of groundwater use, enhanced recharge, and drought policies on baseflow and groundwater droughts (Figure 1.1). The purpose of this chapter is to show how these result chapters address the research objectives and finally, to give recommendations for further research to build on presented findings of this thesis.

7.1 Research objective 1: impact of groundwater use on groundwater droughts

The first research objective was addressed by the regional groundwater drought analysis in the UK case study presented in Chapter 3. The presented framework compared potentially influenced groundwater level observations to near-natural (or uninfluenced) observations and from this comparison, it was found that drought characteristics of influenced sites differed significantly from those of near-natural sites indicating the impact of groundwater use on groundwater droughts, confirming the earlier regional drought studies in human-modified settings (Lorenzo-Lacruz et al., 2017; Lee et al., 2018). In the result chapter, two main drought responses were identified that were summarised in a more general, asymmetric, drought response typology in which drought response was related to the long-term balance between groundwater recharge and abstraction. It was found that when groundwater abstraction is less than long-term groundwater recharge, drought duration and intensity decreases, but drought frequency increases. The opposite patterns was identified when groundwater abstractions approached long-term recharge with lengthened droughts that occur less frequently as a result. These observations were confirmed by drought reports that found an increase and aggravation of groundwater deficits as a consequence of the increased groundwater use (Walker et al., 1998; Marsh et al., 2013; Rey et al., 2017; Rio et al., 2018). However, the presented research is the first in identifying this asymmetric impact of groundwater use that had only been hypothesised by Gleeson et al. (2020). The more extreme case that is included in the typology but not observed in the UK, shows the impact of a long-term negative balance resulting in severe groundwater droughts and a long-term decline of groundwater level. This is observed in many heavily-stressed and depleted aquifers, and regional models confirm this overall pattern resulting from groundwater use (Konikow, 2011; Rateb et al., 2020). In conclusion, the first research objective was addressed by Chapter 3 presenting framework to analyse groundwater droughts and summarising characteristic drought responses in a general typology that related asymmetric impact of groundwater use on groundwater droughts to the long-term balance between groundwater recharge and abstraction.

7.2 Research objective 2: impact of enhanced groundwater recharge on groundwater droughts

The second research objective was met by the initial exploration of long-term impact of Managed Aquifer Recharge (MAR) on groundwater storage (Chapter 4) and the follow-up study focusing on groundwater trends and droughts highlighting the potential of MAR as drought mitigation strategy (Chapter 5). Chapter 4 presented an application of the framework developed in Chapter 3 to the Californian case study investigating long-term impact of enhanced recharge. Even though this chapter did not focus specifically on groundwater droughts, findings showed an increase in long-term groundwater storage that pointed out the positive impact of enhanced recharge on largely deprived groundwater storage levels. The positive impact is remarkable as Tulare is classified as a heavily-stressed aquifer section (DWR, 2016), in which modelled and remotely-sensed groundwater storage show an overall negative trend (Faunt et al., 2009; Famiglietti et al., 2011; Brush et al., 2013). Further investigations in Chapter 5 related these long-term impacts of enhanced recharge to groundwater trends and groundwater droughts. In other words, both chapters assessed the impact of enhanced groundwater recharge, finding that groundwater drought duration and severity reduced in regions where long-term MAR is present. Actively recharging the aquifer has thus regional impacts on groundwater storage and regional groundwater drought characteristics showing shorter, less intense and even alleviated groundwater droughts despite an extreme meteorological drought. Long-term cumulative impact of enhanced recharge resulted in positive groundwater trends despite long-term negative precipitation trends and extensive groundwater use. The long-term accumulation of storage was also noted in a water balance approach of Xiao et al. (2017) and found by Thomas (2019), who concluded that groundwater use in this region was more sustainable compared to other sections in the Southern Central Valley. Even though these mitigated groundwater droughts demonstrate the positive impact of enhanced recharge in a heavily-stressed aquifer, other studies highlight the importance of careful implementation of MAR and risk-based guidance (Dillon et al., 2019; Dillon et al., 2020) that ensures the longevity of MAR facilities and thereby its success as a drought mitigation strategy. In conclusion, the impact of enhanced groundwater recharge was assessed by a case study in California showing the significant positive impact of actively recharging of the aquifer on reducing and alleviating groundwater droughts, proving the suitability of MAR as a drought mitigation strategy.

7.3 Research objective 3: impact of drought policies on hydrological droughts

The third research objective was addressed by the socio-hydrological model scenarios in Chapter 6 that showed the impact of drought policies on hydrological droughts. The idealised socio-hydrological model represented a water balance model (storing both surface water and groundwater) based on the previous work of Van Lanen et al. (2013). This model was used to meet environmental and anthropogenic water demand, adding the water use component to the existing model. Water demand was met by surface water (from a surface water reservoir) and groundwater storage modelled for a range of different hydrogeological conditions. Documented drought management strategies were tested separately and combined in designed scenarios that changed water demand and water supply resulting in altered baseflow and groundwater drought response. Scenarios show that hydrological droughts can be reduced and alleviated using a combination of drought management strategies depending on dominant hydrogeological conditions. For example, conjunctive use is highly effective in alleviating hydrological droughts in low groundwater storage systems, confirming findings of Bredehoeft (2011). In high groundwater storage systems, restricted use of groundwater to maintain low flows is most effective in reducing and alleviating hydrological droughts, as was modelled by Graaf et al. (2019). Both drought management strategies have a large impact on hydrological droughts, but their impact is sensitive to the low or high groundwater storage (and baseflow) component. Drought management strategies that reduce water demand and increase in water supply based on the drought severity were found insensitive to hydrogeological conditions, although these strategies are most effective in reducing hydrological droughts when applied simultaneously. Changing the overall proportion of water used relative to the available water resulted in the largest impact on hydrological droughts indicating the considerable pressure on water resources. In conclusion, the third research objective focusing on the impact of drought policies on hydrological droughts was assessed using a socio-hydrological model that highlighted strengths and weaknesses of drought management strategies given dominant hydrogeological conditions and the overall pressure on water resources.

7.4 Overall conclusions

The presented four result chapters showed the three aspects of human-influence on hydrological droughts, particularly groundwater droughts, and thereby advanced hydrological drought research set in human-modified environments. In all chapters, the long-term balance between groundwater storage and water use was an important component for understanding the human-influence on hydrological droughts. For example, Chapter 3 showed how this long-term balance determines the asymmetric drought response to groundwater use. In Chapter 4 and 5, it was shown how regional groundwater droughts were reduced and alleviated thanks to the considerable volume of imported surface water, actively recharged in the aquifer, altered regional drought response and the relative pressure on groundwater storage. In Chapter 6, different management strategies altered the balance between groundwater storage and groundwater use and thereby affecting hydrological droughts. However, the largest impact was seen when the overall water allocation was in/decreased that directly changes the long-term balance of water use and groundwater storage resulting in a disproportional drought response. In sum, the four result chapters revealed how the long-term balance between groundwater storage and groundwater use is important to improve our understanding of human-influence on hydrological droughts.

The presented analyses also showed how short-term measures impact this long-term balance. In Chapter 3, short-term increases in water use resulted in more frequent drought events, observed in mainly (not exclusively) influenced groundwater monitoring sites. This could be explained by the expansion of groundwater abstractions across the basin since 2000 as part of implementing Water Framework Directive guidelines (Ohdedar, 2017; Howarth, 2018), but more in research would be required to confirm this. On the other hand, the large-scale reductions in water use since 2000 coincided with less severe groundwater droughts, a pattern that could be similar to the observed revived groundwater levels in India (Bhanja et al., 2017), although (again) more research is required to confirm the role of water use restrictions given the episodic nature of droughts. In Chapter 4 and 5, both short-term and long-term impact of enhanced recharge were identified. The sudden rise in groundwater levels was identified in the cluster analysis (Chapter 4). In Chapter 5, shortened droughts and a quicker recovery of deficits in groundwater was found in sites in vicinity of MAR facilities thanks to the short-term MAR impact. Thomas (2019) relates this pattern to an increase in sustainable groundwater management, although MAR in the Central Valley would be need to scale up significantly to realise sustainable groundwater use in other sections of the aquifer (Kocis et al., 2017; Alam et al., 2020). In Chapter 6, drought management scenarios introduced short-term changes to the balance between groundwater storage and groundwater use resulting in alleviated droughts when the pressure on groundwater sources was eased (and complemented by imported surface water). It may be questioned if this is a sustainable solution, although recent water resource modelling shows that (increased) flexibility will result in increased resilience on the short-term (Dobson et al., 2020). The import of surface water was particularly crucial in the low groundwater storage system. In the high groundwater storage system, the timing of water use was key to alleviate droughts, as restricting groundwater use temporarily to preserve environmental flow requirements alleviated hydrological droughts effectively without reducing the proportion of groundwater use and surface water use. This adaptive water management seems promising for future drought mitigation strategies, confirming the work of Thomann et al. (2020), although practical constrains, costs and benefits to increasing flexibility in water supply, and consequences for water consumers would have to be considered to make more firm conclusions. Overall, the three assessed aspects of human-influence on hydrological droughts have increased our understanding of human-influence and findings highlight the importance of the long-term water balance between water use and water storage, the crucial timing of water use, and alignment of short-term and long-term mitigation strategies to manage and alleviate human-influence on hydrological droughts.

7.5 Outlook

Since this is one of the first studies focusing on primarily groundwater droughts in human-modified environments, the developed methodology and presented findings point towards a number of possible directions for future research. Firstly, the developed framework could be improved by a more advanced clustering technique based on features in time series instead of the whole standardised time series (Haaf et al., 2018; Heudorfer et al., 2019). That could potentially group groundwater monitoring sites more effectively and isolate or even extract features related to human influence (either groundwater use or enhanced recharge). Extracting these groundwater signatures could perhaps also facilitate early detection of human-influence and possibly prediction of consequences of in/decreased groundwater use (Haaf et al., 2020).

When applying the method to regions with enhanced recharge, it might be possible to extract short-term MAR signatures, as it is already possible to detect functional enhanced recharge sites with groundwater observations only. Advancing this field sheds new light on the global growth of largely unmonitored managed aquifer recharge facilities (Dillon et al., 2019). Because by detecting and identifying these facilities in, for example, regions in India (Tushaar, 2009) or Europe (Sprenger et al., 2017), regional impact of enhanced recharge can be mapped and further expanded.

Alternative, analytical methods to improve the developed framework could also address the dynamic component in human influence. For example, if additional abstraction data were available, it might be possible to extend the developed methodology to an attribution study similar to Viglione et al. (2016). With the abstraction records, it would also be possible to identify sudden changes in groundwater use, e.g. due to a new water law, and relate changes in water use to groundwater level observations using a frequency time series analysis (Bhanja et al., 2017; Dountcheva et al., 2020). However, future analytical analysis should also include recent advancement on tele-connections and climate change signatures in groundwater level time series (Rust et al., 2019; Bloomfield et al., 2019) (in the UK specifically), as long-term weather patterns also reflect in multi-year variations in groundwater level time series that should not be confused with human-influence (Dountcheva et al., 2020). Obtaining abstraction data can be difficult. In the Californian case study, it is unlikely given current water rights to gather more information about groundwater use. However, this might changes with further implementation of SGMA (Thomas, 2019) for which groundwater use needs to be monitored. This would create possibilities to advance the current investigation and attribute hydrological droughts to both groundwater use and enhanced recharge.

Building further on presented result chapters, some research outcomes could be included in ongoing modelling studies. For example, the identified asymmetric impact of groundwater use in the UK case study could be included in large-scale (national or aquifer level) water resource or groundwater models (Lewis et al., 2018; Coxon et al., 2019; Dobson et al., 2020). Additionally, it would be interesting to investigate the impact of dynamic water use in these large-scale models, as many models are developed using either current or historic groundwater abstractions (Shepley et al., 2012). This large-scale modelling could also further the socio-hydrological approach and implement more drought management scenarios, as some mitigation strategies could not be included due to the model setup in Chapter 6. The spatially-distributed structure of models, such as presented in Dobson et al. (2020), could extent the simplified drought management scenarios. However, furthering the socio-hydrological modelling would also require a different setup for the groundwater module, as currently groundwater is represented using an empirical groundwater model (Dobson et al., 2020). For example, different groundwater storage-outflow parameters could be included to integrate both models and include drought policies on a national scale. This would require a significant effort, but results could contribute to long-term water resource planning by including groundwater availability, integrated water use, and the asymmetric impact of groundwater use on hydrological droughts.

Given the extensive modelling in the Central Valley in California, it would be extremely valuable to include the impact of enhanced recharge, as found in Chapter 4 and 5, in existing (distributed) modelling studies (Faunt et al., 2009; Brush et al., 2013; Maxwell et al., 2016). New potential MAR locations could be explored further including FLOOD-MAR for suitable areas (O'Geen et al., 2015; Dahlke et al., 2018b). Ideally, this effort would also integrate newly developed tools to guide decision making for installing MAR facilities (Sallwey et al., 2019; Marechal et al., 2020) and options for financial support for new MAR facilities (Rohde et al., 2014). Encouraging further applications in California and other parts of the USA would, however, benefit from risk-based MAR guidelines as recently updated in Australia to ensure good practice of MAR (Dillon et al., 2020).

The developed socio-hydrological model in Chapter 6 could also in itself be continued for further research, as conceptual modelling can advance our understanding of the impact of drought policies on hydrological droughts. For example, further conceptual modelling could include benchmark droughts (Durant, 2015; Barker et al., 2019) or extreme recharge scenarios (Stoelzle et al., 2014; Mansour et al., 2018; Hellwig et al., 2020) to test additional strain on drought management scenarios. Furthering this approach could include future climate scenarios that would be extremely relevant to future water resource planning (Prudhomme et al., 2014; Wanders et al., 2015; Cuthbert et al., 2019; Hari et al., 2020). Alternatively, given the relatively simple input for drought management strategies, the application can be much improved and set in a wider context. MAR could for example be included, if the model is spatially-distributed and information on available water, hydrogeological setting and institutional support is available (Sprenger et al., 2017). Alternative modelling applications could also focus on pan-European drought management strategies furthering the drought policy studies of Urquijo et al. (2017) and Özerol (2019). The combination of modelling pan-European drought management strategies and future or benchmark droughts could advance both regional and large-scale water management across Europe and advance our understanding of human-modified droughts to align short-term water management goals with long-term sustainability.

7.6 Final remarks

This thesis aimed to advance our understanding of hydrological droughts, particularly groundwater droughts, in a human-modified context. Main findings of the thesis include the two developed methodologies that were applied to different case studies and three different aspects of human influence on groundwater droughts. In general, results showed that the overall long-term balance of groundwater storage and groundwater use was key to estimate the impact on groundwater droughts. It was found that short-term measures can alter this long-term balance, because active water resource management resulted in either exacerbation or alleviation of groundwater droughts. Results also highlighted that this balance of groundwater storage and groundwater use is delicate, stressing the need for careful management to encourage sustainable groundwater use. In summary, the identified modifying aspect of water resource management and its significant impact on groundwater droughts is both terrifying and encouraging. Presented findings can be used to further sustainable groundwater use or continue groundwater exploitation and perturb natural droughts.

The choice is ours.

Supplementary material

S1: Location and purpose of groundwater abstraction wells in the four water management units in the UK

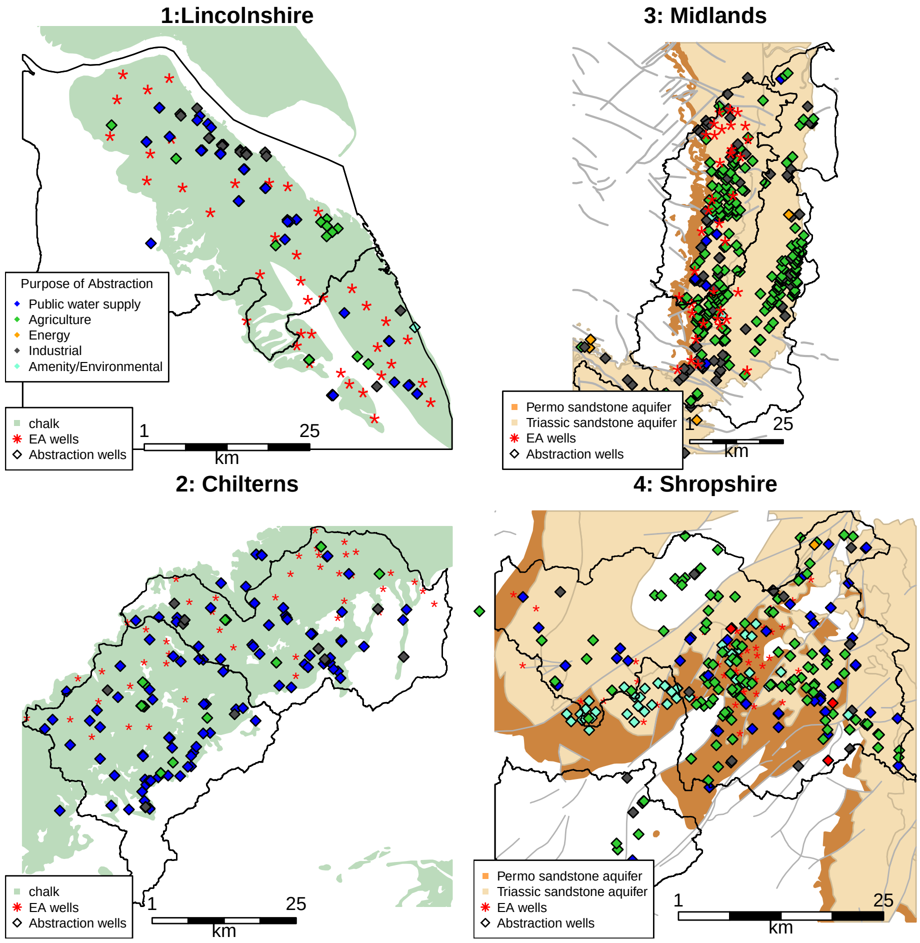


Figure S1: The location and purpose of groundwater abstraction wells in the four water management units. The coloured diamonds indicate locations of abstraction wells and the colours represent the purpose of a provided abstraction licence. Please note that some wells overlap.

