~~Demonstrating the impact of~~ Evaluating integrated ~~drought policies on~~ water management strategies to inform hydrological ~~droughts~~drought mitigation

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Abstract. Managing water-human systems ~~in times of water shortage and~~ during water shortages or droughts is key to avoid overexploitation of water resources ~~, particularly for groundwater, which~~ and in particular groundwater. Groundwater is a crucial water resource during droughts sustaining both environmental and anthropogenic water demand. Drought management is often guided by drought policies to avoid crisis management and ~~to~~ actively introduce management strategies~~during droughts~~.

5   However, the impact of drought management strategies on hydrological droughts is rarely assessed. In this study, we present a newly developed socio-hydrological model, simulating ~~feedbacks~~ the relation between water availability and managed water use over three decades. Thereby, we aim to assess the impact of drought policies on both ~~surface water~~ baseflow and groundwater droughts. We tested this model in an idealised, virtual catchment based on climate data, water resource management practices ~~,~~ and drought policies in England. The model includes surface water storage (reservoir), groundwater storage for a

10   range of hydrogeological conditions and optional imported surface water or groundwater. These modelled water sources can all be used to satisfy anthropogenic and environmental water demand. We tested four aspects of drought management strategies: 1) increased water supply, 2) restricted water demand, 3) conjunctive water use, and 4) maintained environmental flow requirements by restricting groundwater abstractions. These four strategies were evaluated in separate and combined scenarios. Results show mitigated droughts for both ~~streamflow~~ baseflow and groundwater droughts in scenarios applying conjunctive use,

15   particularly in ~~low groundwater storagesystems. In high groundwater storagesystems~~systems with small groundwater storage. In systems with large groundwater storage, maintaining environmental flows reduces hydrological droughts most. Scenarios increasing water supply or restricting water demand have an opposing effect on hydrological droughts, although these scenarios are in balance when combined at the same time. Most combined scenarios reduce the severity and occurrence of hydrological droughts given an incremental dependency on imported water that satisfies up to a third of the total anthropogenic water

20   demand. The necessity for importing water shows the considerable pressure on water resources and the delicate balance of water-human systems during droughts that calls for short-term and long-term sustainability targets within drought policies.

1 Introduction

Groundwater plays a key role sustaining natural and anthropogenic water demand during meteorological droughts (De Graaf
et al., 2019; Siebert et al., 2010; Döll et al., 2012). Meteorological droughts, defined as periods of sustained dry weather (Mishra
and Singh, 2010), reduce water availability in soil moisture, surface water ~~, and groundwater.~~ and eventually groundwater. Due
to the natural delay in groundwater recharge, it may take weeks, months, or even years before a precipitation deficit ~~propagate~~
propagates through the hydrological cycle~~. Groundwater is available~~, reducing groundwater storage levels (Tallaksen and Van Lanen, 2004;
~~.~~ This natural delay results in groundwater storage being available for longer compared to surface water~~and is often used to~~
~~complement~~, resulting in sustaining and complementing water demand during meteorological droughts (Taylor et al., 2013;
Cuthbert et al., 2019). Increased groundwater use may also result in aggravated streamflow droughts, a deficit in discharge
or reservoir storage (Mishra and Singh, 2010; Wada et al., 2013; Wanders and Wada, 2015). Deficits in groundwater, caused
by either low/absent recharge or increased groundwater use~~result in a~~, result in groundwater drought defined as a ~~below~~
~~normal groundwater level (Yevjevich, 1967; Tallaksen and Van Lanen, 2004). In this study, we focus on the human-modified~~
~~and human-induced hydrological droughts including surface water and groundwater use in below normal availability of~~
~~surface water or groundwater (Van Loon et al., 2016). Overexploitation of groundwater use, periodically during droughts~~
~~or permanently, may lead to groundwater depletion and reduced drought resilience (Custodio, 2002; Custodio et al., 2019).~~
below-normal groundwater levels (Yevjevich, 1967; Tallaksen and Van Lanen, 2004). Despite the important role of ground-
water storage availability during droughts, the question remains how groundwater storage can be managed best and whether
drought management strategies can meet both environmental and anthropogenic water demand (White et al., 2019).

When national or regional drought policies are in place, water management during meteorological and/or hydrological
droughts is guided to structure drought response and create drought resilience (Wilhite et al., 2014). Drought policies vary
in their structure, focus on (different) water users, and implementation ~~. Key elements are 1) a~~ that may be apparent in the
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~~ monitoring systems, risk
management plans and evaluation (Wilhite et al., 2014; De Stefano et al., 2015; 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 and Hayes, 2012), different US states (Fu et al., 2013), and European countries (De Stefano et al.,
2015; 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, EU 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., 2015; Urquijo et al., 2017) and currently there is no consistent methodology to assess drought policies with
respect to their impact on water resources or hydrological droughts.

Methodologies to investigate ~~feedback processes~~ interactions between water resource availability and drought management often use socio-hydrological models to capture both hydrological and anthropogenic responses in time (Sivapalan et al., 2012; Di Baldassarre et al., 2015). ~~In this emerging field of applying~~ Studies that use socio-hydrological models ~~to assess the impact of drought management, most studies~~ often focus on one specific measure of a drought policy. For example, studies focused on maintaining environmental flow requirements (Klaar et al., 2014), increased or altered groundwater use (Martínez-Santos et al., 2008; Apruv et al., 2017), restrictions on water demand (White et al., 2019), conjunctive (or integrated) 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), or creating awareness of water shortage during a meteorological drought (Garcia and Islam, 2019; Gonzales and Ajami, 2017). ~~Jaeger et al. (2019) are~~ Jaeger et al. (2019) were the first to model a set of drought policy measures ~~. They tested drought measures separately and combined, showing that reservoir regulations and timely interventions have a large~~ aiming to conserve water. However, drought policy measures, either separately or combined, were found to have less impact on streamflow droughts compared to timely reservoir regulations. Alternative water sources, such as groundwater were not considered. ~~Given the importance of and~~

Given the increasing dependency on groundwater ~~during drought (Aeschbach-Hertig and Gleeson, 2012; Taylor et al., 2013; Cuthbert et~~ ~~, there is a need to advance current~~ storage during meteorological droughts (Aeschbach-Hertig and Gleeson, 2012; Taylor et al., 2013; Cuthb ~~, drought policy modelling~~ ~~to include policies that apply to~~ should include both surface water and groundwater. ~~,~~ to reflect the additional complexity of different or possibly contrasting groundwater storage availability within or between water management regions. In natural systems, temporal variation in groundwater storage and aquifer-dependent delay between precipitation and groundwater storage and baseflow results in contrasting baseflow and groundwater drought characteristics (Peters et al., 2006; Van Lanen et . These contrasting hydrological drought characteristics change when impacted by (un)managed groundwater use (Tijdeman et al., 2018; We and overall drought resilience reduces when groundwater use exceeds sustainable limits (Custodio, 2002; Custodio et al., 2019) . On the other hand, targeted management strategies can also ease pressure on groundwater systems (Klaar et al., 2014; White et al., 2019) and encourage integrated water use aiming to increase drought resilience (Huggins et al., 2018; Scanlon et al., 2016; Jakeman et al., 2016) , highlighting their potential within drought policies.

This study aims to assess the impact of drought policies on hydrological droughts and water resource availability for a range of hydrogeological conditions. ~~For this, we used a lumped~~ These conditions refer to the availability of groundwater storage in a (virtual) catchment that is modelled for groundwater systems with overall large, medium and small groundwater availability. Hydrological droughts refer to both baseflow and groundwater, which might be either human-modified or human-induced droughts (Van Loon et al., 2016), as a consequence of water management (baseline) or drought management strategies, which are introduced either in separate or combined drought management strategies in an idealised socio-hydrological ~~model to simulate drought management strategies that apply to both surface water and groundwater. The~~ model. This socio-hydrological model represents an idealised ~~(simplified)~~ hydrological system that includes a surface water reservoir, a groundwater module ~~,~~ with either large, medium or small groundwater storage availability and an option to import surface water ~~. Environmental and anthropogenic water demand was met by withdrawing water from both surface water and groundwater stores. Scenarios were used to evaluate separate and combined drought management strategies that altered proportional water demand, source of water~~

90 ~~supply, and volume of imported surface water. These strategies were tested for a range of hydrogeological conditions (high, medium, and low groundwater storage systems) to assess their impact on different hydrological droughts and water resource availability depending on virtual catchment settings.~~ to meet either anthropogenic or environmental water demand.

2 Case study

To test and develop the socio-hydrological model, England is used as an case study considering the publicly available infor-
95 mation 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 demand on average and up to 90% in some densely populated regions (data from 2000-2015 published by Environment Agency (2019a), presented in A1). The privatised drinking water supply sector consists of 18 drinking water companies that provide drinking water in
100 England (Ohdedar, 2017; Ofwat, 2020). 13 out of the 18 companies use both surface water and groundwater, which water re-
source and drought management plans were used to inform baseline conditions and drought management scenarios (see ~~Table A1).~~ 3.2 Data and Table A1 for more details).

Water resource management plans show that the source of water supply varies depending on the regional variability of surface water and groundwater ~~.~~ availability. For example, ~~companies with access to principal aquifers might depend~~ in regions
105 with large groundwater storage availability water supply might rely more on groundwater compared to ~~companies with access to shallow, less productive aquifers~~ regions with smaller groundwater storage availability. In England this regional variability is reflected in the share of either surface water or groundwater for the thirteen drinking water companies (Table A1). In addition to locally available water, water transfers between drinking water companies are regularly used to overcome seasonal or annual shortages. These transfers also ease pressure on water resources and act as emergency supply during droughts (Dobson et al.,
110 2020). The overall pressure on water resources in the case study is considerable. During normal conditions the allocated water represents, on average, 88.5% of the long-term available water that might increase during periods of high water demand or droughts (Table A1, Environment 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 were used in this study (see A2 for references to regional drought management plans).
115 Drought management plans consist of five main components: 1) drought definition, 2) warning system based on drought trig-
ger levels, 3) demand management, 4) supply management, 5) evaluation of drought events (summarised in Table 1). Drought definitions and trigger levels are used to distinguish mild from severe drought events and activate management strategies with increasing severity (Table 1). These drought trigger levels are often based on deficits in ~~seasonal precipitation or the~~ monthly, seasonal or total precipitation in winter months (also called dry winters in drought management plans) that is the main ground-
120 water recharge period in the UK. Water levels in rivers, reservoirs, and selected groundwater boreholes are also used as drought triggers when, for example, flow or storage levels are falling low. Drought management plans list various demand-related and supply-related drought management strategies that are activated for certain drought severity stages (see Table 1). Most com-

Table 1. Recent drought management plans of thirteen drinking water companies with staged drought management strategies according to drought trigger levels (see A2 for references to the drought plans). Average drought trigger levels are shown (range shown in square brackets) based on drought plans with trigger levels under 100 years for initial drought stages. Demand management and water supply strategies are shown per drought severity stage with modelled impact in 4*th*^*th* and 7*th*^*th* column respectively. Note that model scenarios are based on averaged reported effects when estimated (range of expected/reported impact is in parenthesis). Surface water and groundwater are abbreviated as SW and GW respectively for readability.

Drought trigger level	Demand management strategy	Number of companies applying management strategy (#)	Modelled as	Supply management strategy	Number of companies applying management strategy (#)	Modelled as
Mild drought (1 in 8.5 year [5 yr - 20 yr])	Promote water use efficiency	13	Demand reduces	Maximise GW licence	3	GW use increases 4% (2-6%)
	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 (non-essential)	13	Demand reduces 5% (0-15%)	Maximise SW licence	6	SW use increases 6% (1-9%)
Moderate drought (1 in 22.5 year [10 yr - 80 yr])	Reduce pressure on water network	7	-	Deepening boreholes	4	-
				River augmentation	8	-
	Temporary use ban (Commercial)	12	Demand reduces 12% (1-33%)	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%)
				Maximise SW licence	10	SW use increases 14% (1-98%)
Severe drought (1 in 69 year [20 yr - 100 yr])	Phase winter & summer water use	4	-	Installation of additional GW wells	6	-
	Rota cuts	8	Demand reduces 36% (30-40%)	Reuse sewage water	5	-
				Maximise GW licence	10	GW use increases 12% (1-49%)
				Maximise SW licence	9	SW use increases 10% (2-26%)

monly applied strategies were implemented in the model (when permitted by the model setup) using the average effect of these measures, as reported in the drought management plans.

125 ## 3 ~~Model structure and dataThe~~ Modelling framework

The drought policies were modelled in a socio-hydrological model that consists of a water balance model ~~and a water demand model~~with water demand components. The water balance model is driven by daily climate data that was 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. Based on this investigation period, a 5-year spin-up period was used to determine initial conditions ~~(relevant to soil~~

130 ~~moisture and groundwater levels only). Note that this spin-up period includes~~ that included water demand, but no ~~drought~~

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(drought) management strategies. ~~Baseline and drought management scenarios started thus in 1985 and ended in 2017.~~ Natural (no water demand) model runs were used for reference purposes only (see time series in Figure A3).

Hydrological drought characteristics were calculated from the generated baseflow and groundwater level time series by applying a variable 80th percentile corresponding to a 'once every 5 year drought' (Yevjevich, 1967; Tallaksen and Van Lanen, 2004; Mishr. This drought threshold was calculated from the baseline scenario that was applied to drought management scenarios to evaluate the drought impact. In the sensitivity analysis, where alternative storage-outflow parameters were tested, new drought thresholds were calculated taking the 80th percentile of each baseline run (baseflow and groundwater storage time series) with an alternative parameters. Similar to the main analysis, impact of drought management strategies is computed from this baseline and new drought threshold.

~~Socio-hydrological model consisting of a soil moisture balance (1) driven by precipitation (P in mm d^{-1}) and potential evaporation (PET in mm d^{-1}), a reservoir (2) storing runoff (Qr mm d^{-1}), and a groundwater module (3) driven by groundwater recharge (Rch in mm d^{-1}). Anthropogenic water demand (4) is met by reservoir (Ares in mm d^{-1}) and groundwater (Agw in mm d^{-1}) abstractions. Natural water demand is represented by ecological flow requirements (Qeco in mm d^{-1}) abstracted as part of the baseflow (Qb in mm d^{-1}). Remaining baseflow is routed to the reservoir. Additional water is imported in the model when reservoir or groundwater storage is insufficient (Qimp and GSimp both in mm d^{-1}). Drought management scenarios apply to the reservoir, groundwater module, and water demand (illustrated by the yellow box).~~

3.1 ~~Model structure~~ Socio-hydrological model

The socio-hydrological ~~model structure~~ follows a standard conceptual water balance model with additional water demand components (Figure 1). The water balance model was based on the previously described lumped hydrological model of Van Lanen et al. 2013, who ~~followed the widely applicable~~ applied a modified ~~the standard~~ HBV model structure (Bergström, 1976) ~~. We extended the hydrological drought modelling regarding~~ to model hydrological droughts globally. We extended this hydrological drought model with three different groundwater storage options in the groundwater module~~and water demand component. The hydrological~~, introduced a term for environmental water demand, represented by the ecological minimum flow and defined anthropogenic water demand that could be altered following a drought management plan. The model is driven by ~~climate data , used as input for the~~ forcing data that was selected to be representative for the case study (England) and management settings and scenarios were likewise based on a range of water management and drought management plans converted to relative setting to be applied in the socio-hydrological model. In sum, the socio-hydrological model is thus driven by English climate data that drives the daily soil moisture balance, generating runoff ~~and groundwater rechargethat are routed further~~ an groundwater recharge. Runoff is directly routed to the surface water reservoir~~and groundwater module, respectively.~~ ~~The water demand model is based on the regionally-averaged water resource and drought management plans, representing water management in the case study area. .~~ Groundwater recharge is either stored or discharged depending on the groundwater storage option in the groundwater module. Water demand is met using a fraction of stored surface water and/or groundwater that can be imported externally in the model when storage is depleted. Drought management scenarios can alter the fraction of water demand and source of water supply that has an impact on hydrological droughts and water resource availability.
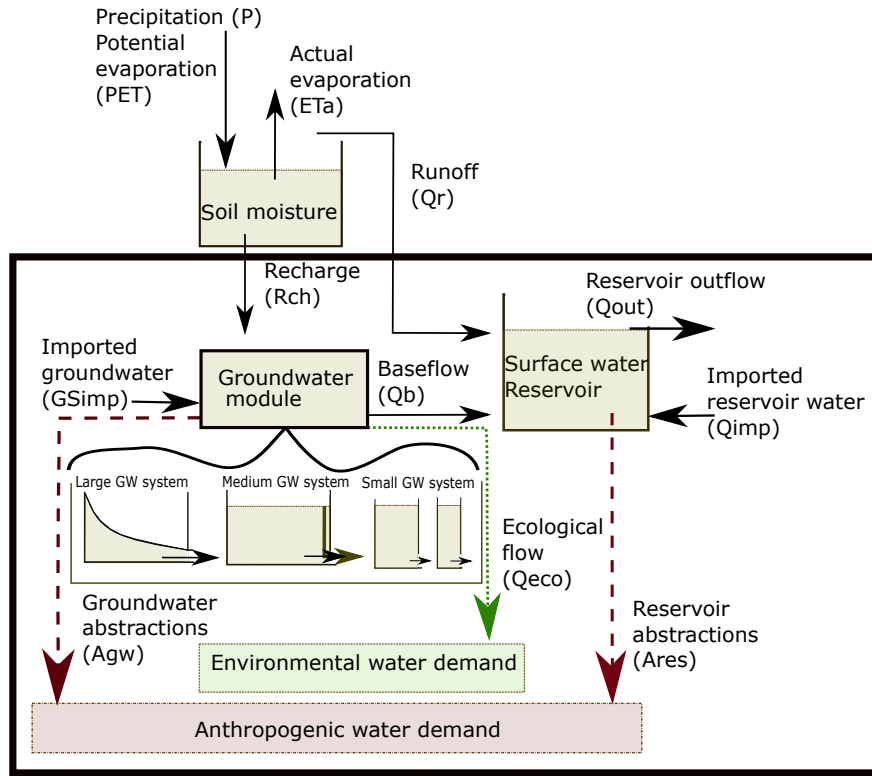
Figure 1. Socio-hydrological model consisting of a soil moisture balance driven by precipitation (P in mm d^{-1}) and potential evaporation (PET in mm d^{-1}), a surface water reservoir storing runoff (Qr mm d^{-1}), and a groundwater module that consists of three groundwater system options (large, medium, small groundwater availability) driven by groundwater recharge (Rch in mm d^{-1}). These three groundwater systems represent large, medium and small groundwater availability, modelled by a power law, by-pass and two parallel reservoir storages, respectively (see 3.2 for details). Anthropogenic water demand is met by reservoir abstractions (Ares in mm d^{-1}) and groundwater abstractions (Agw in mm d^{-1}), both in striped dark red arrows. Natural water demand is represented by ecological flow requirements (Qeco in mm d^{-1}; dotted green arrow) and abstracted as part of the baseflow (Qb in mm d^{-1}). Remaining baseflow is routed to the reservoir. Additional water is imported in the model when reservoir or groundwater storage is insufficient (Qimp and GSimp both in mm d^{-1}). Drought management scenarios apply to the surface water reservoir, groundwater module, and environmental and anthropogenic water demand (all model components in the thick black box).