S2: Example of near-natural, uninfluenced and influenced sites in Lincolnshire

S2 shows an illustrated example of four sites that include a documented near-natural site (first panel), and three groundwater monitoring sites in the paired water management unit. The reference groundwater site (Aylesbury) is an Index well of the Hydrologic Register and is representing near-natural conditions. This Index well is included in the reference cluster for Lincolnshire water management unit (see Figure 3.2). For this reference cluster the lowest SPI_Q-SGI correlation is 0.75, hence monitoring sites with a similar or higher correlation are considered relatively uninfluenced over the 30-year time period. The monitoring site in the second panel is thus considered uninfluenced, as the SPI_Q-SGI correlation is 0.831 using the site-specific optimal precipitation accumulation period (17 months). The other two sites are considered to be influenced, as correlations are lower than the lowest correlation of the reference cluster: 0.561 and 0.566 (third and fourth panel respectively). The SGI of both wells is remarkably different (flashier) compared to the first two SGI time series, but more importantly despite different precipitation accumulation periods SGI variation don't synchronise well with either short-term or long-term SPI_Q (dotted blue line in Figure S2).

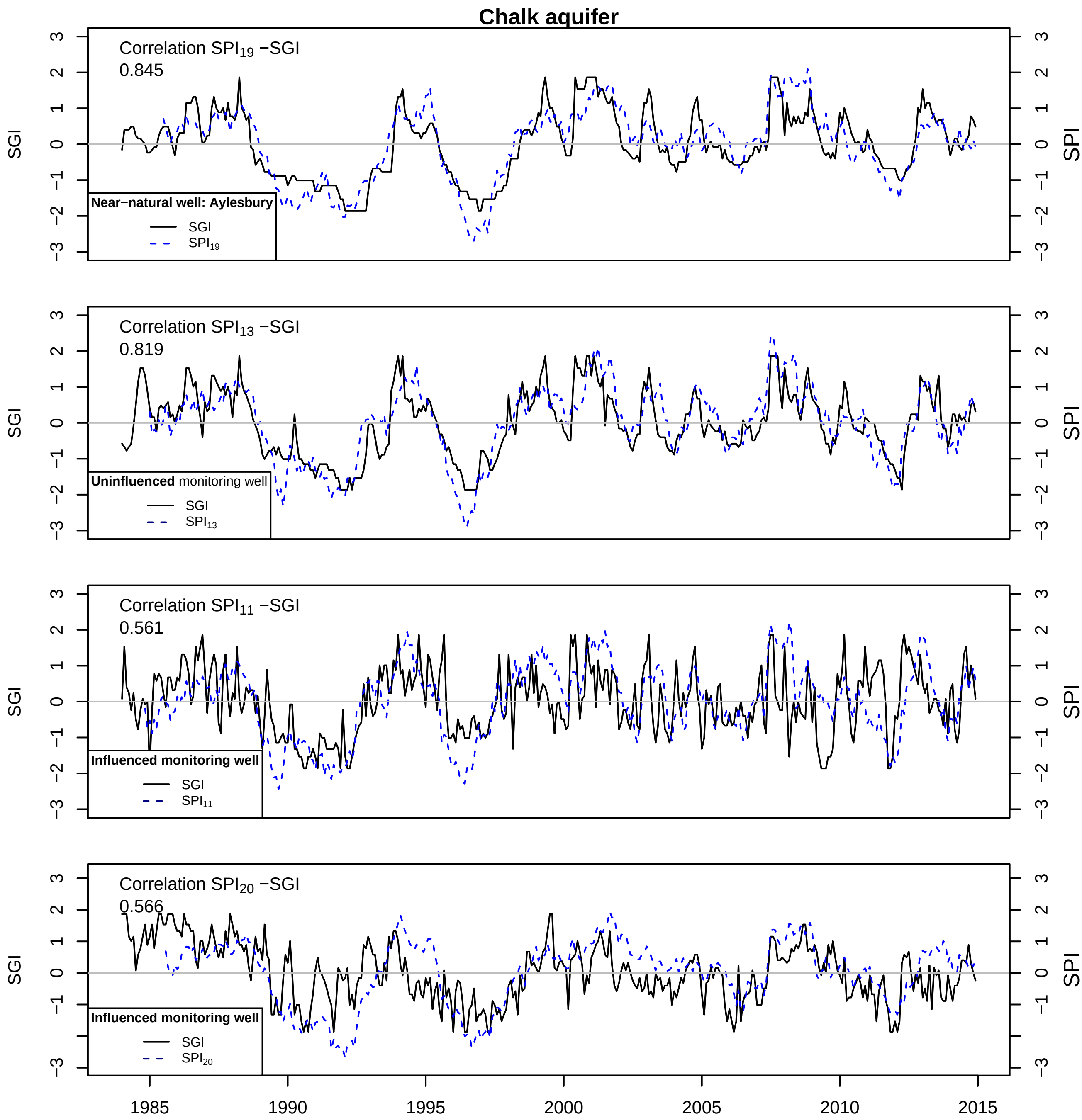


Figure S2: SPI_Q-SGI comparison for a near-natural Index site (top panel), an uninfluenced monitoring site (second panel), and two influenced monitoring sites in Lincolnshire (third and fourth panel). The SGI and SPIQ are shown in black and blue (dashed). The correlation between the SPI_Q-SGI is shown in the top left corner of the hydrograph.

S3: Cluster composition of three clustering techniques applied to near-natural standardised time series

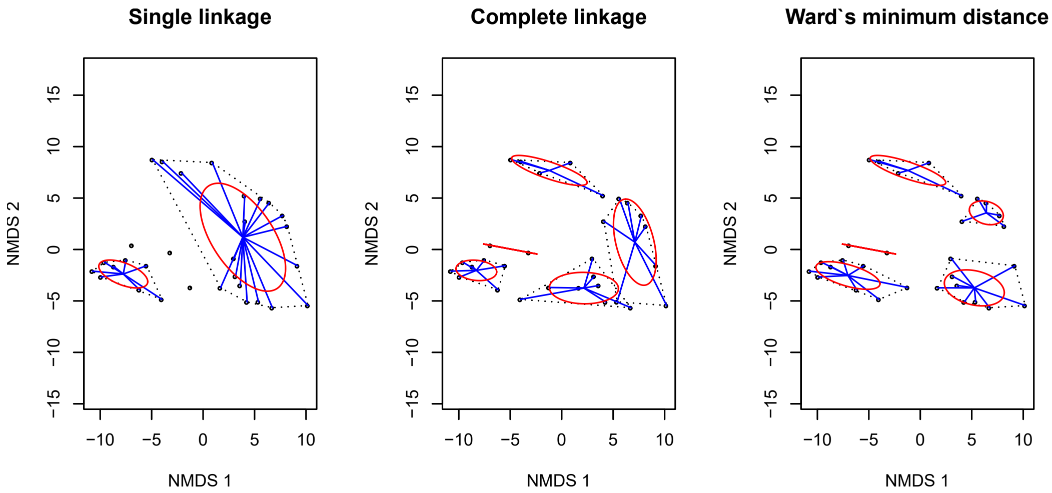


Figure S3: Cluster composition of three clustering techniques (single linkage, complete linkage, and Ward's minimum) shown for the five Chalk clusters using the matrix non-metric multidimensional scaling plot (NMDS) of the vegan package (Dixon, 2003). The clusters in Ward's minimum technique show the least overlap and are therefore selected in further analysis.

S4: Accumulation period of monitoring wells in the four water management units in the UK

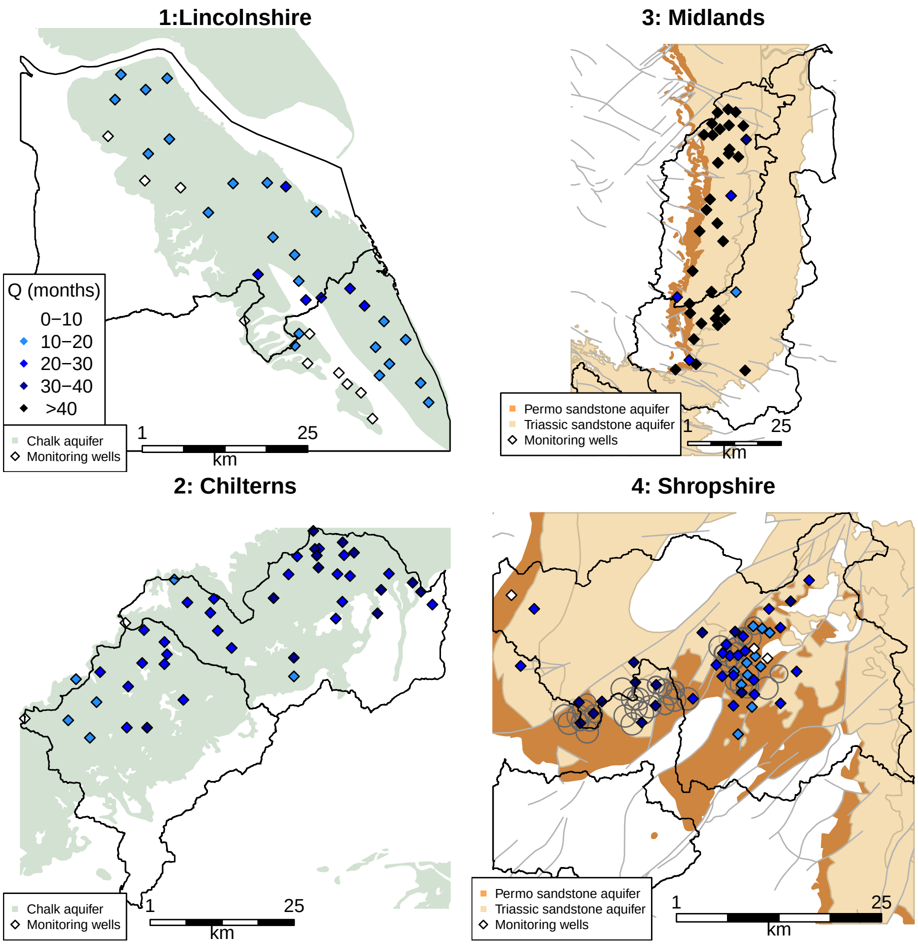


Figure S4: Accumulation period (in months) for monitoring wells in the four water management units.

S5: Distributions of recorded drought frequency of all four water management units for categorised influenced and uninfluenced sites.

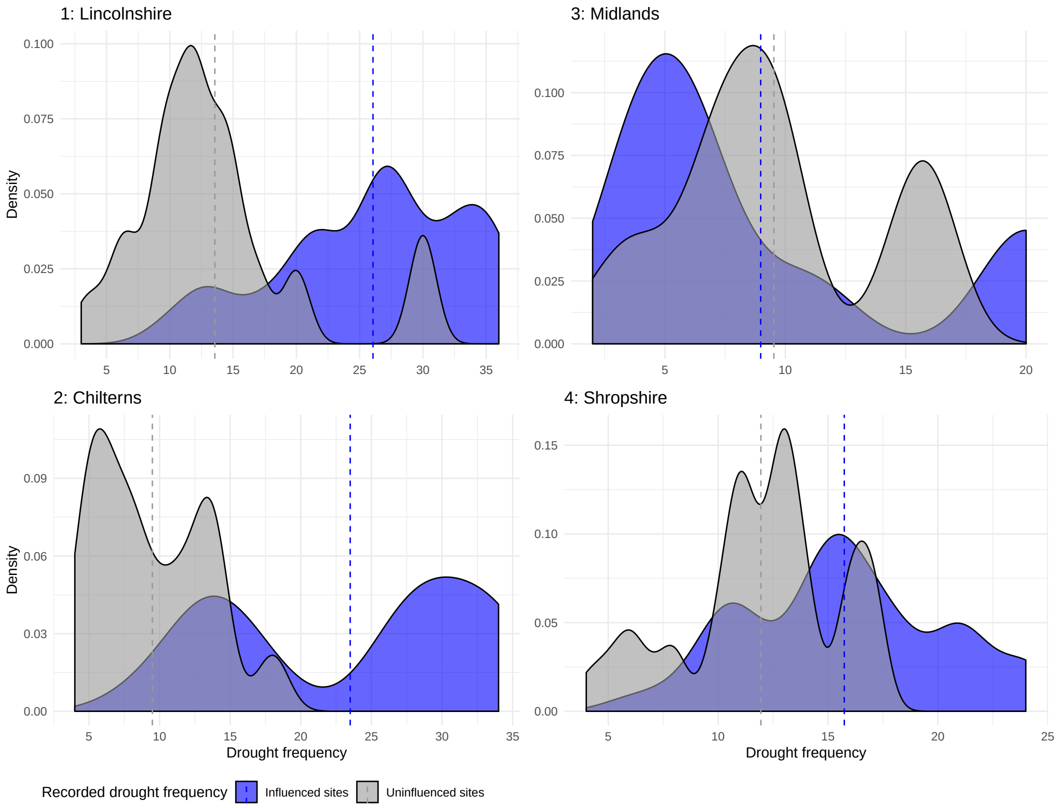


Figure S5: Drought frequency distribution of the four water management units for uninfluenced sites (grey) and influenced (blue). The mean drought frequency is indicated with the dotted vertical line (also in Table 2 in the manuscript).

S6: Distributions of recorded drought duration of all four water management units for categorised influenced and uninfluenced sites.

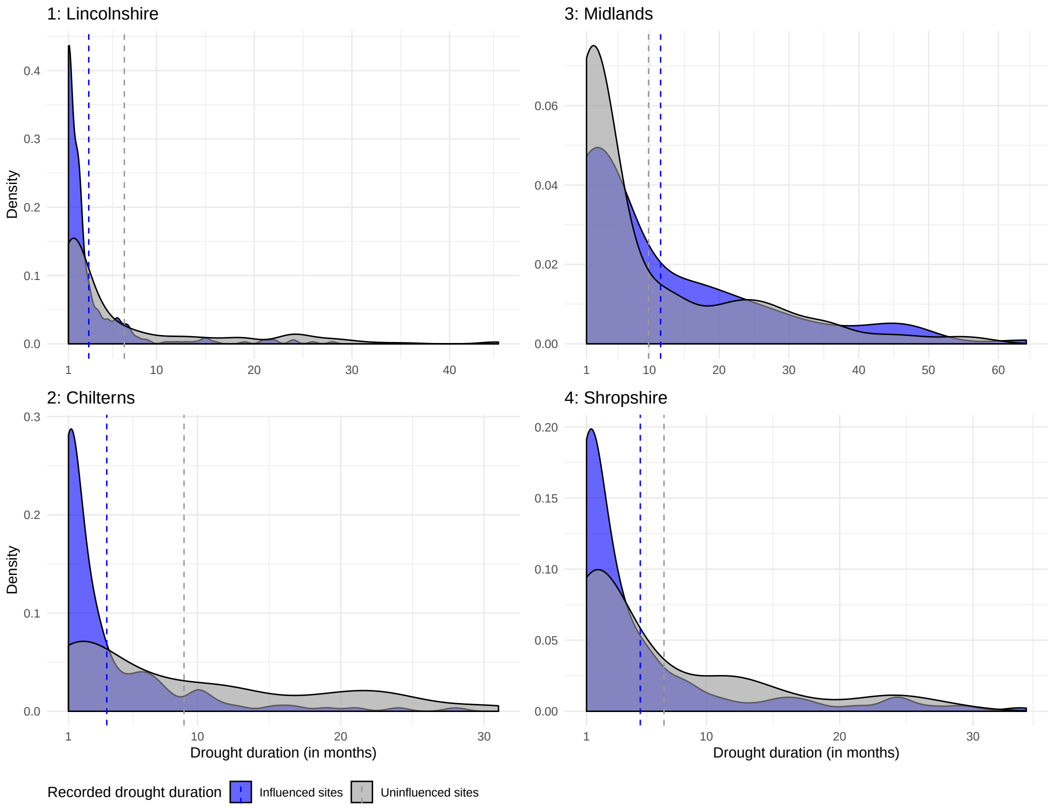


Figure S6: Drought duration distribution of the four water management units for uninfluenced sites (grey) and influenced (blue). The mean drought duration is indicated with the dotted vertical line (also in Table 2 in the manuscript).

S7: Distributions of recorded drought deficit of all four water management units for categorised influenced and uninfluenced sites.

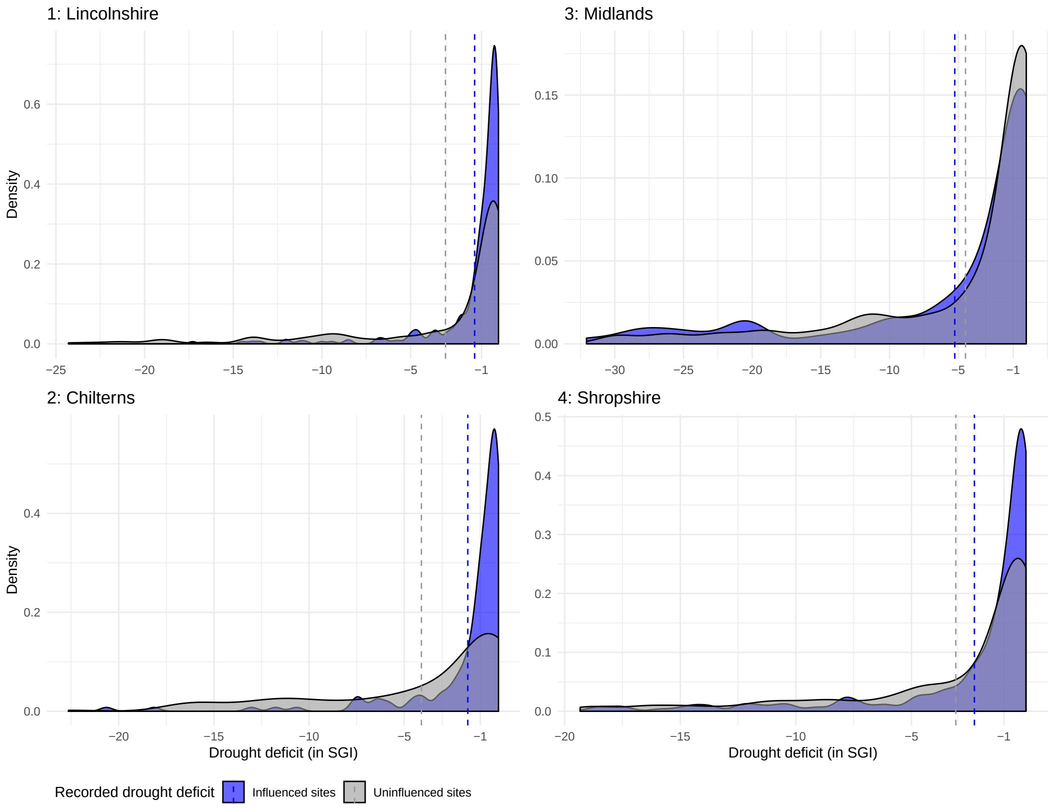


Figure S7: Drought deficit distribution of the four water management units for uninfluenced sites (grey) and influenced (blue). The mean drought deficit is indicated with the dotted vertical line (also in Table 2 in the manuscript).