3.2 Model components

The first model component is the soil moisture balance, represented by a medium soil (light silty loam soil: Soil II). The daily soil moisture balance (SS for daily time steps $_t$ in mm) is determined by incoming precipitation (P in mm d^{-1}), actual

evaporation (ETa in mm d^{-1}) that was calculated from potential evaporation (PET in mm d^{-1}), overland flow or runoff (Qr in mm d^{-1}) and groundwater recharge (Rch in mm d^{-1}) (Van Lanen et al., 2013).

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

ETa was taken equal to PET when SS_t is between field capacity (SS_{FC}) and critical soil moisture content (SS_{CR}), assuming that 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 (SS_{WP}) ETa was assumed to be zero (Van Lanen et al., 2013). 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).

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

Rch is calculated from the daily soil moisture content depending on the soil moisture retention shape parameter (b = 3 in average conditions; Seibert 2000) and the unsaturated hydraulic conductivity of Soil II (k_{FC})Van Lanen et al. 2013; Tanji and Kielen 2002; Equation 3).

$$Rch_t = \begin{cases} 0 & \text{if } SS_t \geq SS_{FC} \\ \left(\frac{SS_t - SS_{CR}}{SS_{FC} - SS_{CR}} \right)^b k_{FC} & \text{if } SS_{CR} < SS_t < SS_{FC} \\ 0 & \text{otherwise } SS_t \leq SS_{CR} \end{cases} \tag{3}$$

The annual average average annual runoff and groundwater recharge generated by the soil moisture balance also define defines the total available water for anthropogenic water demand (ADem in mm d^{-1})), following the water resource management plans in the case study area. Allocated water is taken ADem is defined as a fraction (88.5% f_{dem}) of the total available water and long-term average of annual runoff and groundwater recharge that is divided equally over the days of the year (Table A1). Equation 4). f_{dem} is defined by the proportional water use as reported by drinking water companies, see section 3.3 and Table A1 for more details.

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$$\tag{4}$$

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The second model component is a surface water reservoir storing runoff and baseflow (Figure 1). Stored water (in mm) is used to meet the surface water demand, which is 44.6% of allocated water in the baseline and variable in the drought management scenarios. Maximum reservoir storage is set to one year of winter recharge, defined as the long-term total precipitation in the period December to February. Excess reservoir storage (Qout in mm d^{-1}) leaves the model and is not used to meet surface water demand. When storage declines, additional (unlimited) surface water (Qimp in mm d^{-1}) is imported in the baseline scenario. In drought management scenarios, reservoir storage is refilled when storage levels are below 25%, representing the regular water transfers as part of the drought management strategies (see Table 1; also described in Dobson et al. 2020).

The third model component is the groundwater module ~~that has three different options for hydrogeological conditions used for both baseline and drought management scenarios. These three options represent~~ storing groundwater recharge (groundwater storage (GS in mm) and generating baseflow (Qb in mm d^{-1})~~for different aquifer structures with high, medium, and low groundwater storage (GS in mm). Groundwater storage systems are based on the~~. The groundwater module has three different parallel options for groundwater storage availability, representing different hydrogeological conditions. The first option is named 'large groundwater storage system' referring to an overall large groundwater availability, as typically found in karstic groundwater systems (Stoelzle et al., 2015; Hartmann et al., 2014). The second option in the groundwater module is the 'medium groundwater storage system' referring to medium groundwater availability, as can be found in porous aquifers (Allen et al., 1997; Bloomfiel[d]. The last option is 'small groundwater storage system' referring to small groundwater availability typically found in shallow or weathered fractured aquifers (Allen et al., 1997; Stoelzle et al., 2015). These three parallel options are modelled using different model structures corresponding to a typical karstic, porous ~~, and fractured aquifers in Stoelzle et al. (2015)). Baseflow generation is determined by different~~ and fractured groundwater-outflow release (Stoelzle et al., 2015). Modelled storage-outflow ~~parameter values~~ parameters (s in d^{-1} ~~) and different discharge represented by the different equations for three groundwater systems. Modelled values for s~~ in Table 2) are based on ~~the range tested by Stoelzle et al. (2015) and cross-verified with mean~~ average characteristics found in English karstic, porous, and fractured ~~aquifer values as observed in England (Allen et al., 1997) (Table 2 with response time (in days) in parenthesis). Presented results are based on~~ aquifers (Allen et al., 1997) and tested parameters by Stoelzle et al. (2015). These two ranges of relevant storage-outflow parameters resulted in a mean s ~~values (third row in Table 2) and alternative s values were~~ parameter for the main result section with a large range tested in the sensitivity analysis.

~~Aquifer structures for high, medium, and low groundwater storage are calculated using different equations based on the work of Stoelzle et al. (2015). The high~~ The large groundwater storage system ~~is modelled with~~ was modelled by a non-linear power law (Equation 5) ~~using an average B value (~~representing the non-linear groundwater release in karstic aquifers (Wittenberg, 2003; Stoelzle et al., 2015). The non-linearity of outflow release was taken as 0.5 ~~) based on the tested range of B values by Stoelzle et al. (2015).~~ (B in Equation 5) allowing some turbulent flow that is typical for unconfined karstic aquifers

(Wittenberg, 2003).

~~High groundwater storage system =~~Large groundwater storage system =
$$\begin{cases} Qb_t = sGS_t^B \\ GS_t = GS_{t-1} + Rch_t - Qb_t - Agw_t \end{cases} \tag{5}$$

The medium groundwater storage system is ~~computed~~ represented by a linear storage reservoir with additional by-pass component (D; Equation 6) ~~. The by-pass component has a tested range of~~ that corresponds to the typical slow porous flow with possible leakage in English Permo-Triassic sandstone aquifers (Shepley et al., 2008; Allen et al., 1997). Possible leakage of groundwater recharge represents 10% based on the tested range (0.07-0.12~~by Stoelzle et al. (2015) and we used the average value (0.1) to allow 10% of groundwater recharge to by pass the groundwater system.~~) by Stoelzle et al. (2015), indicated with the coloured arrow in Figure 1.

Medium groundwater storage system =
$$\begin{cases} Qb_t = sGS_t + DRch_t \\ GS_t = GS_{t-1} + (1-D)Rch_t - Qb_t - Agw_t \end{cases} \tag{6}$$

The ~~low~~ small groundwater storage system is represented by two parallel linear storage reservoirs ~~with different storage-outflow parameters~~ (Equation 7)~~. The~~, referring to weathered, fractured aquifers with variable storage-outflow release (Stoelzle et al., 2015; Allen e. When applying this option in the groundwater module, total groundwater storage is a sum of both parallel storage reservoirs with different s parameter values, for which recharge and water demand is equally divided.

~~Low groundwater storage system =~~Small groundwater storage system =
$$\begin{cases} Qb_t = s_1GS1_t + s_2GS2_t \\ GS1_t = GS1_{t-1} + \frac{1}{2}Rch_t - s_1GS1_t - \frac{1}{2}Agw_t \\ GS2_t = GS2_{t-1} + \frac{1}{2}Rch_t - s_2GS2_t - \frac{1}{2}Agw_t \end{cases} \tag{7}$$

Groundwater abstractions (Agw in mm d^{-1}) were taken from the daily groundwater storage balance resulting in different time series for baseflow and groundwater storage for the three groundwater systems. From the generated baseflow, the ecological minimum flow (Qeco mm d^{-1}) is first withdrawn to allocate water for the environmental water demand. The remainder of baseflow is routed to the reservoir and available for anthropogenic surface water demand (Ares). This implies that on days when baseflow is less or equal to Qeco, no baseflow is routed to the reservoir and all available water is allocated for environmental water demand, even though this might be less than the environmental flow requirements. Maintaining environmental flow requirements is only applied in some drought management scenarios, in which groundwater demand is restricted when flows fall below the ecological flow threshold. If groundwater storage is depleted, additional (unlimited) groundwater storage (GSimp in mm d^{-1}) is imported to meet the groundwater demand that is additional to the water balance. In reality, additional groundwater would come from ~~other aquifer sections , extending~~ deeper or connected aquifer sections that would extend groundwater abstractions beyond the surface water catchment boundaries. ~~Hydrological drought characteristics were calculated applying a variable 80th percentile of the baseline baseflow and groundwater time series corresponding to a 'once every 5 year~~

250   ~~this baseline and new drought threshold.~~

Table 2. Groundwater storage-outflow s values (in d^{-1}) 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 (mean) s values for the three groundwater options in Equations 5-7. 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~~Large storage system (s in d^{-1})	Medium storage system (s in d^{-1})	~~Low~~Small storage system (s in d^{-1})
Optimal s values 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
Mean English s values by Allen et al. (1997)	0.009-0.04	0.0008-0.004	0.002-0.02
Modelled 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	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)

3.3   Data

Climate data for the hydrological model was selected to represent average climate conditions in England, providing an estimate for precipitation (P) and reference potential evaporation (PET). Therefore, a regionally-weighted precipitation product was selected (at a daily time scale; Alexander and Jones 2001). In the absence of a regional (weighted) product for PET, a centroid

255   location was selected to extracted daily time series from the (gridded) CHESS dataset of Robinson et al. 2016.

Water resource management plans were used to determine long-term (2000-2015) water demand and water availability for normal year (Environment Agency, 2019b). These documented water demand volumes were converted into a percentage (water use divided by available water) representing water allocation per drinking water company (see Table A1). ~~The average water allocation was 88.5% representing both surface water and groundwater demand. Between~~ This water allocation percentage

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260   is also called headroom by drinking water companies, as it indicates remaining room given the long-term water availability and allocated water use. Between the drinking water companies, water allocation varied between 82% and 95% (Table A1) with an average of 88.5%, which was used in the main analysis to define the total anthropogenic water demand as a fraction of the long-term available water (f_{dem} in Equation 4). The range of higher/lower water allocation was further explored in the sensitivity analysis by in/decreasing water allocation with 5% (to 93.5% and 83.5% respectively). The proportions of

265   surface water and groundwater allocation also varied between companies and an average was used for surface water (44.6%) and groundwater (48.5%) demand. The remaining water demand (6.9%) was provided by imported water representing water transfers between companies during normal conditions and during droughts (Dobson et al., 2020). Considering the large range of surface water and groundwater demand between the companies (15-88% and 10-84%, respectively), alternative proportions of surface water and groundwater demand were tested in the scenarios.

270   Data from the regionally-averaged drought management plans was used to define drought trigger levels and activate drought management strategies related to the indicated drought severity by trigger levels (Table 1). Modelled trigger levels were based on averaged reported ~~drought trigger levels , excluding extremely~~ levels for precipitation anomalies (in monthly SPI). This average excludes reported extremely low SPI values (SPI < -2.32) or long return periods (100-150 year) for initial drought stages. Trigger levels are applied to precipitation (~~using monthly SPI) , streamflow ,~~ in SPI) and converted to percentiles for

275   streamflow and groundwater level time series, as is common for the drinking water companies. For example, ~~if either~~ the first category of drought management strategies can be activated due to a anomaly in precipitation, surface water or groundwater falls below the trigger level ~~, for example, in~~ corresponding to a 1 in 8.5 year drought event ~~, the first category of drought management strategies will be activated.~~ (SPI < -1.18). Different trigger levels are applied to reservoir storage levels that are kept relatively full with a 30-60 day emergency storage. Reservoir trigger levels in the first drought category typically start

280   from 80% to 60% of reservoir storage, second category from 60% to 30%, and the last from 30% to 12%. These percentages are converted to reservoir trigger levels of 75%, 50%, and 25%.

    Based on the listed drought management strategies, four scenarios were developed testing first four separate strategies (Table 3). The first scenario focuses on water supply and includes an increase in water ~~demand~~ supply for both surface water and groundwater based on the reported range in Table 1. The second scenario focused on restricting water demand and

285   reduces surface water and groundwater demand based on reported (achieved or modelled) water demand reductions (Table 1). The third scenario introduced conjunctive water use as a drought management strategy that integrates surface water and groundwater demand. ~~Daily~~ In this scenario, daily water demand is provided by either water source depending on the highest available storage. The fourth scenario ~~maintains~~ meets ecological flow requirements that aims to maintain baseflow in connected streams by reducing groundwater abstractions (also known as 'hands off flow'~~). Environmental water demand~~ :

290   Environment Agency 2019c). This scenario is relevant to drinking water companies using both surface water and groundwater that might apply for drought permits reducing ecological flows during severe droughts (Environment Agency, 2016). In this scenario, the ecological minimum flow (represented by environmental water demand), is maintained by restricting groundwater demand when baseflow falls below the seasonal ecological minimum flow threshold (80th ~~percentage~~percentile based on monthly data). In addition to these four separate drought management strategy scenarios, two combined scenarios were tested

295 to investigate the combined effect of gradual in/decrease of water demand with either conjunctive use (scenario 'combined 1-2-3'), or maintaining the ecological flow (scenario 'combined 1-2-4').

Table 3. Description of rules applicable to the four separate drought management strategy scenarios. 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. Modelled scenarios are based on (averaged) documented drought management strategies, see Table 1 for details.

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

4 Results

The results are presented in four sections starting with baseline conditions for the three modelled hydrogeological conditions. Next, drought management scenarios are presented and their impact on hydrological droughts is shown relative to the baseline.
300 The sensitivity analysis with alternative groundwater-outflow parameters and baseline water demand is presented last.