S8: Main water users in England

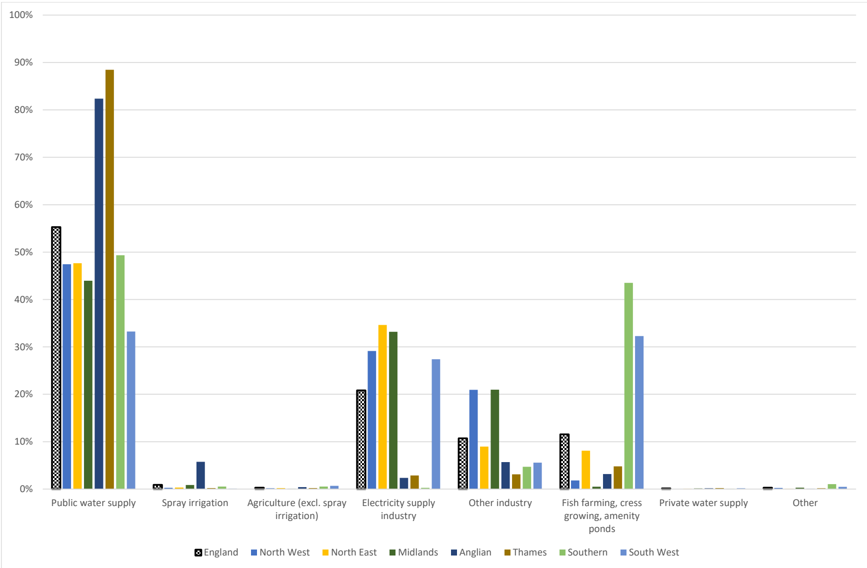


Figure S8: Regionally-averaged water users in England (dotted black and white bar) by allocated surface water and groundwater licences (data from 2000-2015; Environment Agency). Regional water use is shown in coloured bars. Data can be found in Environment Agency - Abstraction tables 2020.

S9: Inter-annual variation in modelled soil moisture balance

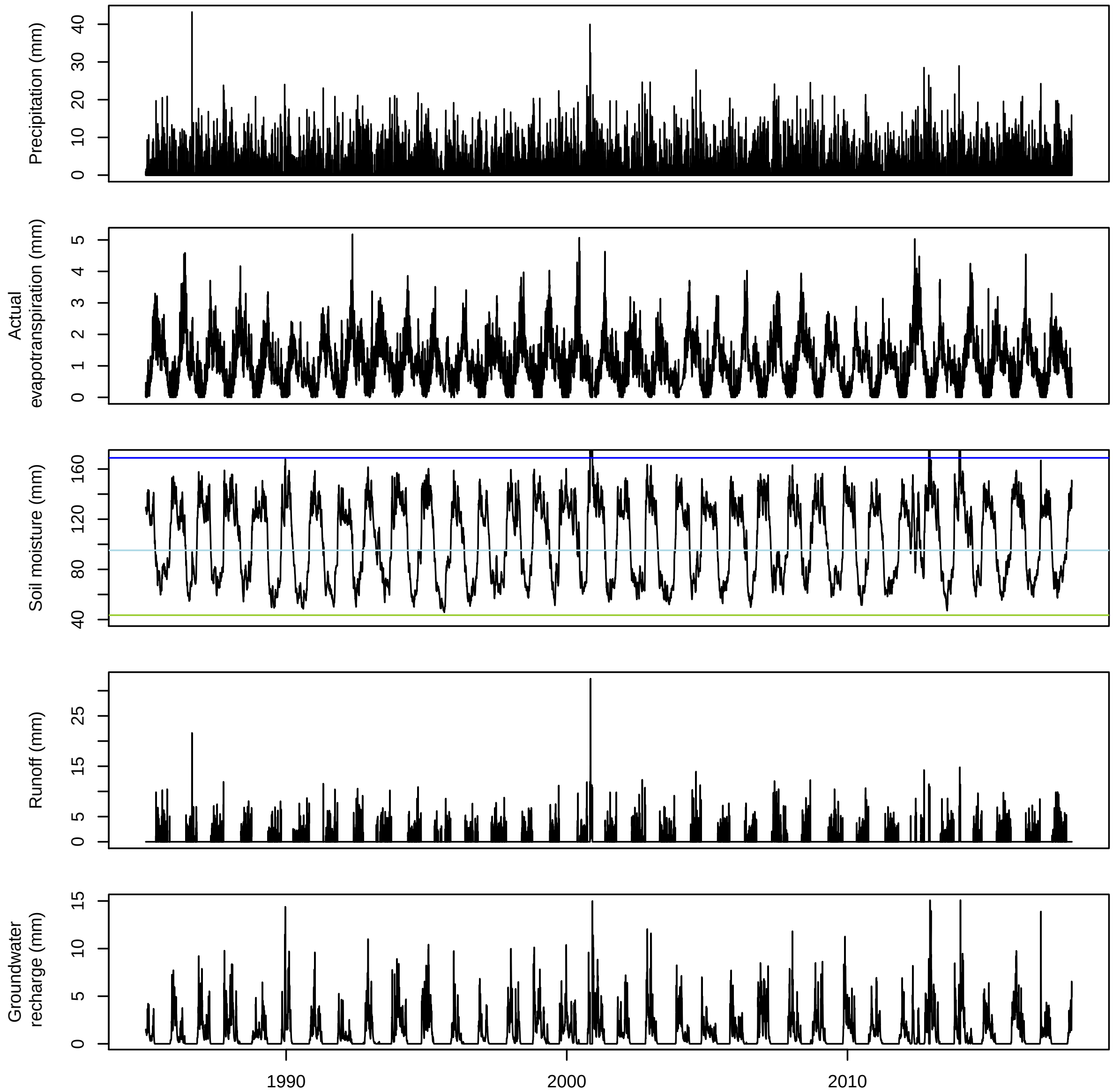


Figure S9: Inter-annual variation of the soil moisture balance in the socio-hydrological model. The five panels show long-term time series of precipitation actual evapotranspiration, soil moisture, runoff, and groundwater recharge (all in mm). The first 5 years are part of the spin-off period, the remainder (1985-2017) are used in the analysis.

S10: Natural and human-modified groundwater storage level variation

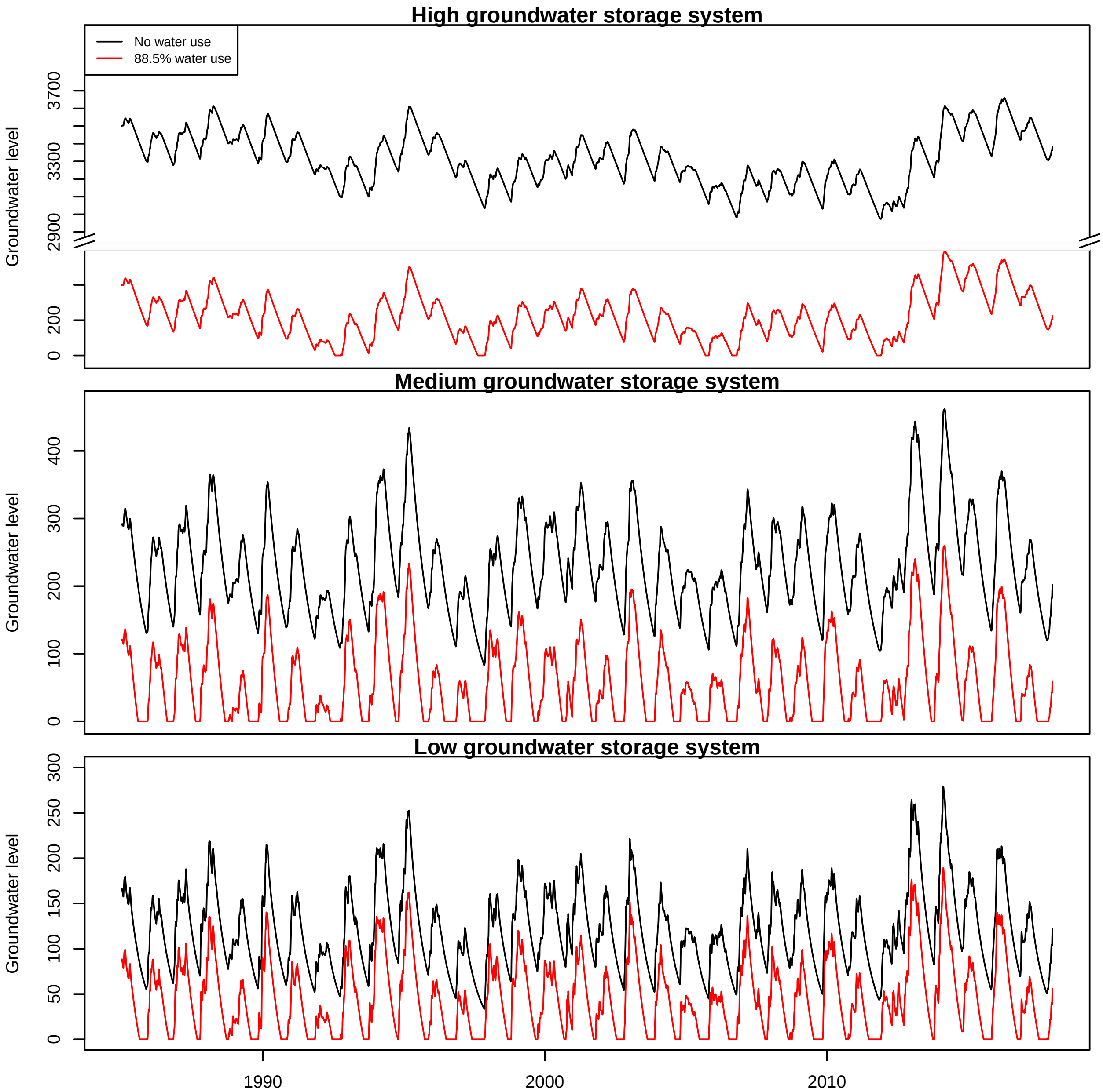


Figure S10: Natural and human-influenced conditions of groundwater storage levels in time (1985-2017). The three panels show the high, medium, and low groundwater storage systems. Note that y-axis are different due to the large variation in groundwater storage for each system.

S11: Test with alternative proportional use of surface water and groundwater demand

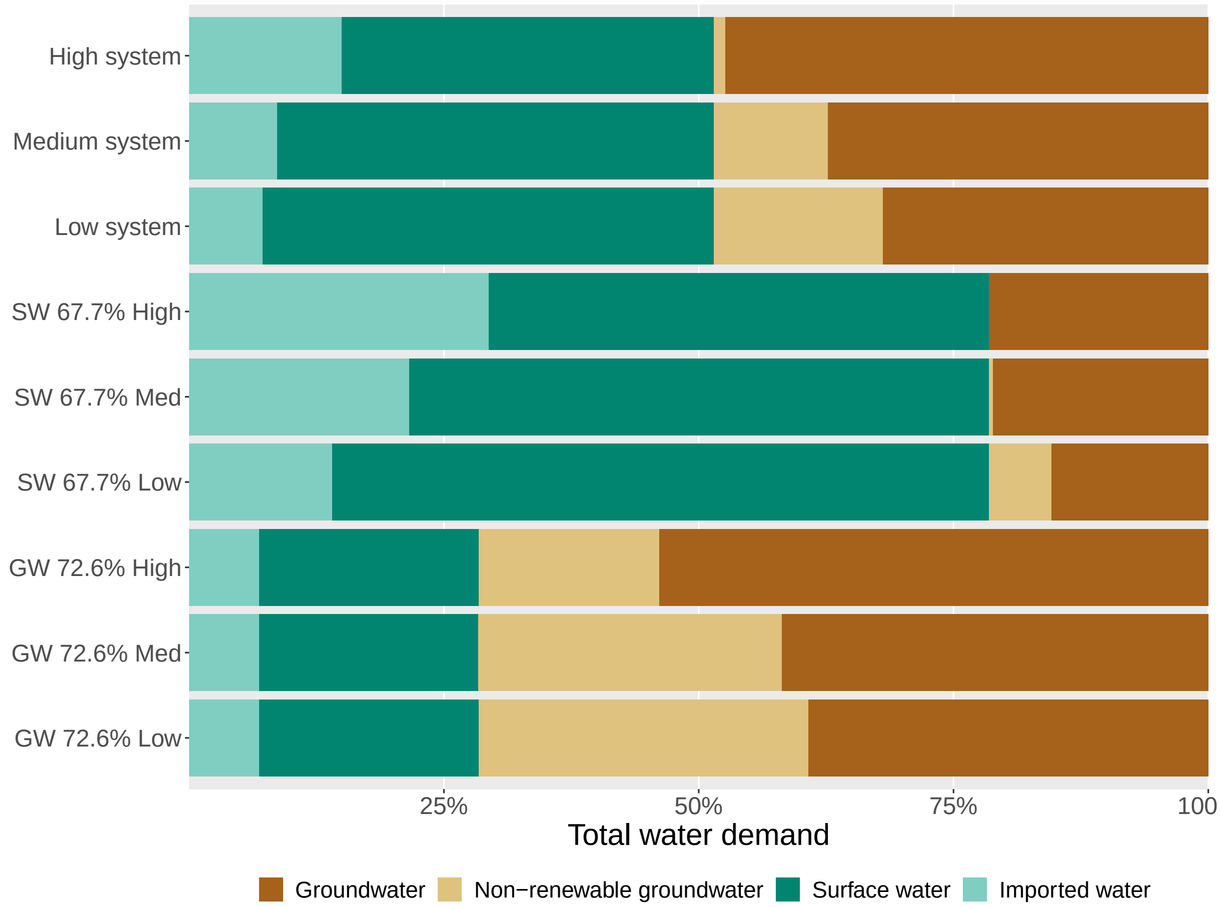


Figure S11: Total water demand for the three groundwater systems for alternative proportional surface water and groundwater use in the baseline. Baseline water use is shown in the top three rows with surface water demand (44.6%), groundwater demand (48.5%) and imported surface water (6.9%). This amount of imported water remains constant, but increases when additional surface water is required (rows 1 & 2 and 4-6). Rows 4-6 show the tested increased surface water demand (SW 67.7%) and increased groundwater (GW 72.6%) use in rows 7-9.

S12: Surface water storage with combined 1-2-4 scenario in the high and low groundwater storage system

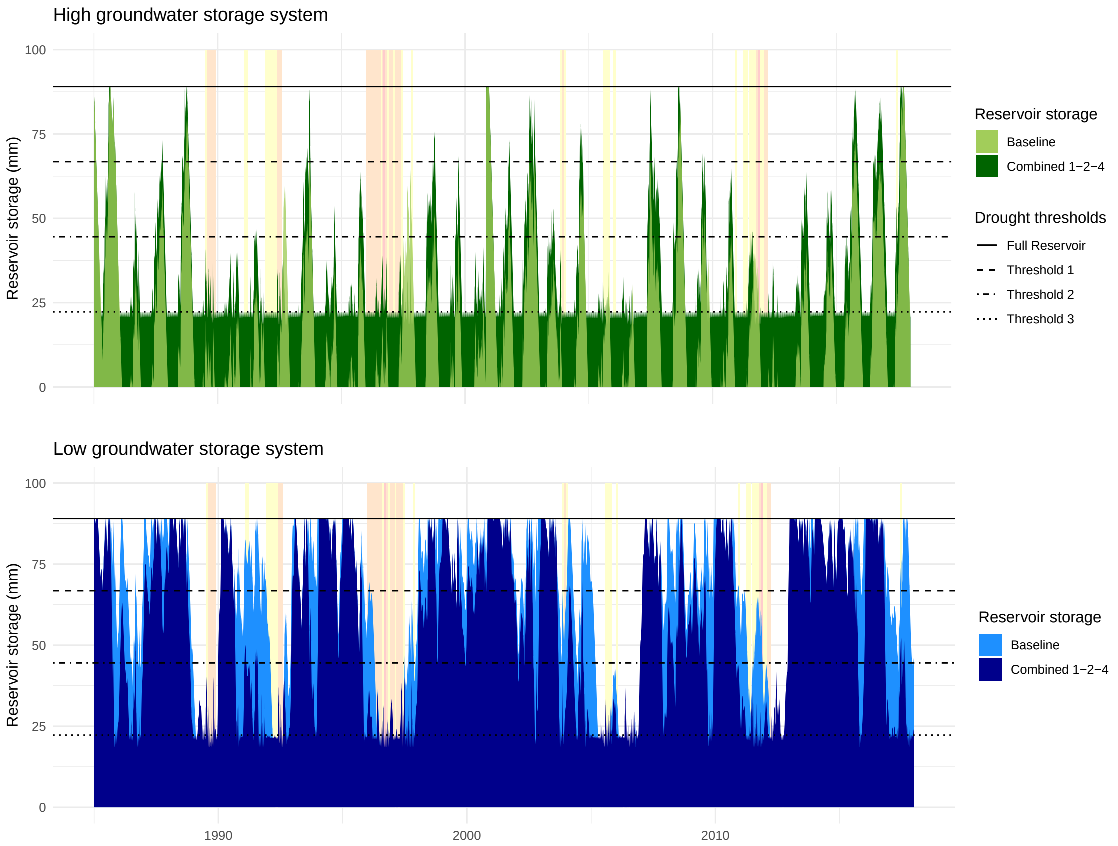


Figure S12: Surface reservoir storage in baseline scenario (no drought measures applied) for high groundwater storage catchment (first panel, in light green) and low groundwater storage catchment (second panel, in light blue). Darker green and blue colours indicate the difference in surface water storage as the reservoir is fuller/emptier. Coloured surfaces indicate below-normal periods in precipitation (measured in SPI) following Figure 6.3. Drought thresholds for the surface water reservoir follow the documented range for trigger levels (see Table 6.1 and section 2.1 Data).