4.1 Baseline

In the baseline scenario, the soil moisture balance 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 A2). 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
305 June 2017. These periods are colour-coded according to drought definitions in Table 1 in Figure 2. Periods of above-normal precipitation are noted in 1991, 2001 and 2012 resulting in a saturated soil with excess runoff generation instead of recharge.
Reservoir storage in the baseline follows the inter-annual variability in runoff and baseflow that is generated by the groundwater module (Figure 2). Reservoir storage is lowest in the ~~high~~ large groundwater storage system (mean: 16%, range: 0-89%). In the medium and ~~low~~ small groundwater storage systems, surface water storage levels are higher with on average 36% and
310 66% reservoir storage, respectively. ~~In the low groundwater storage system ,~~ Excess surface water storage (Qout) represents a small proportion of surface water demand in the large and medium groundwater system (2% and 5%) compared to 22% in the small groundwater system, suggesting larger reservoir storage might avoid the low reservoir levels that occur during mild droughts ~~only~~ in the baseline. When reservoir storage declines, additional surface water is imported to meet the daily surface
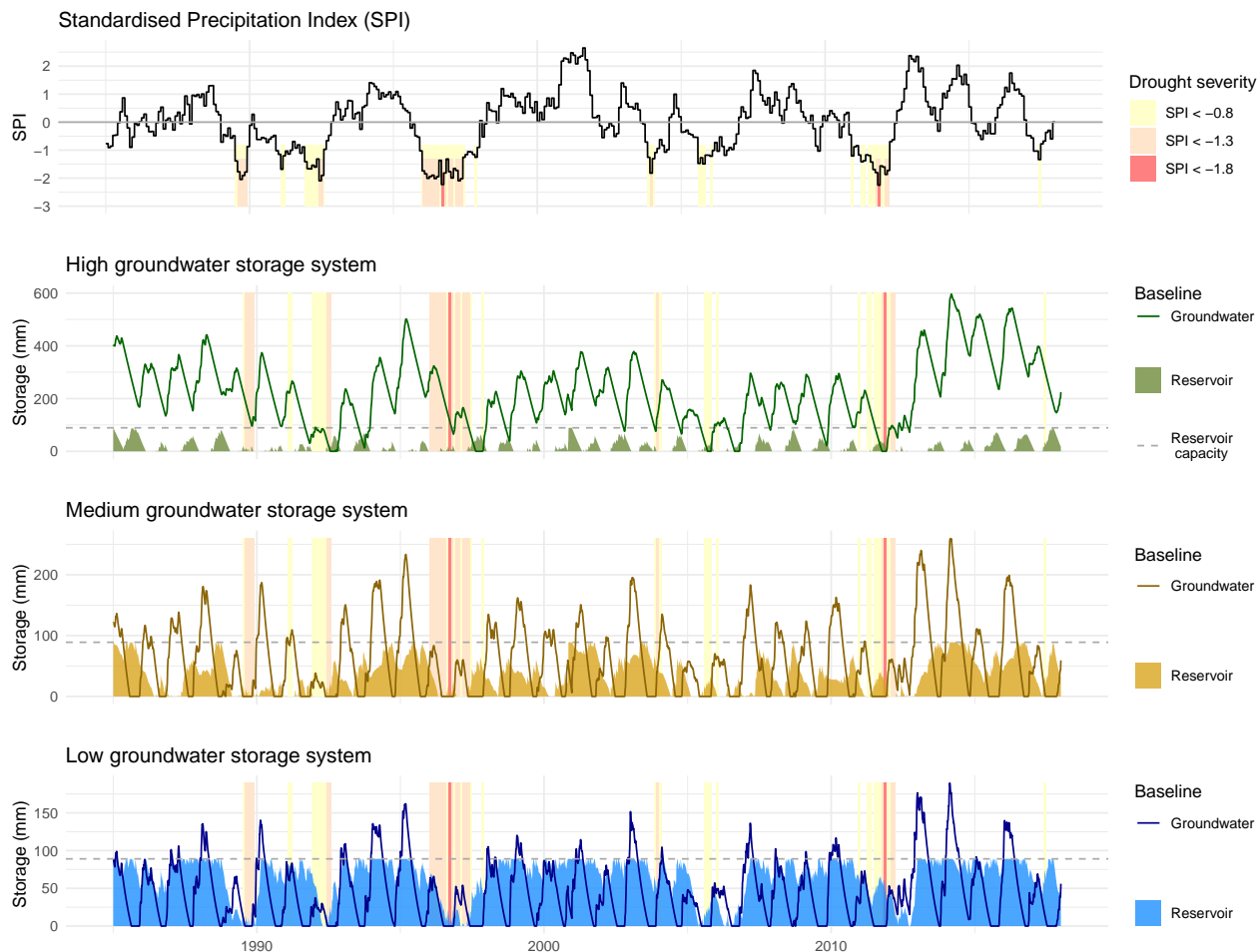
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Figure 2. First panel shows the ~~standardised~~ Standardised Precipitation Index (SPI) for regionally averaged *monthly* precipitation. Drought severity is indicated in three colours according to three drought stages in drought management plans (Table 1). Other three panels show *daily* baseline conditions for reservoir storage and groundwater availability for ~~high~~ large (green), medium (gold), and ~~low~~ small (blue) groundwater storage systems. Note that y-axes are different for the three systems. Reservoir capacity is defined as the total long-term winter precipitation and therefore constant in the three systems.

water demand. This additional import represents 8.1%, 1.7%, and 0.3% of the total water demand for the ~~high~~large, medium, and ~~low~~ small groundwater storage systems, respectively (Figure 3). The proportions of additional surface water imports are considered within the range of common in/exports of surface water in England (see A1).

Groundwater storage availability is highest in the ~~high~~ large groundwater storage system and smaller for the other two systems (medium and ~~low~~ small groundwater storage systems; Figure 2). Groundwater storage in the ~~high storage system~~ large storage system shows a slower decline and therefore buffers more mild meteorological droughts compared to the other

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320   two systems, for which groundwater storage ~~depletes~~ declines rapidly in summer months resulting in lower baseflow and ecological flow requirements in these systems. These results are similar for alternative storage-discharge parameters (A5), suggesting the difference is inherit to the different model structures. Compared to scenarios without water demand (Figure A3), groundwater storage and baseflow are much lower, showing the pressure on groundwater systems given the current anthropogenic groundwater demand. The required additional groundwater import to meet the daily groundwater abstractions

325   represents a relatively small proportion of the total water demand (1%) in the ~~high~~ large groundwater storage system. In the medium and ~~low~~ small systems this share is larger (11% and 17% respectively; see Figure 3). Considering the similarity in results for the medium and ~~low~~ small groundwater storage systems in surface water and groundwater availability, results for the drought management scenarios are only shown for the ~~high and low~~ large and small groundwater storage systems.
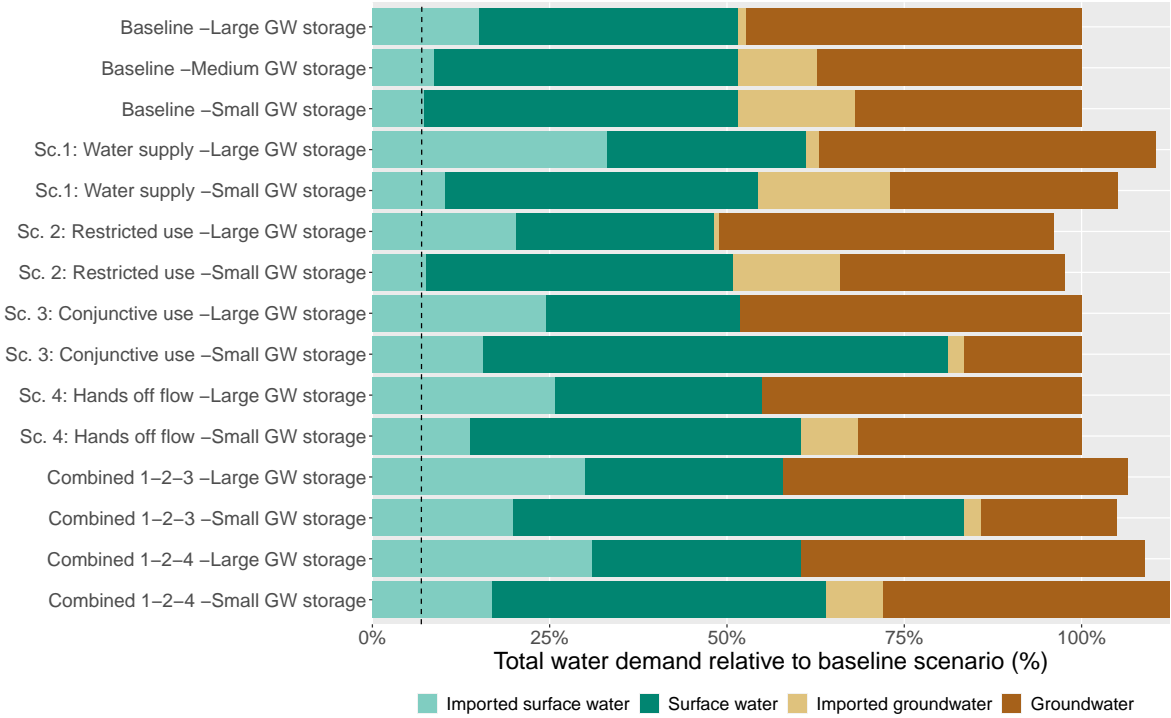
Figure 3. Total water demand for the baseline scenario for the three groundwater storage systems (rows 1-3). Total water demand is met by a combination of surface water (imported and in reservoir) and groundwater (imported and locally available). The constant surface water import of 6.9% of the total anthropogenic water demand is indicated by the dotted vertical line. Separate drought management scenarios (rows 4-11) and combined scenarios (12-15) are shown for the ~~high~~ large and ~~low~~ small groundwater storage systems only. Note that total water demand in scenarios can be different to baseline conditions due to the drought management strategies and that 100% refers to the total water demand in the baseline. Names of both groundwater storage systems are abbreviated as '~~High~~Large/~~Low~~ Small GW storage' for readability.