S13: Baseline conditions for groundwater storage under a range of storage-outflow parameters

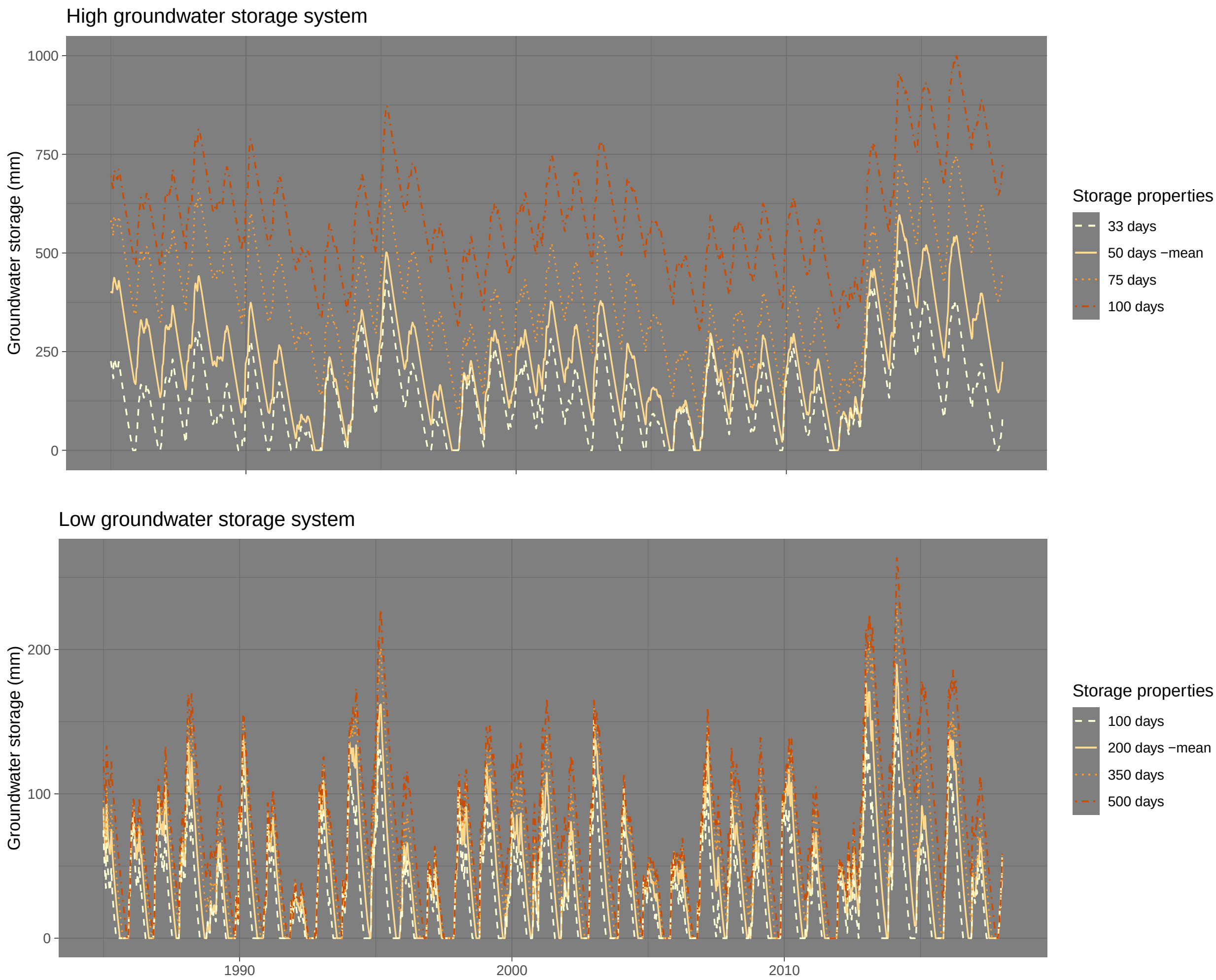


Figure S13: Baseline conditions for groundwater storage modelled using different groundwater storage-outflow parameters, as given in Table 6.3. The first and second panel represent the high and low groundwater storage system.

S14: Groundwater drought duration and severity for baseline and combined scenarios applying a range of groundwater storage-outflow parameters

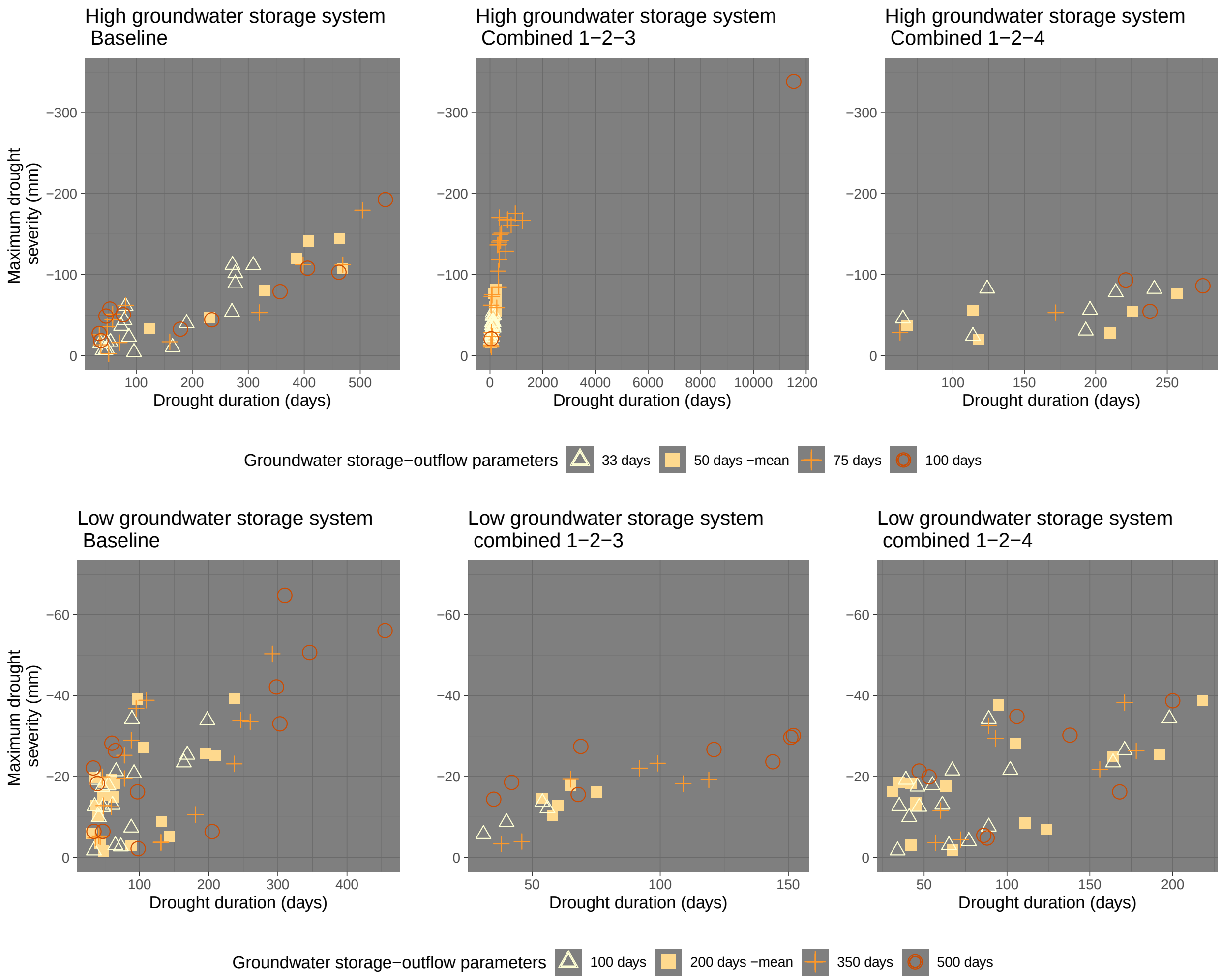


Figure S14: Groundwater drought duration and severity for baseline conditions and two combined scenarios (1-2-3 and 1-2-4) in the two groundwater storage systems. The range of groundwater storage-outflow parameters can be found in Table 6.3.

S15: Groundwater drought duration and severity for baseline and combined scenarios applying an increase (93%) and decrease (83.5%) in water allocation.

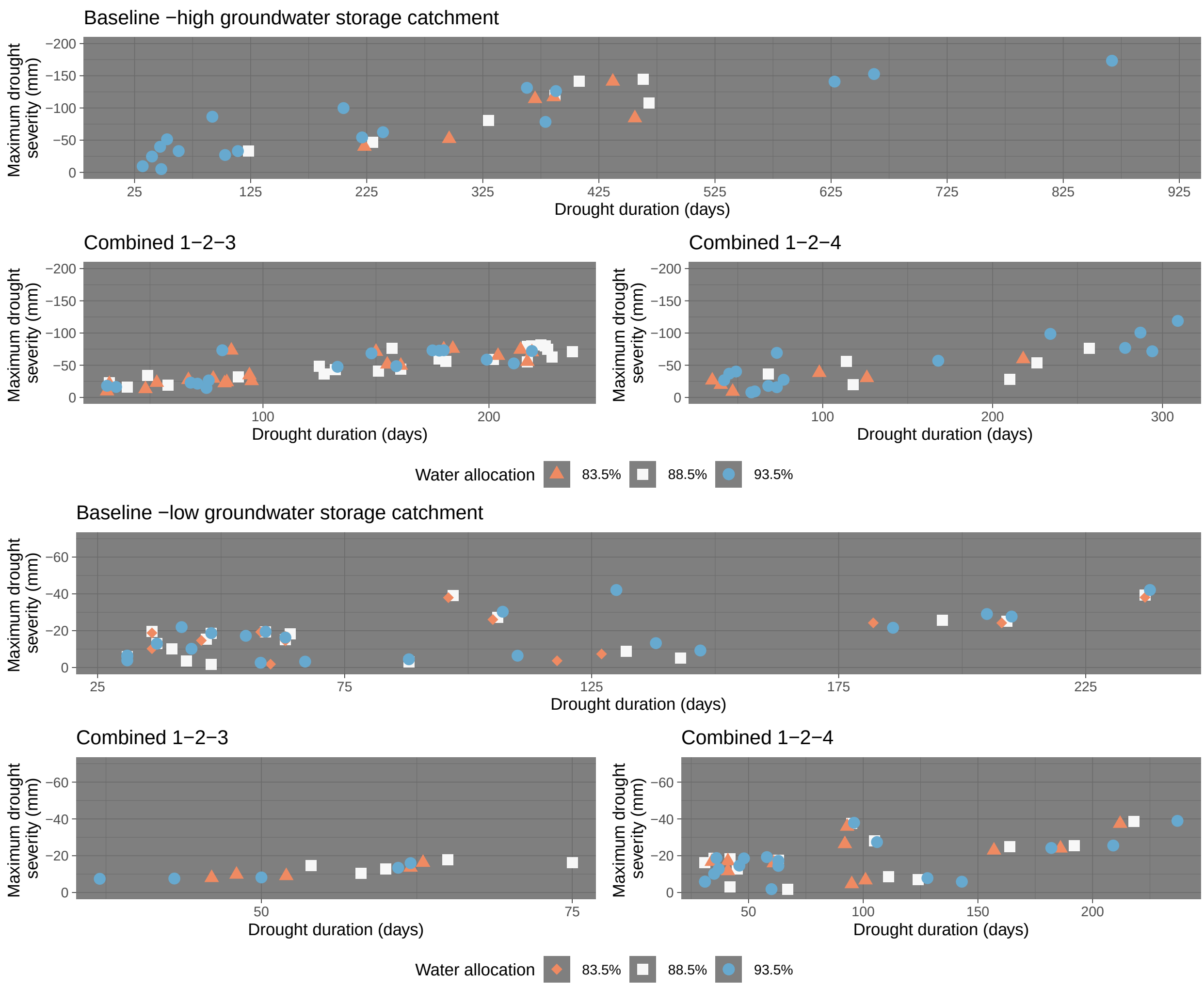


Figure S15: Groundwater drought duration and severity for baseline conditions and two combined scenarios (1-2-3 and 1-2-4) in the two groundwater storage systems. These tests are part of the sensitivity analysis for which the proportional water allocation was increased and decreased with 5%.

S17: Duration and occurrence of minor droughts in Lincolnshire, Chilterns, and Shropshire.

Water management units	Average duration of minor droughts (in months)	Average autocorrelation (in months)	Occurrence of minor droughts 24 months before reference droughts (%)	Occurrence of minor droughts during reference droughts (%)
1: Lincolnshire	3.1	11.6	27	60
2: Chilterns	3.7	17.3	34	27
4: Shropshire	5.0	15.1	43	23

Table S17: Duration and occurrence of minor droughts in influenced sites in Lincolnshire, Chilterns, and Shropshire. Results show that the average during is shorter than the average auto-correlation (calculated from groundwater level observations).

S18: Drought management plans of drinking water companies

Table S18: Locations of drought management plans of thirteen drinking water company in England. All drought management plans are publicly available (websites are stated in second column). Most recent date is shown in third column with the last access date.

Drinking water company	Drought management plan	Dated at	Last accessed
Affinity Water	affinitywater.co.uk/drought-management	2018	2-9-2020
Anglian Water	anglianwater.co.uk/drought-plan	2019	2-9-2020
Bristol Water	bristolwater.co.uk/planning-for-drought	2018	2-9-2020
Portsmouth Water	portsmouthwater.co.uk/final-drought-plan-2019	2019	2-9-2020
Severn Trent Water	severntrent.com/our-plans	2019	2-9-2020
South East Water	corporate.southeastwater.co.uk/drought-plans	2019	2-9-2020
Southern Water	southernwater.co.uk/our-drought-plan	2019	2-9-2020
South Staffs Water	stwater.co.uk/drought-plan	2019	2-9-2020
2 Sutton & East Surrey Water	seswater.co.uk/publication$_{d}rought$	2019	2-9-2020
Thames Water	thameswater.co.uk/drought-plan	2017	2-9-2020
United Utilities	unitedutilities.com/drought-plan	2018	2-9-2020
Wessex Water	wessexwater.co.uk/drought-plan	2018	2-9-2020
Yorkshire Water	yorkshirewater.com/resources	2019	2-9-2020

S19: Water use and main water sources of drinking water companies in England

Table S19: Summary of water use, supply, and headroom of selected drinking water companies sourcing from surface water and groundwater in England. Note that this excludes drinking water companies South West and Northumbrian water. Data of latest water resource management plans has been used (see S18). Imported and exported percentages are marked (*) when the source was undefined or potentially mixed. Thames Water values are taken for London and outer areas in parenthesis. Headroom percentage is calculated by dividing reported baseline conditions demand by the supply (dated in 2019/20) and double-checked with published data of Agency (2019b).

Drinking water company	Supplies to # customers	Surface water (%)	Groundwater (%)	Imported water (%)	Headroom (%)
Affinity Water	3.6	28	65	7	86
Anglian Water	6	41	50	9	86
Bristol Water	1.2	42	12	42	93
Portsmouth Water	0.7	35	55	10	94
Severn Trent Water	8	67	33	-	92
South East Water	2.2	28.5	70	1.5	83
Southern Water	2.3	22	70	8	82
South Staffs Water	1.3	60	40	-	95
Sutton & East Surrey Water	0.7	15	84	1*	84
Thames Water	15	80 (25)	20 (70)	- (5)	91
United Utilities	3	88	10	2	94
Wessex Water	2.8	21	75	4	88
Yorkshire Water	2.3	71	25	4	83
Average	3.8	44.6	48.5	6.7	88.5

References

Aeschbach-Hertig, W. and T. Gleeson (2012). "Regional strategies for the accelerating global problem of groundwater depletion". In: *Nature Geoscience* 5.12, p. 853.

Agency, Environment (2019a). *ENV15 - Water abstraction tables for England*. Last accessed on 27-08-20. Environment Agency. DOI: https://www.gov.uk/government/statistical-data-sets/env15-water-abstraction-tables. URL: https://www.gov.uk/government/statistical-data-sets/env15-water-abstraction-tables.

— (2019b). *Revised Draft Water Resources Management Plan 2019 Supply-Demand Data at Company Level 2020/21 to 2044/45*. Last accessed on 5-10-2020. Environment Agency. DOI: https://data.gov.uk/dataset/fb38a40c-ebc1-4e6e-912c-bb47a76f6149/revised-draft-water-resources-management-plan-2019-supply-demand-data-at-company-level-2020-21-to-2044-45#licence-info. URL: https://data.gov.uk/dataset/fb38a40c-ebc1-4e6e-912c-bb47a76f6149/revised-draft-water-resources-management-plan-2019-supply-demand-data-at-company-level-2020-21-to-2044-45#licence-info.

Aghabozorgi, Saeed, Ali Seyed Shirkhorshidi, and Teh Ying Wah (2015). "Time-series clustering – A decade review". In: *Information Systems* 53, pp. 16–38. ISSN: 0306-4379.

AghaKouchak, Amir (Aug. 2015). "Recognize anthropogenic drought". English. In: *Nature* 524.7566, pp. 409–411. ISSN: 00280836.

Alam, Sarfaraz, Mekonnen Gebremichael, Ruopu Li, Jeff Dozier, and Dennis P. Lettenmaier (Dec. 2019). "Climate change impacts on groundwater storage in the Central Valley, California". In: *Climatic Change* 157.3, pp. 387–406. ISSN: 1573-1480. DOI: 10.1007/s10584-019-02585-5.

Alam, Sarfaraz, Mekonnen Gebremichael, Ruopu Li, Jeff Dozier, and Dennis P. Lettenmaier (2020). "Can Managed Aquifer Recharge Mitigate the Groundwater Overdraft in California's Central Valley?" In: *Water Resources Research* 56.8, e2020WR027244. DOI: https://doi.org/10.1029/2020WR027244.

Alexander, LV and PD Jones (2001). "Updated precipitation series for the UK and discussion of recent extremes". In: *Atmospheric science letters* 1.2, pp. 142–150.

Allen, D.J., L.J. Brewerton, L.M. Coleby, B.R. Gibbs, M.A. Lewis, A.M. MacDonald, S.J. Wagstaff, and A.T. Williams (1997). *The physical properties of major aquifers in England and Wales*. Ed. by D.J. Allen, J.P. Bloomfield, and V.K. Robinson. British Geological Survey (WD/97/034).