4.2 Drought management scenarios

330 Out of the four drought management scenarios, conjunctive use of surface water and groundwater has the largest impact on surface water and groundwater availability in the ~~high and low~~ large and small groundwater storage system (Figure 4). Results of the medium groundwater storage system are not shown as results are very similar to the ~~low~~ small groundwater storage system. In the conjunctive use scenario, surface water and groundwater use are integrated meeting the overall water demand resulting in flexible water demand. In the ~~low~~ small groundwater storage system, reservoir storage is used more intensively representing

335 65.6% of total water demand (Figure 3). Applying conjunctive water use increases groundwater storage, as groundwater use decreases to 17% resulting in a 50% increase in baseflow compared to the baseline. In the ~~high~~ large groundwater storage system, surface water and groundwater use change mainly in timing and show a minimal change in proportional surface water and groundwater use compared to the baseline (Figure 3). Baseflow remains high, similar to the baseline, although groundwater storage reduces slightly (Figure 4). Additional groundwater import reduces to a minimum in both systems, although this comes

340 at the expense of imported surface water, which increases with 9.6% and 8.3% to 24.5% and 15.5% in the ~~high and low~~ large and small groundwater storage systems respectively (Figure 3).

Second to the conjunctive use scenario, the fourth scenario 'hands off flow' also has substantial impact on the ~~high~~ large groundwater storage system resulting in higher groundwater storage and baseflow (on average 14%; groundwater time series shown in Figure 4). The restrictive use of groundwater to maintain ecological minimum flow requirements results in a con-

345 tinuous increase in groundwater storage in the ~~high~~ large storage system, compared to periodic increases in storage in the ~~low~~ small storage system. The periodically increasing groundwater storage results in a small increase in baseflow (on average 1%) suggesting that this scenario has much less impact in the ~~low~~ small groundwater storage system. With the restricted use of groundwater, surface water demand increases 2.2% to meet the anthropogenic water demand. Consequently, imported surface water increases 6.5% in the ~~low~~ small storage system. In the ~~high~~ large storage system, reservoir storage is already

350 optimised and a larger proportion of imported surface water (additional 10.7%) is used to meet the remaining anthropogenic water demand (Figure 3).

The first ~~and second scenarios that~~ two scenarios introduce drought mitigation strategies during meteorological droughts that result in periodic in/decreases of surface water and groundwater storage (Figure 4). The first scenario that increases water supply during droughts results in small storage deficits that recover after the drought events. The second scenario introducing

355 reductions in water demand shows a similar, but opposite, pattern with increasing groundwater storage during most severe meteorological droughts caused by the severe restrictions on water demand. Compared to the baseline, water restrictions in the second scenario reduce the overall water demand slightly for ~~high and low~~ large and small storage system (96% and 98%, respectively; Figure 3). The impact of the first scenario (increased water supply) is larger, as the total water demand exceeds the baseline water demand with 11% and 5% respectively for ~~high and low~~ large and small groundwater storage systems due

360 to increased surface water import (Figure 3).

The two combined drought management scenarios show an overall increase in baseflow and groundwater storage. Combining conjunctive use with scenarios 1 and 2 (combined 1-2-3 scenario) increases groundwater storage in the ~~low~~ small groundwater
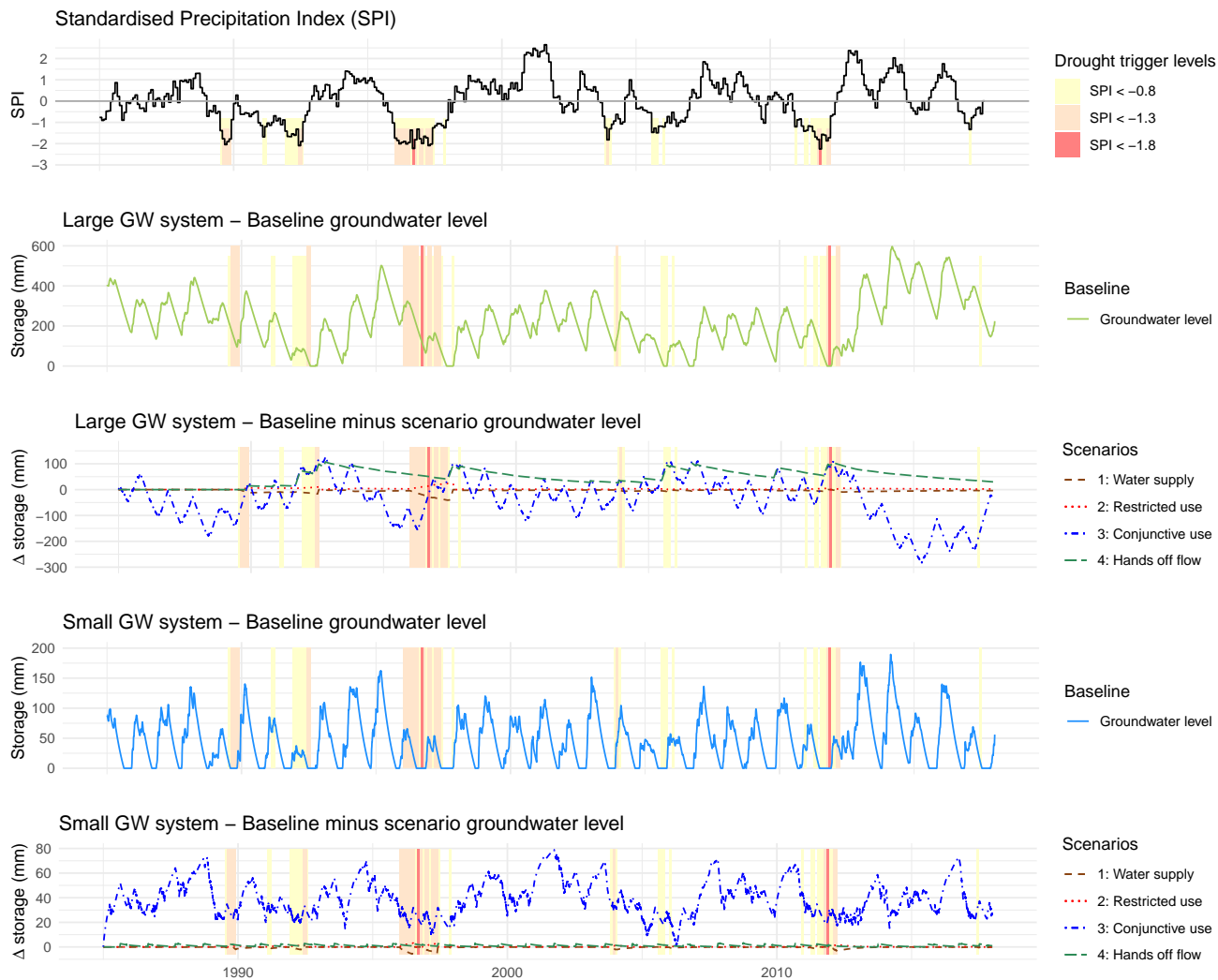
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Figure 4. Impact on groundwater storage following from the four separate drought management scenarios. Coloured surfaces match the increasing severity of meteorological droughts (related to trigger levels, see Table 1). Baseline conditions for ~~high~~ large and ~~low~~ small groundwater storage systems are shown in the first and third panel. Second and fourth panel show the impact on storage (baseline minus scenario). Applied rules for the four separate drought management strategies are presented in Table 2.

system resulting in higher baseflow of 42% on average. Groundwater storage reduces slightly in the ~~high~~ large storage system, but baseflow remains high. For the ~~high~~ large storage system in particular, combining 'hands off flow' with scenarios 1 and 2 (combined 1-2-4 scenario) increases baseflow up to 14% compared to only a 1% increase in the storage ~~low~~ small system. Both combined scenarios result in a slightly higher total water demand compared to baseline due to increased water supply during droughts in scenario 1. However, the total water demand is lower compared to scenario 1 implying that water demand

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restrictions (scenario 2) compensate for additional water supply during droughts. The use of imported groundwater reduces in both combined scenarios, but the dependency on imported surface water increases, which is related to import of surface water as reservoir levels fall below 25% (Table 3). This is because, reservoir triggers are activated during most meteorological droughts importing surface water to complement low reservoir levels (time series of reservoir levels in Figure A4).