Apruv, T., M. Sivapalan, and X. Cai (Nov. 2017). "Understanding the Role of CLimate Characteristics in Drought propagation". In: *Water Resources Research* 53, pp. 9304–9329.

Ascott, Matthew J., Ben P. Marchant, David Macdonald, Andrew A. McKenzie, and John Paul Bloomfield (2017). "Improved understanding of spatio-temporal controls on regional scale groundwater flooding using hydrograph analysis and impulse response functions". In: *Hydrological Processes* 31.25, pp. 4586–4599. DOI: 10.1002/hyp.11380.

Asoka, Akarsh, Tom Gleeson, Yoshihide Wada, and Vimal Mishra (2017). "Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India". In: *Nature Geoscience* 10.2, pp. 109–117.

Barker, Lucy J., Jamie Hannaford, Simon Parry, Katie A. Smith, Maliko Tanguy, and Christel Prudhomme (Nov. 2019). "Historic hydrological droughts 1891-2015: systematic characterisation for a diverse set of catchments across the UK". English. In: *HYDROLOGY AND EARTH SYSTEM SCIENCES* 23.11, 4583–4602. ISSN: 1027-5606. DOI: {10.5194/hess-23-4583-2019}.

Bergström, Sten (1976). *Development and application of a conceptual runoff model for Scandinavian catchments*. RHO, Hydrology and Oceanography, ISSN 0347-7827 ; 7. Norrkoping, Sweden: Report RHO 7.SMHI.

Bertoldi, Gilbert L, Richard H Johnston, and Kristin D Evenson (1991). *Groundwater in the Central Valley, California; a summary report*. Tech. rep.

BGS (2015). *Current UK groundwater use*. Website.

Bhanja, Soumendra N, Abhijit Mukherjee, Matthew Rodell, Yoshihide Wada, Siddhartha Chattopadhyay, Isabella Velicogna, Kishore Pangaluru, and James S Famiglietti (2017). "Groundwater rejuvenation in parts of India influenced by water-policy change implementation". In: *Scientific reports* 7.1, p. 7453. DOI: https://doi.org/10.1038/s41598-017-07058-2.

Bloomfield, J. P., L. J. Brewerton, and D. J. Allen (1995). "Regional trends in matrix porosity and dry density of the Chalk of England". In: *Quarterly Journal of Engineering Geology and Hydrogeology* 28.Supplement 2, S131–S142. ISSN: 1470-9236. DOI: 10.1144/GSL.QJEGH.1995.028.S2.04.

Bloomfield, J. P. and B. P. Marchant (2013). "Analysis of groundwater drought building on the standardised precipitation index approach". In: *Hydrology and Earth System Sciences* 17.12, pp. 4769–4787. ISSN: 10275606. DOI: 10.5194/hess-17-4769-2013.

Bloomfield, J. P., B. P. Marchant, S. H. Bricker, and R. B. Morgan (2015). "Regional analysis of groundwater droughts using hydrograph classification". In: *Hydrology and Earth System Sciences* 19.10, pp. 4327–4344. ISSN: 16077938. DOI: 10.5194/hess-19-4327-2015.

Bloomfield, J. P., B. P. Marchant, and A. A. McKenzie (2019). "Changes in groundwater drought associated with anthropogenic warming". In: *Hydrology and Earth System Sciences* 23.3, pp. 1393–1408. DOI: 10.5194/hess-23-1393-2019.

Bloomfield, John (1996). "Characterisation of hydrogeologically significant fracture distributions in the Chalk: an example from the Upper Chalk of southern England". In:

Journal of Hydrology 184.3, pp. 355–379. ISSN: 0022-1694. DOI: 10.1016/0022-1694(95)02954-0.

Botterill, Linda Courtenay and Michael J. Hayes (Oct. 2012). "Drought triggers and declarations: science and policy considerations for drought risk management". In: *Natural Hazards* 64.1, pp. 139–151. ISSN: 0921-030X. DOI: 10.1007/s11069-012-0231-4.

Bouwer, Herman (Feb. 2002). "Artificial recharge of groundwater: hydrogeology and engineering". In: *Hydrogeology Journal* 10.1, pp. 121–142. ISSN: 1435-0157. DOI: 10.1007/s10040-001-0182-4.

Bredehoeft, John (2011). "Hydrologic Trade-Offs in Conjunctive Use Management". In: *Groundwater* 49.4, pp. 468–475. DOI: 10.1111/j.1745-6584.2010.00762.x.

Brush, Charles Frank, Emin C Dogrul, and Tariq N Kadir (2013). *Development and calibration of the California Central Valley groundwater-surface water simulation model (C2VSim), version 3.02-CG*. Version R374 of the C2VSIM-CG model. Version 3.02-CG. DWR Technical Memorandum.

Bryant, SJ, NW Arnell, and FM Law (1994). "The 1988–92 drought in its historical perspective". In: *Water and Environment Journal* 8.1, pp. 39–51.

Caball, Remy and Shirin Malekpour (2019). "Decision making under crisis: Lessons from the Millennium Drought in Australia". In: *International Journal of Disaster Risk Reduction* 34, pp. 387–396. ISSN: 2212-4209. DOI: https://doi.org/10.1016/j.ijdrr.2018.12.008.

California Department of Water Resources (2020). *State Water Project*. https://water.ca.gov/swp. DWR.

Capone, F and ME Bonfanti (2015). "MARSOL demonstrating managed aquifer recharge as a solution to water scarcity and drought". In: *Legislative Framework Review and Analysis Deliverable* D17, p. 1.

Carlier, Claire, Stefanie B Wirth, Fabien Cochand, Daniel Hunkeler, and Philip Brunner (2019). “Exploring Geological and Topographical Controls on Low Flows with Hydrogeological Models”. In: *Groundwater* 57.1, pp. 48–62.

Carrão, H., G. Naumann, and P. Barbosa (2016). “Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability”. In: *Global Environmental Change* 39, pp. 108–124. ISSN: 0959-3780. DOI: https://doi.org/10.1016/j.gloenvcha.2016.04.012.

CASGEM (Sept. 2017). *California State-wide Groundwater Elevation Monitoring*. Last accessed on 5-9-2017. CA.gov.

Chang, T.J. and C.B. Teoh (Dec. 1995). “Use of the kriging method for studying characteristics of ground water droughts”. English. In: *Water Resources Bulletin* 31.6, 1001–1007. ISSN: 0043-1370.

Chao, BF., YH. Wu, and YS. Li (2008). “Impact of Artificial Reservoir Water Impoundment on Global Sea Level”. In: *Science* 320.5873, pp. 212–214. ISSN: 0036-8075. DOI: 10.1126/science.1154580.

Christian-Smith, J., M.C. Levy, and P.H. Gleick (July 2015). “Maladaptation to drought: a case report from California, USA”. In: *Sustainability Science* 10.3, pp. 491–501. ISSN: 1862-4065. DOI: 10.1007/s11625-014-0269-1.

Condon, Laura E. and Reed M. Maxwell (2019). “Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion”. In: *Science Advances* 5.6. DOI: 10.1126/sciadv.aav4574.

Coxon, G., N. Addor, J. P. Bloomfield, J. Freer, M. Fry, J. Hannaford, N. J. K. Howden, R. Lane, M. Lewis, E. L. Robinson, T. Wagener, and R. Woods (2020). “CAMELS-GB: hydrometeorological time series and landscape attributes for 671 catchments in Great Britain”. In: *Earth System Science Data* 12.4, pp. 2459–2483. DOI: 10.5194/essd-12-2459-2020.

Coxon, G., J. Freer, R. Lane, T. Dunne, W. J. M. Knoben, N. J. K. Howden, N. Quinn, T. Wagener, and R. Woods (2019). "DECIPHeR v1: Dynamic fluxEs and ConnectIvity for Predictions of HydRology". In: *Geoscientific Model Development* 12.6, pp. 2285–2306. DOI: 10.5194/gmd-12-2285-2019.

Cruz-Ayala, Mary B. and Sharon B. Megdal (Feb. 2020). "An Overview of Managed Aquifer Recharge in Mexico and Its Legal Framework". English. In: *WATER* 12.2. DOI: {10.3390/w12020474}.

Custodio, Emilio (Apr. 2002). "Aquifer overexploitation: what does it mean?" In: *Hydrogeology Journal* 10.2, pp. 254–277. ISSN: 1431-2174. DOI: 10.1007/s10040-002-0188-6.

Custodio, Emilio, Andres Sahuquillo, and Jose Albiac (MAR 2019). "Sustainability of intensive groundwater development: experience in Spain". English. In: *SUSTAINABLE WATER RESOURCES MANAGEMENT* 5.1, SI, 11–26. ISSN: 2363-5037. DOI: {10.1007/s40899-017-0105-8}.

Cuthbert, M. O. (2009). "An improved time series approach for estimating groundwater recharge from groundwater level fluctuations". In: *Water Resources Research* 46.9. DOI: 10.1029/2009WR008572.

Cuthbert, M. O., T. Gleeson, N. Moosdorf, K. M. Befus, A. Schneider, J. Hartmann, and B. Lehner (2019). "Global patterns and dynamics of climate-groundwater interactions". In: *Nature Climate Change* 9.2, pp. 137–141. ISSN: 1758-6798.

Dahlke, Helen, Andrew Brown, Steve Orloff, Daniel Putnam, Toby O'Geen, et al. (2018a). "Managed winter flooding of alfalfa recharges groundwater with minimal crop damage". In: *California Agriculture* 72.1, pp. 65–75.

Dahlke, Helen E., Gabriel T. LaHue, Marina R.L. Mautner, Nicholas P. Murphy, Noelle K. Patterson, Hannah Waterhouse, Feifan Yang, and Laura Foglia (2018b). "Chapter Eight - Managed Aquifer Recharge as a Tool to Enhance Sustainable Groundwater Management in California: Examples From Field and Modeling Studies". In: *Advanced Tools for Integrated Water Resources Management*. Ed. by Jan Friesen and Leonor

Rodríguez-Sinobas. Vol. 3. Advances in Chemical Pollution, Environmental Management and Protection. Elsevier, pp. 215–275. DOI: https://doi.org/10.1016/bs.apmp.2018.07.003.

Dai, Aiguo (Jan. 2013). "Increasing drought under global warming in observations and models". English. In: *Nature Climate Change* 3.1, 52–58. ISSN: 1758-678X. DOI: {10.1038/NCLIMATE1633}.

De Stefano, L, J Urquijo, E Kampragkou, and D Assimacopoulos (2015a). "Lessons learnt from the analysis of past drought management practices in selected European regions: experience to guide future policies". In: *European Water* 49, pp. 107–117.

De Stefano, L., J.M. Fornés, J.A. López-Geta, and F. Villarroya (2015b). "Groundwater use in Spain: an overview in light of the EU Water Framework Directive". In: *International Journal of Water Resources Development* 31.4, pp. 640–656. DOI: 10.1080/07900627.2014.938260.

Di Baldassarre, G., A. Viglione, G. Carr, L Kuil, K. Yan, Luigia Brandimarte, and G. Bloschl (2015). "Debates- Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes". In: *Water Resources Research*, pp. 4770–4781. DOI: 10.1002/2014WR016416.Received.

Di Baldassarre, Giuliano, Niko Wanders, Amir AghaKouchak, Linda Kuil, Sally Rangecroft, Ted I. E. Veldkamp, Margaret Garcia, Pieter R. van Oel, Korbinian Breinl, and Anne F. Van Loon (2018). "Water shortages worsened by reservoir effects". In: *Nature Sustainability* 1.11, pp. 617–622. ISSN: 2398-9629.

Dillon, P., I. Gale, S. Contreras, P. Pavelic, R. Evans, and J. Ward (2009). "Managing aquifer recharge and discharge to sustain irrigation livelihoods under water scarcity and climate change." In: ed. by G. Blöschl, N. van de Giesen, D. Muralidharan, L. Ren, F. Seyler, U. Sharma, and J. Vrba. Wallingford, UK: IAHS Press, pp. 1–12.

Dillon, P., P. Stuyfzand, T. Grischek, M. Lluria, R. D. G. Pyne, R. C. Jain, J. Bear, J. Schwarz, W. Wang, E. Fernandez, C. Stefan, M. Pettenati, J. van der Gun, C.

Sprenger, G. Massmann, B. R. Scanlon, J. Xanke, P. Jokela, Y. Zheng, R. Rossetto, M. Shamrukh, P. Pavelic, E. Murray, A. Ross, J. P. Bonilla Valverde, A. Palma Nava, N. Ansems, K. Posavec, K. Ha, R. Martin, and M. Sapiano (2019). "Sixty years of global progress in managed aquifer recharge". In: *Hydrogeology Journal* 27.1, pp. 1–30. ISSN: 1435-0157.

Dillon, Peter (Mar. 2005). "Future management of aquifer recharge". In: *Hydrogeology Journal* 13.1, pp. 313–316. ISSN: 1435-0157. DOI: 10.1007/s10040-004-0413-6.

Dillon, Peter, Enrique Escalante Fernandez, and Albert Tuinhof (2012). "Management of aquifer recharge and discharge processes and aquifer storage equilibrium. IAH contribution to GEF-FAO Groundwater Governance Thematic Paper 4". In:

Dillon, Peter, Declan Page, Joanne Vanderzalm, Simon Toze, Craig Simmons, Grant Hose, Russell Martin, Karen Johnston, Simon Higginson, and Ryan Morris (Feb. 2020). "Lessons from 10 Years of Experience with Australia's Risk-Based Guidelines for Managed Aquifer Recharge". English. In: *WATER* 12.2. DOI: {10.3390/w12020537}.

Directive, EU (2000). "60/EC (2000) Directive of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. The European parliament and the Council of the European Union". In: *Official Journal L* 327.22, p. 12.

Dixon, Philip (2003). "VEGAN, a package of R functions for community ecology". In: *Journal of Vegetation Science* 14.6, pp. 927–930. DOI: 10.1111/j.1654-1103.2003.tb02228.x.

Dobson, Barnaby, Gemma Coxon, Jim Freer, Helen Gavin, Mohammad Mortazavi-Naeini, and Jim W. Hall (2020). "The Spatial Dynamics of Droughts and Water Scarcity in England and Wales". In: *Water Resources Research* 56.9. e2020WR027187 2020WR027187, e2020WR027187. DOI: 10.1029/2020WR027187.

Döll, P., H. Hoffmann-Dobrev, F.T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg, and B.R. Scanlon (2012). "Impact of water withdrawals from groundwater and surface water on continental water storage variations". In: *Journal of Geodynamics* 59, pp. 143–156. ISSN: 02643707. DOI: 10.1016/j.jog.2011.05.001.

Döll, Petra, Hannes Müller Schmied, Carina Schuh, Felix T. Portmann, and Annette Eicker (2014). "Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites". In: *Water Resources Research* 50.7, pp. 5698–5720. DOI: 10.1002/2014WR015595.

Dountcheva, Iordanka, David Sanz, Eduardo Cassiraga, Vassil Galabov, and Juan José Gómez-Alday (2020). "Identifying non-stationary and long-term river–aquifer interactions as a response to large climatic patterns and anthropogenic pressures using wavelet analysis (Mancha Oriental Aquifer, Spain)". In: *Hydrological Processes*, pp. 1–12. DOI: 10.1002/hyp.13934.

Downing, Richard Allen, Michael Price, and GP Jones (1993). *The hydrogeology of the Chalk of north-west Europe*. Ed. by Jones. Clarendon Press.

Durant, M (2015). "Description of groundwater droughts in the UK: 1890 to 2015". In: *Nottingham, UK, British Geological Survey* (OR/15/007), p. 52.

DWR (2016). *California's Groundwater Working Toward Sustainability*. Tech. rep. Bulletin 118. Department of Water Resources (DWR).

Eltahir, Elfatih A B and Pat J F Yeh (1999). "On the asymmetric response of aquifer water level to floods and droughts in Illinois". In: *Water Resources Research* 35.4, pp. 1199–1217. ISSN: 00431397. DOI: 10.1029/1998WR900071.

Environment Agency (2010). *Vale of St. Albans Numerical Groundwater Model Final Report*. Tech. rep. Environment Agency Thames Region and Atkins.

— (2016). *Managing water abstraction*. Tech. rep. 5. EA, Bristol.

Famiglietti, J. S. (Nov. 2014). "The global groundwater crisis". English. In: *Nature Climate Change* 4.11, pp. 945–948. ISSN: 1758-678X. DOI: {10.1038/nclimate2425}.

Famiglietti, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage, and M. Rodell (Feb. 2011). "Satellites measure recent rates of groundwater depletion in California's Central Valley". In: *Geophysical Research Letters* 38.3, n/a–n/a. ISSN: 00948276. DOI: 10.1029/2010GL046442.

Farrell, Rolf, Marcel Ververs, Paul Davison, Paul Howlett, and Mark Whiteman (2017). "Splicing recharge and groundwater flow models in the Environment Agency National Groundwater Modelling System". In: *Geological Society, London, Special Publications* 408.1, pp. 55–69. ISSN: 0305-8719. DOI: 10.1144/SP408.14.

Faunt, Claudia, Randall Hanson, Kenneth Belitz, Wolfgang Schmid, SP Predmore, DL Rewis, and KR McPherson (Apr. 2009). "Chapter C. Numerical model of the hydrologic landscape and groundwater flow in California's Central Valley". In: in: Faunt, C.C., ed., 2009, Groundwater Availability of the Central Valley Aquifer, California, pp. 121–212.

Faunt, Claudia C., Michelle Sneed, Jon Traum, and Justin T. Brandt (May 2016). "Water availability and land subsidence in the Central Valley, California, USA". In: *Hydrogeology Journal* 24.3, pp. 675–684. ISSN: 1431-2174. DOI: 10.1007/s10040-015-1339-x.

Fleig, a. K., L. M. Tallaksen, H. Hisdal, and S. Demuth (2006). "A global evaluation of streamflow drought characteristics". In: *Hydrology and Earth System Sciences Discussions* 2.6, pp. 2427–2464. ISSN: 1607-7938. DOI: 10.5194/hessd-2-2427-2005.

Foley, Jonathan A., Ruth DeFries, Gregory P. Asner, Carol Barford, Gordon Bonan, Stephen R. Carpenter, F. Stuart Chapin, Michael T. Coe, Gretchen C. Daily, Holly K. Gibbs, Joseph H. Helkowski, Tracey Holloway, Erica A. Howard, Christopher J. Kucharik, Chad Monfreda, Jonathan A. Patz, I. Colin Prentice, Navin Ramankutty, and Peter K. Snyder (2005). "Global Consequences of Land Use". In: *Science* 309.5734, pp. 570–574. ISSN: 0036-8075. DOI: 10.1126/science.1111772.

Fowler, HJ, CG Kilsby, and J Stunell (2007). “Modelling the impacts of projected future climate change on water resources in north-west England”. In: *Hydrol. Earth Syst. Sci* 11.3, pp. 1115–1126.

Fu, Xinyu, Mark Svoboda, Zhenghong Tang, Zhijun Dai, and Jianjun Wu (2013). “An overview of US state drought plans: crisis or risk management?” In: *Natural Hazards* 69.3, pp. 1607–1627. ISSN: 1573-0840.

Gailey, Robert M., Graham E. Fogg, Jay R. Lund, and Josué Medellín-Azuara (June 2019). “Maximizing on-farm groundwater recharge with surface reservoir releases: a planning approach and case study in California, USA”. In: *Hydrogeology Journal* 27.4, pp. 1183–1206. ISSN: 1435-0157. DOI: 10.1007/s10040-019-01936-x.

Garcia, M., K. Portney, and S. Islam (2016). “A question driven socio-hydrological modeling process”. In: *Hydrology and Earth System Sciences* 20.1, pp. 73–92. DOI: 10.5194/hess-20-73-2016.

Garcia, Margaret, Elena Ridolfi, and Giuliano Di Baldassarre (2020). “The interplay between reservoir storage and operating rules under evolving conditions”. In: *Journal of Hydrology* 590, p. 125270. ISSN: 0022-1694. DOI: https://doi.org/10.1016/j.jhydrol.2020.125270.

Ghasemizade, Mehdi, Kwabena O Asante, Christian Petersen, Tiffany Kocis, Helen Dahlke, and Thomas Harter (2019). “An integrated approach toward sustainability via groundwater banking in the Southern Central Valley, California”. In: *Water Resources Research*.

Gleeson, T and B Richter (2017). “How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers”. In: *River Research and Applications* 34.1, pp. 83–92.

— (2018). “How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers”. In: *River Research and Applications* 34.1, pp. 83–92. DOI: 10.1002/rra.3185.

Gleeson, Tom, William M Alley, Diana M Allen, Marios A Sophocleous, Yangxiao Zhou, Makoto Taniguchi, and Jonathan VanderSteen (2012a). "Towards sustainable groundwater use: setting long-term goals, backcasting, and managing adaptively". In: *Groundwater* 50.1, pp. 19–26.

Gleeson, Tom, Mark Cuthbert, Grant Ferguson, and Debra Perrone (2020). "Global Groundwater Sustainability, Resources, and Systems in the Anthropocene". In: *Annual Review of Earth and Planetary Sciences* 48.1, pp. 431–463. DOI: 10.1146/annurev-earth-071719-055251.

Gleeson, Tom, Jonathan VanderSteen, Marios a. Sophocleous, Makoto Taniguchi, William M. Alley, Diana M. Allen, and Yangxiao Zhou (2010). "Groundwater sustainability strategies". In: *Nature Geoscience* 3.6, pp. 378–379. ISSN: 1752-0894. DOI: 10.1038/ngeo881.

Gleeson, Tom, K Villholth, R Taylor, D Perrone, and D Hyndman (2019). "Groundwater: a call to action." In: *Nature* 576.7786, p. 213.

Gleeson, Tom, Yoshihide Wada, Marc F. P. Bierkens, and Ludovicus P. H. van Beek (2012b). "Water balance of global aquifers revealed by groundwater footprint". In: *Nature* 488.7410, pp. 197–200. ISSN: 0028-0836. DOI: 10.1038/nature11295.

Gonzales, Patricia and Newsha Ajami (2017). "Social and Structural Patterns of Drought-Related Water Conservation and Rebound". In: *Water Resources Research* 53.12, pp. 10619–10634. DOI: 10.1002/2017WR021852.

Graaf, Inge EM de, Tom Gleeson, LPH Rens van Beek, Edwin H Sutanudjaja, and Marc FP Bierkens (2019). "Environmental flow limits to global groundwater pumping". In: *Nature* 574.7776, pp. 90–94.

Grant, Stanley B., Tim D. Fletcher, David Feldman, Jean-Daniel Saphores, Perran L. M. Cook, Mike Stewardson, Kathleen Low, Kristal Burry, and Andrew J. Hamilton (Oct. 2013). "Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia". In: *Environ. Sci. Technol.* 47.19, pp. 10727–10734. ISSN: 0013-936X. DOI: 10.1021/es400618z.

Griffin, Daniel and Kevin J Anchukaitis (2014). "How unusual is the 2012 – 2014 California drought ?" In: *Geophysical Research Letters* 41, pp. 9017–9023. ISSN: 00948276. DOI: 10.1002/2014GL062433.1..

Gun, Jac Van der, L. Amore, Unesco, and World Water Assessment Programme (United Nations) (2012). *The United Nations World Water Development Report – N° 4 – Groundwater and Global Change: Trends, Opportunities and Challenges*. Side publications series. Paris, France: UNESCO. ISBN: 9789230010492.

Haaf, Ezra and Roland Barthel (2018). "An inter-comparison of similarity-based methods for organisation and classification of groundwater hydrographs". In: *Journal of Hydrology* 559, pp. 222–237. ISSN: 0022-1694.

Haaf, Ezra, Markus Giese, Benedikt Heudorfer, Kerstin Stahl, and Roland Barthel (2020). "Physiographic and Climatic Controls on Regional Groundwater Dynamics". In: *Water Resources Research* 56.10. e2019WR026545 2019WR026545, e2019WR026545. DOI: 10.1029/2019WR026545.

Haas, J. C. and S. Birk (2017). "Characterizing the spatiotemporal variability of groundwater levels of alluvial aquifers in different settings using drought indices". In: *Hydrology and Earth System Sciences* 21.5, pp. 2421–2448. DOI: 10.5194/hess-21-2421-2017.

Hamed, Khaled H. (2008). "Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis". In: *Journal of Hydrology* 349.3, pp. 350–363. ISSN: 0022-1694. DOI: 10.1016/j.jhydrol.2007.11.009.

Hanak, Ellen, Alvar Escriva-Bou, Brian Gray, Sarge Green, Thomas Harter, Jelena Jezdimirovic, Jay Lund, Josué Medellın-Azuara, Peter Moyle, and Nathaniel Seavy (2019). "Water and the Future of the San Joaquin Valley". In: *Public Policy Institute of California.*

Hari, Vittal, Oldrich Rakovec, Yannis Markonis, Martin Hanel, and Rohini Kumar (2020). "Increased future occurrences of the exceptional 2018-2019 Central European drought under global warming". In: *Scientific Reports* 10.1, p. 12207. ISSN: 2045-2322.

Hayden, Hanna and Tsvetan Tsvetanov (2019). "The Effectiveness of Urban Irrigation Day Restrictions in California". In: *Water Economics and Policy* 05.03, p. 1950001. DOI: 10.1142/S2382624X19500012.

He, Xiaogang, Yoshihide Wada, Niko Wanders, and Justin Sheffield (2017). "Intensification of hydrological drought in California by human water management". In: *Geophysical Research Letters* 44.4, pp. 1777–1785.

Hellwig, J., M. Stoelzle, and K. Stahl (2020). "Stress-testing groundwater and baseflow drought responses to synthetic climate change-informed recharge scenarios". In: *Hydrology and Earth System Sciences Discussions* 2020, pp. 1–26. DOI: 10.5194/hess-2020-211.

Heudorfer, B., E. Haaf, K. Stahl, and R. Barthel (2019). "Index-Based Characterization and Quantification of Groundwater Dynamics". In: *Water Resources Research* 55.7, pp. 5575–5592. DOI: 10.1029/2018WR024418.

Holley, Cameron, Darren Sinclair, Elena Lopez-Gunn, and Edella Schlager (2016). "Conjunctive management through collective action". In: *Integrated groundwater management.* Springer, Cham, pp. 229–252. DOI: 10.1007/978-3-319-23576-9_9.

Howarth, William (2018). "Going with the flow: Integrated Water Resources Management, the EU Water Framework Directive and ecological flows". In: *Legal Studies* 38.2, pp. 298–319. DOI: 10.1017/lst.2017.13.

Huggins, Xander, Tom Gleeson, Hailey Eckstrand, and Ben Kerr (Oct. 2018). "Streamflow Depletion Modeling: Methods for an Adaptable and Conjunctive Water Management Decision Support Tool". English. In: *JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION* 54.5, 1024–1038. ISSN: 1093-474X. DOI: {10.1111/1752-1688.12659}.

Huning, Laurie S. and Amir AghaKouchak (2020). “Global snow drought hot spots and characteristics”. In: *Proceedings of the National Academy of Sciences* 117.33, pp. 19753–19759. ISSN: 0027-8424. DOI: 10.1073/pnas.1915921117.

Hutchinson, MJ, RGS Ingram, MW Grout, and PJ Hayes (2012). “A successful model: 30 years of the Lincolnshire Chalk model”. In: *Geological Society, London, Special Publications* 364.1, pp. 173–191.

Jackson, Christopher R., John P. Bloomfield, and Jonathan D. Mackay (2015). “Evidence for changes in historic and future groundwater levels in the UK”. In: *Progress in Physical Geography: Earth and Environment* 39.1, pp. 49–67. DOI: 10.1177/0309133314550668.

Jackson, Christopher R., Rakia Meister, and Christel Prudhomme (2011). “Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections”. In: *Journal of Hydrology* 399.1, pp. 12–28. ISSN: 0022-1694. DOI: https://doi.org/10.1016/j.jhydrol.2010.12.028.

Jacobs, HE, JL Du, P Nel, N Nel, S Gugushe, and S Levin (Jan. 2020). “Baseline adjustment methodology in a shared water savings contract under serious drought conditions”. In: *Water SA* 46.1. DOI: 10.17159/wsa/2020.v46.i1.7874.

Jaeger, William K., Adell Amos, David R. Conklin, Christian Langpap, Kathleen Moore, and Andrew J. Plantinga (2019). “Scope and limitations of drought management within complex human-natural systems”. In: *Nature Sustainability* 2.8, pp. 710–717. ISSN: 2398-9629.

Jain, Anil K. (2010). “Data clustering: 50 years beyond K-means”. In: *Pattern Recognition Letters* 31.8. Award winning papers from the 19th International Conference on Pattern Recognition (ICPR), pp. 651–666. ISSN: 0167-8655. DOI: https://doi.org/10.1016/j.patrec.2009.09.011.

Jakeman, A.J., O. Barreteau, R.J. Hunt, J.D. Rinaudo, and A. Ross (2016). *Integrated groundwater management: concepts, approaches and challenges*. Springer International Publishing, p. 756. DOI: 10.1007/978-3-319-23576-9.

Jones, DKC (1980). “The Tertiary evolution of south-east England with particular reference to the Weald”. In: *The shaping of southern England*. Vol. 11. Academic Press London, pp. 13–47.

Kakaei, Elham, Hamid Reza Moradi, Alireza Moghaddam Nia, and Henny A.J. Van Lanen (2019). “Quantifying Positive and Negative Human-Modified Droughts in the Anthropocene: Illustration with Two Iranian Catchments”. In: *Water* 11.5. ISSN: 2073-4441. DOI: 10.3390/w11050884.

Kazner, Christian, Thomas Wintgens, and Peter Dillon (2012). *Water reclamation technologies for safe managed aquifer recharge*. IWA publishing.

KCWA (Feb. 2010). *Kern Fan groundwater storage projects*. https://cwc.ca.gov/Water-Storage/WSIP-Project-Review-Portal/All-Projects/Kern-Fan-Groundwater-Storage-Project. Last accessed:1-10-2018. Bakersfield, CA: Kern County Water Agency.

Kendall, Maurice George (1948). “Rank correlation methods. 1948”. In: *London: Charles Griffin*, p. 160.

Kern County (CA) (2020). *Implementation of SGMA in Kern County*. https://www.wakc.com/water-issues/groundwater-regulation/. Last visit: 24-01-2020.

Kiparsky, Michael, Anita Milman, Dave Owen, and Andrew T Fisher (2017). “The importance of institutional design for distributed local-level governance of groundwater: The case of California’s Sustainable Groundwater Management Act”. In: *Water* 9.10, p. 755.

Klaar, Megan J., Michael J. Dunbar, Mark Warren, and Rob Soley (2014). “Developing hydroecological models to inform environmental flow standards: a case study from England”. In: *WIREs Water* 1.2, pp. 207–217. DOI: 10.1002/wat2.1012.

Kletzing, Russell (1987). “Imported Groundwater Banking: The Kern Water Bank–A Case Study”. In: *Pac. LJ* 19, p. 1225.

Kocis, Tiffany N and Helen E Dahlke (2017). "Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California". In: *Environmental Research Letters* 12.8, p. 084009.

Konikow, L. F. and S. A. Leake (2014). "Depletion and capture: revisiting "the source of water derived from wells"". In: *Ground water* 52, pp. 100–111. ISSN: 17456584. DOI: 10.1111/gwat.12204.

Konikow, L.F. (2011). "Contribution of global groundwater depletion since 1900 to sea-level rise". In: *Geophysical Research Letters* 38.17. DOI: 10.1029/2011GL048604.

Kourakos, George, Helen E. Dahlke, and Thomas Harter (2019). "Increasing Groundwater Availability and Seasonal Base Flow Through Agricultural Managed Aquifer Recharge in an Irrigated Basin". In: *Water Resources Research* 55.9, pp. 7464–7492. DOI: 10.1029/2018WR024019.

Kumar, Rohini, Jude L. Musuuza, Anne F. Van Loon, Adriaan J. Teuling, Roland Barthel, Jurriaan Ten Broek, Juliane Mai, Luis Samaniego, and Sabine Attinger (2016). "Multiscale evaluation of the Standardized Precipitation Index as a groundwater drought indicator". In: *Hydrology and Earth System Sciences* 20.3, pp. 1117–1131. ISSN: 16077938. DOI: 10.5194/hess-20-1117-2016.

Lawrimore, Jay, Richard R Heim Jr, Mark Svoboda, Val Swail, and Phil J Englehart (2002). "Beginning a new era of drought monitoring across North America". In: *Bulletin of the American Meteorological Society* 83.8, pp. 1191–1192.

Leblanc, Marc J., Paul Tregoning, Guillaume Ramillien, Sarah O. Tweed, and Adam Fakes (Apr. 2009). "Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia". In: *Water Resources Research* 45.4. ISSN: 00431397. DOI: 10.1029/2008WR007333.

Lee, Jae Min, Jong Hoon Park, Euijin Chung, and Nam C Woo (2018). "Assessment of Groundwater Drought in the Mangyeong River Basin, Korea". In: *Sustainability* 10.3, p. 831.

Lewis, Elizabeth, Stephen Birkinshaw, Chris Kilsby, and Hayley J. Fowler (2018). "Development of a system for automated setup of a physically-based, spatially-distributed hydrological model for catchments in Great Britain". In: *Environmental Modelling & Software* 108, pp. 102–110. ISSN: 1364-8152. DOI: https://doi.org/10.1016/j.envsoft.2018.07.006.

Li, Bailing and Matthew Rodell (2015). "Evaluation of a model-based groundwater drought indicator in the conterminous US". In: *Journal of Hydrology* 526, pp. 78–88.

Li, Ruopu, Gengxin Ou, Mahesh Pun, and Lance Larson (2018). "Evaluation of groundwater resources in response to agricultural management scenarios in the Central Valley, California". In: *Journal of Water Resources Planning and Management* 144.12, p. 04018078. DOI: 10.1061/(ASCE)WR.1943-5452.0001014.

Liu, Bo, Xiangqian Zhou, Wei Li, Chengpeng Lu, and Longcang Shu (2016). "Spatiotemporal characteristics of groundwater drought and its response to meteorological drought in Jiangsu Province, China". In: *Water* 8.11, p. 480.

Lorenzo-Lacruz, Jorge, Celso Garcia, and Enrique Morán-Tejeda (2017). "Groundwater level responses to precipitation variability in Mediterranean insular aquifers". In: *Journal of Hydrology* 552, pp. 516–531. ISSN: 0022-1694. DOI: https://doi.org/10.1016/j.jhydrol.2017.07.011.

Low, Kathleen G., Stanley B. Grant, Andrew J. Hamilton, Kein Gan, Jean-Daniel Saphores, Meenakshi Arora, and David L. Feldman (July 2015). "Fighting drought with innovation: Melbourne's response to the Millennium Drought in Southeast Australia". en. In: *Wiley Interdisciplinary Reviews: Water* 2.4, pp. 315–328. ISSN: 2049-1948. DOI: 10.1002/wat2.1087.

LTRID (Nov. 2017). *Landowner groundwater recharge & banking interim policy*. Last accessed on 24-2-2018. Lower Tulare Irrigation District. URL: http://www.ltrid.org/wp-content/uploads/_pdf/sgma/ilrp_approved_nov2017.pdf.

Maggioni, Elena (Jan. 2015). "Water demand management in times of drought: What matters for water conservation". In: *Water Resources Research* 51.1, pp. 125–139. ISSN: 00431397. DOI: 10.1002/2014WR016301.

Maliva, Robert G (2019). *Anthropogenic Aquifer Recharge*. Springer, Cham.

Mall, Natalie K and Jonathan D Herman (Oct. 2019). "Water shortage risks from perennial crop expansion in California's Central Valley". In: *Environmental Research Letters* 14.10, p. 104014. DOI: 10.1088/1748-9326/ab4035.

Mann, Henry B. (July 1945). "Nonparametric Test Against Trend". English. In: *Econometrica* 13.3, 245–259. ISSN: 0012-9682. DOI: {10.2307/1907187}.

Manning, Colin, Martin Widmann, Emanuele Bevacqua, Anne F Van Loon, Douglas Maraun, and Mathieu Vrac (Aug. 2019). "Increased probability of compound long-duration dry and hot events in Europe during summer (1950–2013)". In: *Environmental Research Letters* 14.9, p. 094006. DOI: 10.1088/1748-9326/ab23bf.