4.3 Impact on hydrological droughts

In the baseline, there is a large difference in hydrological drought characteristics between the two groundwater storage systems (Table 4). Baseline conditions show longer baseflow and groundwater droughts (on average 333 and 344 days) in the ~~high~~ large groundwater storage system compared to shorter hydrological droughts in the ~~low~~ small storage system (66 and 88 days for baseflow and groundwater). ~~The~~ Alternative storage-discharge parameters including longer response times (Table 2) result in a slight increase in average drought duration and particularly large increase for maximum drought duration (Figure A6). The drought intensity of shorter hydrological droughts are remarkably ~~intense~~ high in the small groundwater storage system, resulting in no flow or extremely low storage levels with a rapid recovery during winter months and an overall flashy time series for both baseflow and groundwater ~~in the low groundwater storage system~~ (Figure 5). When winter recharge is low, high drought intensities are found compared to hydrological drought intensity of the ~~high~~ large groundwater storage system. Due to the higher storage component, precipitation deficits have a longer propagation with consequently fewer, more intense hydrological droughts. The ~~low~~ small groundwater storage system is on the other end of the spectrum with double the amount of groundwater droughts compared to meteorological droughts. Given the different drought characteristics in the ~~high and low~~ large and small groundwater storage systems, the impact of drought management strategies (separately or combined) is also variable and sensitive to the primary groundwater storage ~~conditions~~availability.

In the combined scenario including conjunctive use (combined 1-2-3), groundwater droughts are shorter in both systems compared to baseline conditions (Table 4). Hydrological drought intensities reduce in the ~~high~~ large groundwater storage system, compared to a slight increase in baseflow droughts in the ~~low~~ small 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~~ large storage system, compared to a reduction in hydrological droughts in the ~~low~~ small storage system. Groundwater time series in the ~~low~~ small storage system in Figure 5 show that short groundwater droughts are alleviated and remaining events are of a shorter duration and reduced intensity. However, in the ~~high~~ large storage system, hydrological drought frequency increases ~~.~~and when longer response times are modelled, drought duration increases too (A6). Drought events occur without initial precipitation deficits, which might be related to the altered reservoir and groundwater abstractions.

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~~ large groundwater storage system, drought intensity and duration reduce on average compared to baseline conditions (Table 4). This result is consistent for alternative storage-discharge parameters (A6). Time series show alleviated groundwater droughts in 1993 and 2009 (Figure 5). In the ~~low~~ small storage system, however, the impact of the 1-2-4

Table 4. Hydrological drought duration, maximum intensity, and drought frequency for the ~~high~~ large and ~~low~~ small groundwater storage systems. Mean hydrological (baseflow and groundwater) droughts are presented for baseline, combined 1-2-3, and combined 1-2-4 scenarios. See Table 3 for specific drought strategies in these scenarios. Groundwater storage time series and groundwater droughts are shown in Figure 5.

		Drought duration (in days)		Maximum drought intensity (in mm)		Drought frequency (count of events)	
		Baseflow	Groundwater	Baseflow	Groundwater	Baseflow	Groundwater
Large groundwater storage system	Baseline scenario	333	344	-0.16	-96.2	7	7
	Combined 1-2-3 scenario	145	152	-0.04	-51.7	24	23
	Combined 1-2-4 scenario	165	166	-0.04	-45.1	6	6
Small groundwater storage system	Baseline scenario	66	88	-0.31	-16.0	25	20
	Combined 1-2-3 scenario	58	62	-0.38	-14.3	8	5
	Combined 1-2-4 scenario	67	92	-0.32	-18.2	20	15

combined scenario is much lower with a slight reduction in drought intensity and duration. This is not surprising considering the overall low ecological minimum flow and respectively limited impact with introducing groundwater use restrictions.

4.4 Sensitivity analysis

The sensitivity analysis aims to test ~~averaged model parameters considering the large range~~ mean parameter values in the context of a larger relevant range, as reported in the case study. ~~The first tested parameter is~~ Firstly, the groundwater storage-outflow parameter ~~using a wide range of parameters based on previous work relevant to the case study (Allen et al., 1997) and modelling work (Stoelzle et al., 2015)~~ is tested using the reported mean characteristics for karstic, porous and fractured aquifers in England (Allen et al., 1997) and tested parameters in Stoelzle et al. (2015), see also Table 2. The second ~~tested parameter~~ parameter test examines the large range of overall water demand based on the reported range by drinking water companies (A1). Other parameters in the water balance model were not changed from ~~widely applicable HBV model structure (Bergström, 1976) or the~~ the previously tested hydrological drought model by Van Lanen et al. (2013).

4.4.1 Groundwater storage-outflow parameters

~~Alternative groundwater storage-outflow parameters are based on aquifer characteristics in England (Allen et al., 1997) and the range of optimal groundwater storage-outflow coefficients by Stoelzle et al. (2015) (parameters are shown in Table 2). These sensitivity~~ Sensitivity tests show that the absolute groundwater storage in the ~~high~~ large groundwater storage system is highly
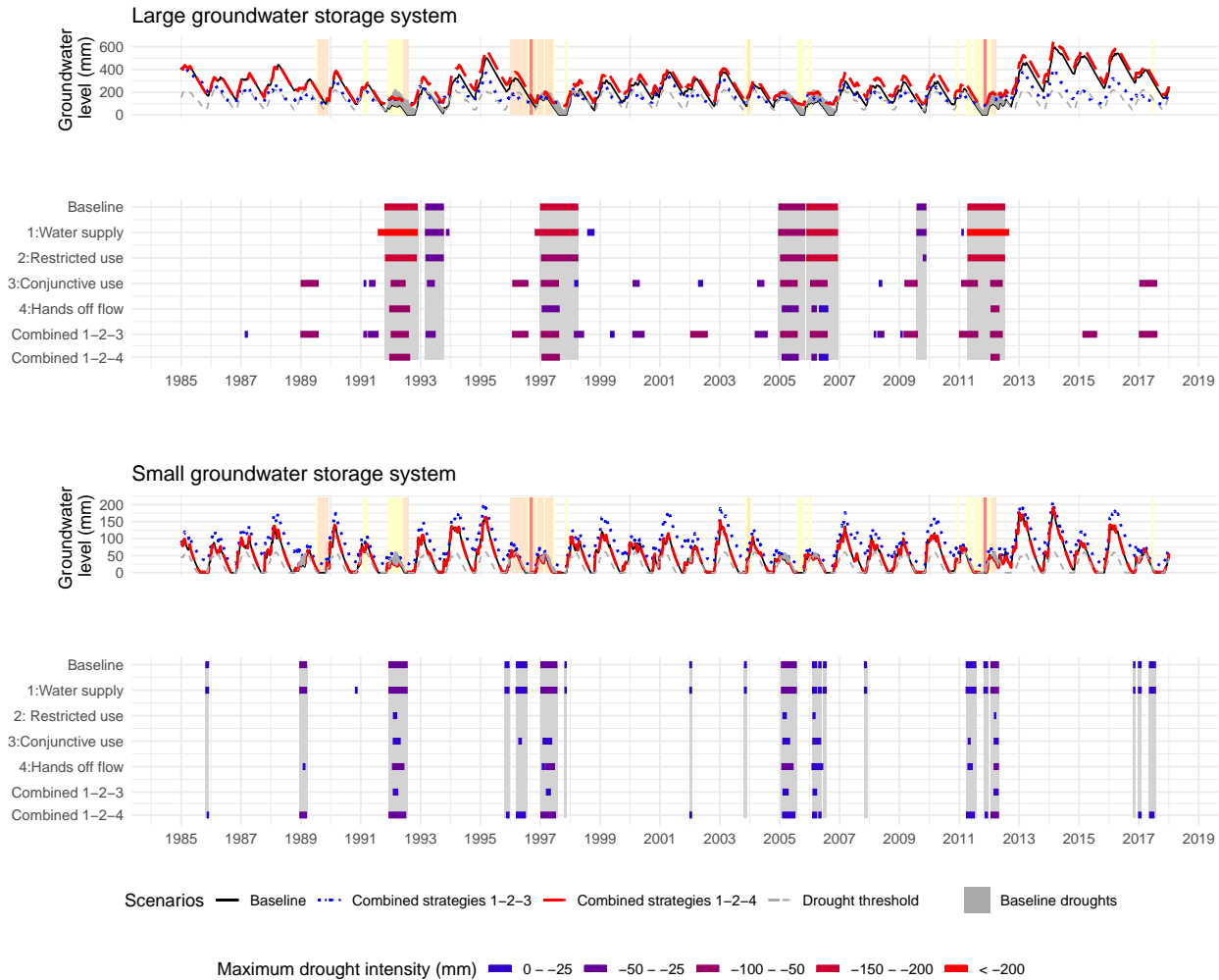
Figure 5. Hydrological droughts shown for the baseline scenario and the six tested drought management scenarios (four separate scenarios and two combined scenarios). In the first and third panel, time series of groundwater level variation in the two groundwater storage systems (~~high~~ large and ~~low~~small) 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 1 and colour scale of Figure 2. 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.

sensitive compared to the ~~low~~ small groundwater storage system (~~Figure~~ time series shown in A5). However, this sensitivity

has limited consequences for hydrological droughts in the large groundwater system, as drought duration and intensity increase slightly for each drought event (Figure 6). ~~In the low~~ In the small groundwater system, ~~for which the absolute change in storage is small,~~ hydrological drought duration nearly ~~double~~ doubles when modelling longer response times (smaller storage-outflow parameters). Maximum hydrological drought duration increase from 137 days (baseflow) and 237 days (groundwater), to 273 and 455 days, respectively. These droughts also increase slightly in intensity, but much less compared to the drought duration (Figure ~~A5).~~ 6).