Mansour, M.M. and A.G. Hughes (2018). "Summary of results for national scale recharge modelling under conditions of predicted climate change". British Geological Survey 136pp. (OR/17/026) (Unpublished). Nottingham, UK.

Maples, Stephen R., Graham E. Fogg, and Reed M. Maxwell (Dec. 2019). "Modeling managed aquifer recharge processes in a highly heterogeneous, semi-confined aquifer system". In: *Hydrogeology Journal* 27.8, pp. 2869–2888. ISSN: 1435-0157. DOI: 10.1007/s10040-019-02033-9.

Marchant, BP and JP Bloomfield (2018). "Spatio-temporal modelling of the status of groundwater droughts". In: *Journal of Hydrology* 564, pp. 397–413.

Marechal, Jean-Christophe, Madjid Bouzit, Jean-Daniel Rinaudo, Fanny Moiroux, Jean-Francois Desprats, and Yvan Caballero (Mar. 2020). "Mapping Economic Feasibility of Managed Aquifer Recharge". English. In: *WATER* 12.3. DOI: {10.3390/w12030680}.

Margariti, J., S. Rangecroft, S. Parry, D.E Wendt, and A.F Van Loon (July 2019). “Anthropogenic activities alter drought termination”. In: *Elementa: Science of the Anthropocene* 7. Open Access paper - full text available via Official URL link.

Marsh, Terry, Gwyneth Cole, and Rob Wilby (2007). “Major droughts in England and Wales, 1800-2006”. In: *Royal Meteorological Society* 62.4, pp. 87–93. ISSN: 00431656. DOI: 10.1002/wea.67.

Marsh, Terry and Jamie Hannaford, eds. (2008). *UK hydrometric register. A catalogue of river flow gauging stations and observation wells and boreholes in the United Kingdom together with summary hydrometric and spatial statistics*. Hydrological Data UK. Centre for Ecology & Hydrology.

Marsh, Terry, Simon Parry, Mike Kendon, and Jamie Hannaford (Oct. 2013). *The 2010-12 drought and subsequent extensive flooding: a remarkable hydrological transformation*. Tech. rep. Wallingford.

Martínez-Santos, Pedro, M. Ramón Llamas, and Pedro E. Martínez-Alfaro (2008). “Vulnerability assessment of groundwater resources: A modelling-based approach to the Mancha Occidental aquifer, Spain”. In: *Environmental Modelling and Software* 23.9, pp. 1145–1162. ISSN: 13648152. DOI: 10.1016/j.envsoft.2007.12.003.

Masciopinto, Costantino, Michele Vurro, Vito Nicola Palmisano, and Isabella Serena Liso (2017). “A Suitable Tool for Sustainable Groundwater Management”. In: *Water Resources Management* 31.13, pp. 4133–4147. ISSN: 1573-1650.

Maurice, L.D., T.C. Atkinson, J.A. Barker, J.P. Bloomfield, A.R. Farrant, and A.T. Williams (2006). “Karstic behaviour of groundwater in the English Chalk”. In: *Journal of Hydrology* 330.1, pp. 63–70. ISSN: 0022-1694. DOI: https://doi.org/10.1016/j.jhydrol.2006.04.012.

Maxwell, Reed M. and Laura E. Condon (2016). “Connections between groundwater flow and transpiration partitioning”. In: *Science* 353.6297, pp. 377–380. ISSN: 0036-8075. DOI: 10.1126/science.aaf7891.

Mckee, Thomas B, Nolan J Doesken, and John Kleist (1993). “The relationship of drought frequency and duration to time scales”. In: 1. Fort Collins, Colorado, pp. 179–184. DOI: citeulike-article-id:10490403.

Medellín-Azuara, Josué, Duncan MacEwan, Richard E. Howitt, George Koruakos, Emin C. Dogrul, Charles F. Brush, Tariq N. Kadir, Thomas Harter, Forrest Melton, and Jay R. Lund (2015). “Hydro-economic analysis of groundwater pumping for irrigated agriculture in California’s Central Valley, USA”. In: *Hydrogeology Journal* 23.6, pp. 1205–1216. ISSN: 1435-0157.

Megdal, Sharon B., Peter Dillon, and Kenneth Seasholes (2014). “Water Banks: Using Managed Aquifer Recharge to Meet Water Policy Objectives”. In: *Water* 6.6, pp. 1500–1514. ISSN: 2073-4441. DOI: 10.3390/w6061500.

Mishra, Ashok K. and Vijay P. Singh (2010). “A review of drought concepts”. In: *Journal of Hydrology* 391.1-2, pp. 202–216. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2010.07.012.

Muller, M (2018). “Cape Town’s drought: don’t blame climate change.” In: *Nature* 559.7713, pp. 174–176.

Mustafa, Syed Md. Touhidul, Khodayar Abdollahi, Boud Verbeiren, and Marijke Huysmans (Aug. 2017). “Identification of the influencing factors on groundwater drought and depletion in north-western Bangladesh”. In: *Hydrogeology Journal* 25.5, pp. 1357–1375. ISSN: 1435-0157. DOI: 10.1007/s10040-017-1547-7.

Niswonger, Richard G, Eric D Morway, Enrique Triana, and Justin L Huntington (2017). “Managed aquifer recharge through off-season irrigation in agricultural regions”. In: *Water Resources Research* 53.8, pp. 6970–6992.

Noorduijn, Saskia L., Peter G. Cook, Craig T. Simmons, and Stuart B. Richardson (2019). “Protecting groundwater levels and ecosystems with simple management approaches”. In: *Hydrogeology Journal* 27.1, pp. 225–237. ISSN: 1435-0157.

O’Geen, A, Matthew Saal, Helen Dahlke, David Doll, Rachel Elkins, Allan Fulton, Graham Fogg, Thomas Harter, J Hopmans, Chuck Ingels, et al. (2015). “Soil suitability index identifies potential areas for groundwater banking on agricultural lands". In: *California Agriculture* 69.2, pp. 75–84.

O'Meagher, B., L. G. Du Pisani, and D. H. White (1998). "Evolution of drought policy and related science in Australia and South Africa". In: *Agricultural Systems* 57.3, pp. 231–258. ISSN: 0308521X. DOI: 10.1016/S0308-521X(98)00017-1.

Ofwat (2020). *Water companies in England and Wales*. Website: last visit on 2-09-2020. Ofwat.

Ohdedar, Birsha (2017). "Groundwater law, abstraction, and responding to climate change: assessing recent law reforms in British Columbia and England". In: *Water International* 42.6, pp. 691–708. DOI: 10.1080/02508060.2017.1351059.

Ojha, Chandrakanta, Manoochehr Shirzaei, Susanna Werth, Donald F. Argus, and Tom G. Farr (2017). "Sustained Groundwater Loss in California's Central Valley Exacerbated by Intense Drought Periods". In: *Water Resources Research* 54.0, pp. 1–11. DOI: 10.1029/2017WR022250.

Özerol, Gül (2019). "National and Local Actors of Drought Governance in Europe". In: *Facing Hydrometeorological Extreme Events*. John Wiley |& Sons, Ltd. Chap. 12, pp. 171–188. ISBN: 9781119383567. DOI: 10.1002/9781119383567.ch12.

Panda, Dileep K., A. Mishra, S.K. Jena, B.K. James, and A. Kumar (2007). "The influence of drought and anthropogenic effects on groundwater levels in Orissa, India". In: *Journal of Hydrology* 343.3, pp. 140–153. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2007.06.007.

Parry, Simon, Rob Wilby, Christel Prudhomme, Paul Wood, and Andrew McKenzie (June 2018). "Demonstrating the utility of a drought termination framework: prospects for groundwater level recovery in England and Wales in 2018 or beyond". English. In: *Environmental Research Letters* 13.6. DOI: {10.1088/1748-9326/aac78c}.

Pathak, Abhishek A. and B. M. Dodamani (Oct. 2018). "Trend Analysis of Groundwater Levels and Assessment of Regional Groundwater Drought: Ghataprabha River Basin, India". In: *Natural Resources Research.* ISSN: 1573-8981. DOI: 10.1007/s11053-018-9417-0.

Peters, E., G. Bier, H. A J Van Lanen, and P. J J F Torfs (2006). "Propagation and spatial distribution of drought in a groundwater catchment". In: *Journal of Hydrology* 321.1-4, pp. 257–275. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2005.08.004.

Preston, William L (1981). *Vanishing landscapes: Land and life in the Tulare Lake Basin.* University of California Press.

Prudhomme, Christel, Ignazio Giuntoli, Emma L Robinson, Douglas B Clark, Nigel W Arnell, Rutger Dankers, Balázs M Fekete, Wietse Franssen, Dieter Gerten, Simon N Gosling, Stefan Hagemann, David M Hannah, Hyungjun Kim, Yoshimitsu Masaki, Yusuke Satoh, Tobias Stacke, Yoshihide Wada, and Dominik Wisser (Mar. 2014). "Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment." In: *Proceedings of the National Academy of Sciences of the United States of America* 111.9, pp. 3262–3267. ISSN: 1091-6490. DOI: 10.1073/pnas.1222473110.

Radcliffe, John C. (2015). "Water recycling in Australia – during and after the drought". In: *Environ. Sci.: Water Res. Technol.* 1 (5), pp. 554–562. DOI: 10.1039/C5EW00048C.

Rangecroft, Sally, Anne F. Van Loon, Héctor Maureira, Koen Verbist, and David M. Hannah (2019). "An observation-based method to quantify the human influence on hydrological drought: upstream–downstream comparison". In: *Hydrological Sciences Journal* 64.3, pp. 276–287. DOI: 10.1080/02626667.2019.1581365.

Rateb, Ashraf, Bridget R. Scanlon, Donald R. Pool, Alexander Sun, Zizhan Zhang, Jianli Chen, Brian Clark, Claudia C. Faunt, Connor J. Haugh, Mary Hill, Christopher Hobza, Virginia L. McGuire, Meredith Reitz, Hannes Müller Schmied, Edwin H. Sutanudjaja, Sean Swenson, David Wiese, Youlong Xia, and Wesley Zell (2020). "Comparison of Groundwater Storage Changes from GRACE Satellites with Monitoring and Modeling of Major U.S. Aquifers". In: *Water Resources Research* in press, e2020WR027556. DOI: https://doi.org/10.1029/2020WR027556.

Rens, I.E.M. de Graafand, van Beek, Gleeson, Moosdorf, Schmitz, Sutanudjaja, and Bierkens (2017). "A global-scale two-layer transient groundwater model: Development and application to groundwater depletion". In: *Advances in Water Resources* 102, pp. 53–67. ISSN: 0309-1708. DOI: https://doi.org/10.1016/j.advwatres.2017.01.011.

Rey, Dolores, Ian P Holman, and Jerry W Knox (2017). "Developing drought resilience in irrigated agriculture in the face of increasing water scarcity". In: *Regional Environmental Change* 17.5, pp. 1527–1540.

Rio, M., D. Rey, C. Prudhomme, and I. P. Holman (July 2018). "Evaluation of changing surface water abstraction reliability for supplemental irrigation under climate change". English. In: *Agricultural Water Management* 206, 200–208. ISSN: 0378-3774. DOI: {10.1016/j.agwat.2018.05.005}.

Robeson, Scott M (2015). "Revisiting the recent California drought as an extreme value". In: *Geophysical Research Letters* 42.16, pp. 6771–6779.

Robinson, E.L., E. Blyth, D.B. Clark, E. Comyn-Platt, J. Finch, and A.C. Rudd (2016). *Climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain (1961-2015)*. DOI: 10.5285/8baf805d-39ce-4dac-b224-c926ada353b7.

Rodina, Lucy (2019). "Water resilience lessons from Cape Town's water crisis". In: *WIREs Water* 6.6, e1376. DOI: 10.1002/wat2.1376.

Rohde, Melissa, Janny Choy, and Geoff McGhee (2014). *Recharge: Groundwater's Second Act.* Website. DOI: https://waterinthewest.stanford.edu/groundwater/recharge/#note.

Rolls, Robert J., Catherine Leigh, and Fran Sheldon (2012). "Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration". In: *Freshwater Science* 31.4, pp. 1163–1186. DOI: 10.1899/12-002.1.

Russo, Tess A and Upmanu Lall (2017). "Depletion and response of deep groundwater to climate-induced pumping variability". In: *Nature Geoscience* 10.2, p. 105.

Rust, W., I. Holman, J. Bloomfield, M. Cuthbert, and R. Corstanje (2019). "Understanding the potential of climate teleconnections to project future groundwater drought". In: *Hydrology and Earth System Sciences* 23.8, pp. 3233–3245. DOI: 10.5194/hess-23-3233-2019.

Sadri, S., J. Kam, and J. Sheffield (2016). "Nonstationarity of low flows and their timing in the eastern United States". In: *Hydrology and Earth System Sciences* 20.2, pp. 633–649. DOI: 10.5194/hess-20-633-2016.

Sallwey, Jana, Robert Schlick, Jose Pablo Bonilla Valverde, Ralf Junghanns, Felipe Vasquez Lopez, and Catalin Stefan (Nov. 2019). "Suitability Mapping for Managed Aquifer Recharge: Development of Web-Tools". English. In: *WATER* 11.11. DOI: {10.3390/w11112254}.

Scanlon, B. R, C.C. Faunt, L. Longuevergne, R.C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon (2012a). "Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley". In: *Proceedings of the National Academy of Sciences* 109.24, pp. 9320–9325. ISSN: 0027-8424. DOI: 10.1073/pnas.1200311109.

Scanlon, B. R., L. Longuevergne, and D. Long (2012b). "Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA". In: *Water Resources Research* 48.4. DOI: 10.1029/2011WR011312.

Scanlon, Bridget R, Robert C Reedy, Claudia C Faunt, Donald Pool, and Kristine Uhlman (Mar. 2016). "Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona". In: *Environmental Research Letters* 11.3, p. 035013. ISSN: 1748-9326. DOI: 10.1088/1748-9326/11/3/035013.

Seibert, J. (2000). "Multi-criteria calibration of a conceptual runoff model using a genetic algorithm". In: *Hydrology and Earth System Sciences* 4.2, pp. 215–224. DOI: 10.5194/hess-4-215-2000.

SGMA (Sept. 2014). *Sustainable Groundwater Management Act (SGMA)*. Online Legislation : http://www.opr.ca.gov/docs/2014_Sustainable_Groundwater_Management_Legislation_092914.pdf. Last accessed on 24-02-2018. CA.gov.

Shepley, M.G., A.D. Pearson, G.D. Smith, and C.J. Banton (2008). "The impacts of coal mining subsidence on groundwater resources management of the East Midlands Permo-Triassic Sandstone aquifer, England". In: *Quarterly Journal of Engineering Geology and Hydrogeology* 41.3, pp. 425–438. ISSN: 1470-9236. DOI: 10.1144/1470-9236/07-210.

Shepley, M.G., M. Streetly, K. Voyce, and F. Bamford (2009). "Management of stream compensation for a large conjunctive use scheme, Shropshire, UK". In: *Water and Environment Journal* 23.4, pp. 263–271. DOI: 10.1111/j.1747-6593.2008.00158.x.

Shepley, Martin G, MI Whiteman, PJ Hulme, and MW Grout (2012). "Introduction: groundwater resources modelling: a case study from the UK". In: *Geological Society, London, Special Publications* 364.1, pp. 1–6.

Shepley, MG and M Streetly (2007). "The estimation of 'natural'summer outflows from the Permo-Triassic Sandstone aquifer, UK". In: *Quarterly Journal of Engineering Geology and Hydrogeology* 40.3, pp. 213–227.

Siebert, Stefan, Jacob Burke, Jean-Marc Faures, Karen Frenken, Jippe Hoogeveen, Petra Döll, and Felix Theodor Portmann (2010). "Groundwater use for irrigation–a global inventory". In: *Hydrology and earth system sciences* 14.10, pp. 1863–1880. DOI: 10.5194/hess-14-1863-2010.

Simpson, Nicholas Philip, Kayleen Jeanne Simpson, Clifford D. Shearing, and Liza Rose Cirolia (2019). "Municipal finance and resilience lessons for urban infrastructure management: a case study from the Cape Town drought". In: *International Journal of Urban Sustainable Development* 11.3, pp. 257–276. DOI: 10.1080/19463138.2019.1642203.

Sivapalan, Murugesu, Hubert H. G. Savenije, and Günter Blöschl (2012). "Socio-hydrology: A new science of people and water". In: *Hydrological Processes* 26.8, pp. 1270–1276. DOI: 10.1002/hyp.8426.

Sprenger, C., N. Hartog, M. Hernández, E. Vilanova, G. Grützmacher, F. Scheibler, and S. Hannappel (2017). "Inventory of managed aquifer recharge sites in Europe: historical development, current situation and perspectives". In: *Hydrogeology Journal.* ISSN: 1431-2174. DOI: 10.1007/s10040-017-1554-8.

Stagge, J H., Daniel G. Kingston, Lena M. Tallaksen, and David M. Hannah (2017). "Observed drought indices show increasing divergence across Europe". In: *Scientific Reports* 7.1, p. 14045. ISSN: 2045-2322.

Stagge, James H., Lena M. Tallaksen, Lukas Gudmundsson, Anne F. Van Loon, and Kerstin Stahl (Nov. 2015). "Candidate Distributions for Climatological Drought Indices (SPI and SPEI)". In: *International Journal of Climatology* 35.13, pp. 4027–4040. ISSN: 08998418. DOI: 10.1002/joc.4267.

Stefan, Catalin and Nienke Ansems (2018). "Web-based global inventory of managed aquifer recharge applications". In: *Sustainable Water Resources Management* 4.2, pp. 153–162. ISSN: 2363-5045.

Stoelzle, Michael, Kerstin Stahl, Andreas Morhard, and Markus Weiler (2014). "Streamflow sensitivity to drought scenarios in catchments with different geology". In: *Geophysical Research Letters* 41.17, pp. 6174–6183. ISSN: 19448007. DOI: 10.1002/2014GL061344.

Stoelzle, Michael, Markus Weiler, Kerstin Stahl, Andreas Morhard, and Tobias Schuetz (2015). "Is there a superior conceptual groundwater model structure for baseflow simulation?" In: *Hydrological processes* 29.6, pp. 1301–1313.

Stone, Roger C (2014). "Constructing a framework for national drought policy : The way forward – The way Australia developed and implemented the national drought policy". In: *Weather and Climate Extremes* 3, pp. 117–125. ISSN: 2212-0947. DOI: 10.1016/j.wace.2014.02.001.

Svensson, Cecilia, Jamie Hannaford, and Ilaria Prosdocimi (2017). "Statistical distributions for monthly aggregations of precipitation and streamflow in drought indicator applications". In: *Water Resources Research* 53.2, pp. 999–1018. DOI: 10.1002/2016WR019276.

Svoboda, Mark, Doug LeComte, Mike Hayes, Richard Heim, Karin Gleason, Jim Angel, Brad Rippey, Rich Tinker, Mike Palecki, David Stooksbury, et al. (2002). "The drought monitor". In: *Bulletin of the American Meteorological Society* 83.8, pp. 1181–1190.

Swain, Daniel L, Baird Langenbrunner, J David Neelin, and Alex Hall (2018). "Increasing precipitation volatility in twenty-first-century California". In: *Nature Climate Change* 8.5, p. 427.

Tallaksen, Lena M., Hege Hisdal, and Henny A.J. Van Lanen (2009). "Space–time modelling of catchment scale drought characteristics". In: *Journal of Hydrology* 375.3, pp. 363–372. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.06.032.

Tallaksen, Lena M. and Henny A. J. Van Lanen (2004). *Hydrological drought : processes and estimation methods for streamflow and groundwater*. Vol. 48. Elsevier, p. 579. ISBN: 0444517677.

Tanguy, M., H. Dixon, I. Prosdocimi, D. G. Morris, and V. D. J. Keller (2016). *Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2015)*. DOI: 10.5285/33604ea0-c238-4488-813d-0ad9ab7c51ca.

Taniguchi, M. (2011). *Groundwater and Subsurface Environments: Human Impacts in Asian Coastal Cities*. Springer Japan. ISBN: 9784431539049. DOI: 10.1007/978-4-431-53904-9_1.

Tanji, Kenneth K and Neeltje C Kielen (2002). *Agricultural drainage water management in arid and semi-arid areas*. FAO.

Taylor, Richard G., Bridget Scanlon, Petra Doell, Matt Rodell, Rens van Beek, Yoshihide Wada, Laurent Longuevergne, Marc Leblanc, James S. Famiglietti, Mike Edmunds, Leonard Konikow, Timothy R. Green, Jianyao Chen, Makoto Taniguchi, Marc F. P. Bierkens, Alan MacDonald, Ying Fan, Reed M. Maxwell, Yossi Yechieli, Jason J. Gurdak, Diana M. Allen, Mohammad Shamsudduha, Kevin Hiscock, Pat J. -F. Yeh, Ian Holman, and Holger Treidel (Apr. 2013). "Ground water and climate change". English. In: *Nature Climate Change* 3.4, 322–329. ISSN: 1758-678X. DOI: {10.1038/NCLIMATE1744}.

Teuling, Adriaan J. (2018). "A hot future for European droughts". In: *Nature Climate Change* 8.5, pp. 364–365. ISSN: 1758-6798.

Thames Water (2020). *North London Artificial Recharge Scheme*. Website. Thames Water. DOI: https://cycles.thameswater.co.uk/Thames-Water/Thames-Water/help-and-advice/water-quality/where-our-water-comes-from/north-london-artificial-recharge-scheme.

Thomann, Jason A., Adrian D. Werner, Dylan J. Irvine, and Matthew J. Currell (2020). "Adaptive management in groundwater planning and development: A review of theory and applications". In: *Journal of Hydrology* 586, p. 124871. ISSN: 0022-1694. DOI: https://doi.org/10.1016/j.jhydrol.2020.124871.

Thomas, B.F., F.W. Landerer, D.N. Wiese, and J.S. Famiglietti (2016). "A comparison of watershed storage trends over the eastern and upper Midwestern regions of the United States, 2003–2015". In: *Water Resources Research* 52.8, pp. 6335–6347. DOI: 10.1002/2016WR018617.

Thomas, Brian F, Júlio Caineta, and Jamiat Nanteza (2017a). "Global assessment of groundwater sustainability based on storage anomalies". In: *Geophysical Research Letters* 44.22.

Thomas, Brian F. (Feb. 2019). "Sustainability indices to evaluate groundwater adaptive management: a case study in California (USA) for the Sustainable Groundwater Management Act". In: *Hydrogeology Journal* 27.1, pp. 239–248. ISSN: 1435-0157. DOI: 10.1007/s10040-018-1863-6.

Thomas, Brian F. and James S. Famiglietti (Sept. 2015). "Sustainable Groundwater Management in the Arid Southwestern US: Coachella Valley, California". In: *Water Resources Management* 29.12, pp. 4411–4426. ISSN: 0920-4741. DOI: 10.1007/s11269-015-1067-y.

Thomas, Brian F., James S. Famiglietti, Felix W. Landerer, David N. Wiese, Noah P. Molotch, and Donald F. Argus (2017b). “GRACE Groundwater Drought Index: Evaluation of California Central Valley groundwater drought”. In: *Remote Sensing of Environment* 198, pp. 384–392. ISSN: 0034-4257. DOI: https://doi.org/10.1016/j.rse.2017.06.026.

Thorne, J. M., D. A. Savic, and A. Weston (2003). “Optimised Conjunctive Control Rules for a System of Water Supply Sources: Roadford Reservoir System (U.K.)” In: *Water Resources Management* 17.3, pp. 183–196. ISSN: 1573-1650.

Thornton, P.E., M.M. Thornton, B.W. Mayer, Y. Wei, R. Devarakonda, R.S. Vose, and R.B. Cook (2017). *DAYMET: Daily Surface Weather Data on a 1-km Grid for North America, Version 3*. eng. https://daac.ornl.gov/DAYMET/guides/Daymet_V3_CFMosaics.html. DOI: 10.3334/ornldaac/1328.

Tijdeman, E. and L. Menzel (2020). “Controls on the development and persistence of soil moisture drought across Southwestern Germany”. In: *Hydrology and Earth System Sciences Discussions* 2020, pp. 1–20. DOI: 10.5194/hess-2020-307.

Tijdeman, Erik, Jamie Hannaford, and Kerstin Stahl (Feb. 2018). “Human influences on streamflow drought characteristics in England and Wales”. In: *Hydrology and Earth System Sciences* 22.2, pp. 1051–1064.

Tushaar, Shah (July 2009). “Climate change and groundwater: India’s opportunities for mitigation and adaptation”. In: *Environmental Research Letters* 4.3, p. 035005. DOI: 10.1088/1748-9326/4/3/035005.

Urquijo, Julia, David Pereira, Susana Dias, and Lucia De Stefano (Mar. 2017). “A methodology to assess drought management as applied to six European case studies”. In: *International Journal of Water Resources Development* 33.2, pp. 246–269. ISSN: 0790-0627. DOI: 10.1080/07900627.2016.1174106.

USBR (Dec. 2019). *About the Central Valley Project*. https://www.usbr.gov/mp/cvp/about-cvp.html. Last Updated: 12/18/19.

Van Lanen, H A J, N Wanders, L M Tallaksen, and A F Van Loon (2013). “Hydrological drought across the world: impact of climate and physical catchment structure”. In: *Hydrol. Earth Syst. Sci* 17, pp. 1715–1732. DOI: 10.5194/hess-17-1715-2013.

Drought propagation through the hydrological cycle (2006a). Vol. 308. Havana, Cuba, p. 122.

Drought propagation through the hydrological cycle (2006b). Vol. 308. Havana, Cuba, p. 122.

Van Loon, A. F., R. Kumar, and V. Mishra (2017). “Testing the use of standardised indices and GRACE satellite data to estimate the European 2015 groundwater drought in near-real time”. In: *Hydrology and Earth System Sciences* 21.4, pp. 1947–1971. DOI: 10.5194/hess-21-1947-2017.

Van Loon, A. F., S. Rangecroft, G. Coxon, J. A. Breña Naranjo, F. Van Ogtrop, and H. A. J. Van Lanen (2019). “Using paired catchments to quantify the human influence on hydrological droughts”. In: *Hydrology and Earth System Sciences* 23.3, pp. 1725–1739. DOI: 10.5194/hess-23-1725-2019.

Van Loon, A. F., E. Tijdeman, N. Wanders, H. A. J. Van Lanen, A. J. Teuling, and R. Uijlenhoet (Apr. 2014). “How climate seasonality modifies drought duration and deficit”. In: *Journal of Geophysical Research: Atmospheres* 119.8, pp. 4640–4656. ISSN: 2169897X. DOI: 10.1002/2013JD020383.

Van Loon, A. F. and H. A J Van Lanen (2013). “Making the distinction between water scarcity and drought using an observation-modeling framework”. In: *Water Resources Research* 49.3, pp. 1483–1502. ISSN: 00431397. DOI: 10.1002/wrcr.20147.

Van Loon, Anne F. (July 2015). “Hydrological drought explained”. en. In: *Wiley Interdisciplinary Reviews: Water* 2.4, pp. 359–392. ISSN: 2049-1948. DOI: 10.1002/wat2.1085.

Van Loon, Anne F., Tom Gleeson, Julian Clark, Albert I. J. M. Van Dijk, Kerstin Stahl, Jamie Hannaford, Giuliano Di Baldassarre, Adriaan J. Teuling, Lena M. Tallaksen, Remko Uijlenhoet, David M. Hannah, Justin Sheffield, Mark Svoboda, Boud Verbeiren, Thorsten Wagener, Sally Rangecroft, Niko Wanders, and Henny A. J. Van

Lanen (2016a). "Drought in the Anthropocene". In: *Nature Geoscience* 9.2, pp. 89–91. ISSN: 1752-0894. DOI: 10.1038/ngeo2646.

Van Loon, Anne F., Kerstin Stahl, Giuliano Di Baldassarre, Julian Clark, Sally Rangecroft, Niko Wanders, Tom Gleeson, Albert I. J. M. Van Dijk, Lena M. Tallaksen, Jamie Hannaford, Remko Uijlenhoet, Adriaan J. Teuling, David M. Hannah, Justin Sheffield, Mark Svoboda, Boud Verbeiren, Thorsten Wagener, and Henny A. J. Van Lanen (2016b). "Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches". In: *Hydrology and Earth System Sciences* 20.9, pp. 3631–3650. ISSN: 1607-7938. DOI: 10.5194/hess-20-3631-2016.

— (2016c). "Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches". In: *Hydrology and Earth System Sciences* 20.9, pp. 3631–3650. ISSN: 1607-7938. DOI: 10.5194/hess-20-3631-2016.

Van Tiel, M., A. J. Teuling, N. Wanders, M. J. P. Vis, K. Stahl, and A. F. Van Loon (2018). "The role of glacier changes and threshold definition in the characterisation of future streamflow droughts in glacierised catchments". In: *Hydrology and Earth System Sciences* 22.1, pp. 463–485. DOI: 10.5194/hess-22-463-2018.

Viglione, Alberto, Bruno Merz, Nguyen Viet Dung, Juraj Parajka, Thomas Nester, and Günter Blöschl (2016). "Attribution of regional flood changes based on scaling fingerprints". In: *Water Resources Research* 52.7, pp. 5322–5340. DOI: 10.1002/2016WR019036.

Voyce, Kevin (2008). "Groundwater Management: the Shropshire Groundwater Scheme". In: *Proc. Shropsh. Geol. Soc* 14, pp. 20–29.

Wada, Yoshihide, Ludovicus P H van Beek, Niko Wanders, and Marc F P Bierkens (Sept. 2013). "Human water consumption intensifies hydrological drought worldwide". In: *Environmental Research Letters* 8.3, p. 034036. ISSN: 1748-9326. DOI: 10.1088/1748-9326/8/3/034036.

Walker, S and HA Smithers (1998). "A review of the 1995–96 drought in the North West". In: *Water and Environment Journal* 12.4, pp. 273–279.

Wanders, N. and Y. Wada (2015). "Human and climate impacts on the 21st century hydrological drought". In: *Journal of Hydrology* 526, pp. 208–220. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2014.10.047.

Wang, Menghao, Shanhu Jiang, Liliang Ren, Chong-Yu Xu, Fei Yuan, Yi Liu, and Xiaoli Yang (2020). "An approach for identification and quantification of hydrological drought termination characteristics of natural and human-influenced series". In: *Journal of Hydrology* 590, p. 125384. ISSN: 0022-1694. DOI: https://doi.org/10.1016/j.jhydrol.2020.125384.

Ward, Philip J., Marleen C. de Ruiter, Johanna Mård, Kai Schröter, Anne Van Loon, Ted Veldkamp, Nina von Uexkull, Niko Wanders, Amir AghaKouchak, Karsten Arnbjerg-Nielsen, Lucinda Capewell, Maria Carmen Llasat, Rosie Day, Benjamin Dewals, Giuliano Di Baldassarre, Laurie S. Huning, Heidi Kreibich, Maurizio Mazzoleni, Elisa Savelli, Claudia Teutschbein, Harmen van den Berg, Anne van der Heijden, Jelle M.R. Vincken, Maarten J. Waterloo, and Marthe Wens (2020). "The need to integrate flood and drought disaster risk reduction strategies". In: *Water Security* 11, p. 100070. ISSN: 2468-3124. DOI: https://doi.org/10.1016/j.wasec.2020.100070.

Wendt, D. E., A. F. Van Loon, J. P. Bloomfield, and D. M. Hannah (2020). "Asymmetric impact of groundwater use on groundwater droughts". In: *Hydrology and Earth System Sciences* 24.10, pp. 4853–4868. DOI: 10.5194/hess-24-4853-2020.

Wendt, Doris E., Anne F. Van Loon, and Bridget R. Scanlon (Nov. 2019). "Exploring the long-term impact of MAR in Southern California". In: *Managed Aquifer Recharge: Local solutions to the global water crisis.* Ed. by E. Fernández Escalante. TRAGSA. Empresa de Transformación Agraria, S.A. (TRAGSA)C/ Maldonado, 5828006 Madrid, pp. 141–147.

Wendt, Doris Elise, Anne F Van Loon, Bridget R Scanlon, and David M. Hannah (Jan. 2021). "Managed Aquifer Recharge as a drought mitigation strategy in heavily-stressed aquifers". In: *Environmental Research Letters* 16.1, p. 014046. DOI: 10.1088/1748-9326/abcfe1.

Werner, Adrian D., Darren W. Alcoe, Carlos M. Ordens, John L. Hutson, James D. Ward, and Craig T. Simmons (2011). "Current Practice and Future Challenges in Coastal Aquifer Management: Flux-Based and Trigger-Level Approaches with Application to an Australian Case Study". In: *Water Resources Management* 25.7, pp. 1831–1853. ISSN: 1573-1650.

White, David H., Donald A. Wilhite, Bruce O'Meagher, and Graeme L. Hammer (Sept. 2001). "Highlights of Drought Policy and Related Science in Australia and the U.S.A." In: *Water International* 26.3, pp. 349–357. ISSN: 0250-8060. DOI: 10.1080/02508060108686927.

White, E. K., J. Costelloe, T. J. Peterson, A. W. Western, and E. Carrara (2019). "Do groundwater management plans work? Modelling the effectiveness of groundwater management scenarios". In: *Hydrogeology Journal* 27.7, pp. 2447–2470. ISSN: 1435-0157.

White, E. K., T. J. Peterson, J. Costelloe, A. W. Western, and E. Carrara (2016). "Can we manage groundwater? A method to determine the quantitative testability of groundwater management plans". In: *Water Resources Research* 52.6, pp. 4863–4882. DOI: 10.1002/2015WR018474.

Whitehead, Emily and A.R. Lawrence (2006). *The Chalk aquifer system of Lincolnshire*. Tech. rep. Contributors: J P Bloomfield, P J McConvey, J E Cunningham, M G Sumbler, D Watling, M Hutchinson. Keyworth, Nottingham.

Wilhite, D. A. (2000). *Drought: A Global Assessment*. Hazards and Disasters Series. Routledge.

Wilhite, Donald A., Mannava V.K. Sivakumar, and Roger Pulwarty (June 2014). "Managing drought risk in a changing climate: The role of national drought policy". In: *Weather and Climate Extremes* 3, pp. 4–13. ISSN: 22120947. DOI: 10.1016/j.wace.2014.01.002.

Wu, Hong, Mark D. Svoboda, Michael J. Hayes, Donald A. Wilhite, and Fujiang Wen (2007). “Appropriate application of the standardized precipitation index in arid locations and dry seasons”. In: *International Journal of Climatology* 27.1, pp. 65–79. DOI: 10.1002/joc.1371.

Xiao, Mu, Akash Koppa, Zelalem Mekonnen, Brianna R Pagán, Shengan Zhan, Qian Cao, Abureli Aierken, Hyongki Lee, and Dennis P Lettenmaier (2017). “How much groundwater did California’s Central Valley lose during the 2012–2016 drought?” In: *Geophysical Research Letters* 44.10, pp. 4872–4879.

Yang, Qian and Bridget R Scanlon (May 2019). “How much water can be captured from flood flows to store in depleted aquifers for mitigating floods and droughts? A case study from Texas, US”. In: *Environmental Research Letters* 14.5, p. 054011. DOI: 10.1088/1748-9326/ab148e.

Yevjevich, Vujica M (1967). “An objective approach to definitions and investigations of continental hydrologic droughts”. In: *Hydrology papers (Colorado State University); no. 23.*

Yue, Sheng, Paul Pilon, Bob Phinney, and George Cavadias (2002). “The influence of autocorrelation on the ability to detect trend in hydrological series”. In: *Hydrological Processes* 16.9, pp. 1807–1829. DOI: 10.1002/hyp.1095.

Yue, Sheng and ChunYuan Wang (June 2004). “The Mann-Kendall Test Modified by Effective Sample Size to Detect Trend in Serially Correlated Hydrological Series”. In: *Water Resources Management* 18.3, pp. 201–218. ISSN: 1573-1650. DOI: 10.1023/B:WARM.0000043140.61082.60.

Zhang, H. and K.M. Hiscock (2010). “"Modelling the impact of forest cover on groundwater resources: A case study of the Sherwood Sandstone aquifer in the East Midlands, UK"”. In: *"Journal of Hydrology"* 392.3, pp. 136–149. ISSN: 0022-1694. DOI: https://doi.org/10.1016/j.jhydrol.2010.08.002.