When running the drought management scenarios (combined scenarios only) with these different groundwater storage-outflow parameters, a reduction in the overall hydrological drought intensity and duration ~~reduce~~ is evident for most scenarios (see Figure A6). 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~~ longer response times (smaller storage-outflow parameters) in the two different groundwater storage systems (Figure A6). The combined scenario 1-2-3 (including conjunctive use) results in longer droughts, but less severe droughts, particularly for increased storage parameters in the ~~low~~ small groundwater storage system. In the ~~high~~ large groundwater system, groundwater drought duration increases dramatically with the highest groundwater storage parameter, as groundwater storage declines in this scenario and falls below the drought threshold resulting in a depleted system with exceptionally long drought.

4.4.2 Overall water demand

Altering the overall water demand by 5% shows the sensitivity to increasing pressure on water resources resulting in lengthened droughts in the ~~high~~ large groundwater storage system and an increase in surface water import. When increasing the water demand (from 88.5% to 93.5%), hydrological drought duration in the ~~high~~ large groundwater storage system lengthens up to 866 and 867 days for baseflow and groundwater respectively (Figure 6). This is nearly doubling hydrological drought duration in the baseline (Table 4). Increased water demand results also in additional shorter events that increase the drought frequency. Reducing water demand by 5% results in fewer severe droughts (Figure 6). This drought alleviation would, however, require a permanent cut in water consumption in addition to the introduced water restrictions during drought events. In the ~~low~~ small groundwater storage system is much less sensitive to in/decreasing water demand, as drought duration and severity are similar to the baseline. However, drought characteristics might not show the impact of altered water demand, as these tests mainly change the proportion of imported groundwater and surface water.

When testing the total water demand with the combined scenarios, the primary ~~findings~~ finding is an increase in imported surface water and groundwater. Both combined drought scenarios reduce hydrological droughts successfully (Figure A7), although this comes at the cost of increased surface water and groundwater imports. For example, increased water demand (93.5%) in the ~~high~~ large 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 (Figure A7). This drought alleviation comes with an increase of imported surface water representing up to 30% of the total increased water demand. Reduced water demand (83.5%) results in shorter droughts of maximum 218 days with slightly less surface water import (27% of total water
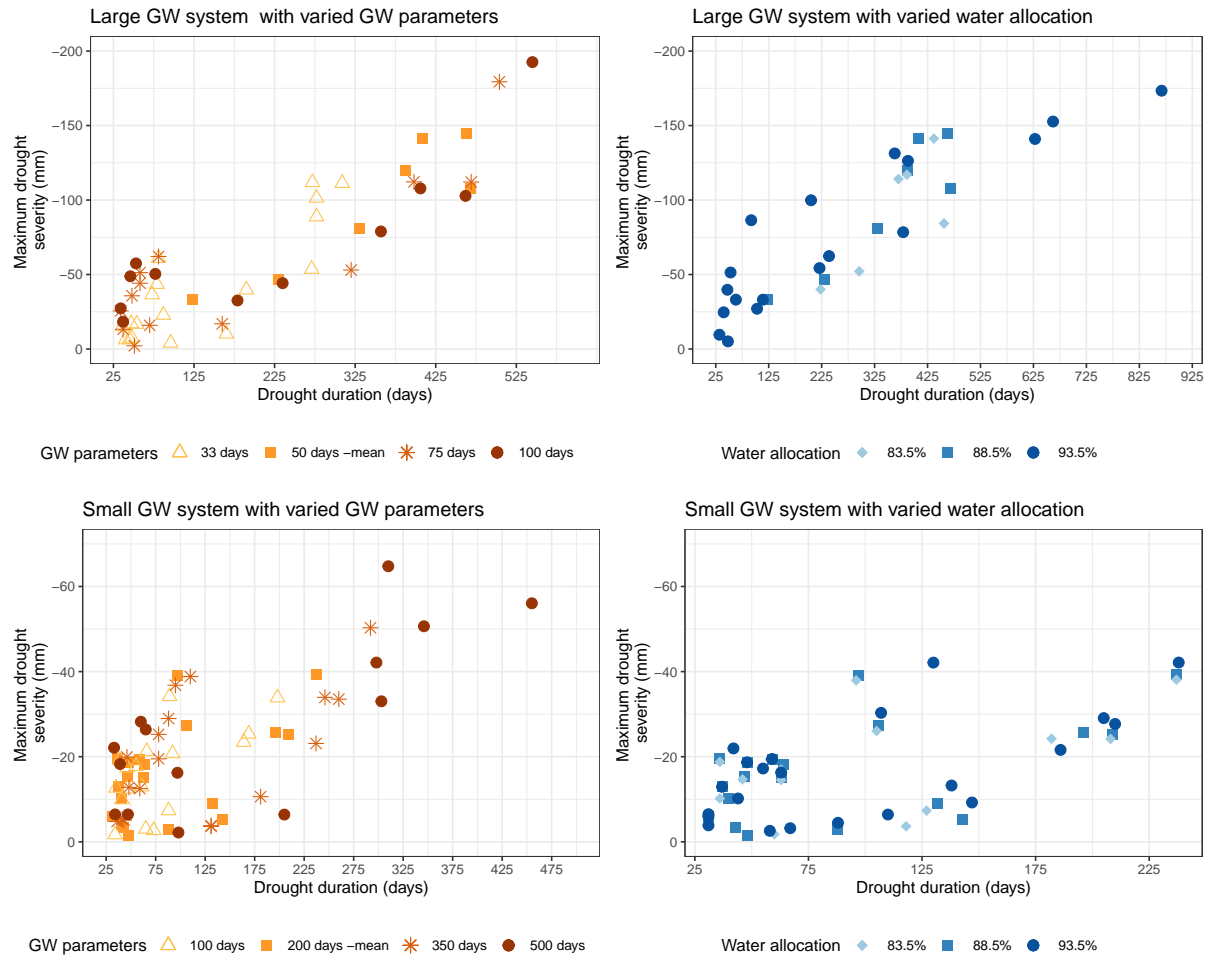
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Figure 6. Impact of in/decrease modelled storage-outflow parameters and in/decreased water demand on groundwater drought characteristics (drought duration and maximum intensity). The range and reference for tested groundwater storage-outflow parameters can be found in Table 2. The range of documented water allocation of the selected drinking water companies can be found in A1. The first two panels show drought characteristics of the ~~high~~ large groundwater storage system. The second two panels represents drought characteristics for the ~~low~~ small groundwater storage system. Drought impacts following mean values for storage-outflow parameters and water allocation are shown in squares (all panels).

450 demand). These increased percentages of imported surface water show the pressure on water resources and true cost to reducing hydrological droughts in combined drought management scenarios.

5 Discussion

5.1 Model

In this study, 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,
as presented here, 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 and Ajami, 2017; Hayden and Tsvetanov, 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 miti-
gated streamflow droughts by altering reservoir storage regulations and transfers. Results in this study agree with these findings
showing reduced baseflow droughts in combined and separate drought management scenarios, but important differences are
found between the tested hydrogeological conditions. When integrating both reservoir and groundwater storage by applying
conjunctive use in a ~~low groundwater storage system~~ system with small groundwater storage availability, baseflow increases
and hydrological droughts reduce. This comes, however, at the expense of additional surface water import that fulfills storage
deficits in groundwater. Even though water is regularly ~~traded~~ transferred between water companies (Dobson et al., 2020), per-
centages exceeding 10% of the total water demand are uncommon (see A1 for normal conditions). In ~~high groundwater storage
systems~~ a system with large groundwater storage availability, conjunctive use reduces the intensity of hydrological droughts,
but restricted groundwater use during low flow periods proves to be most effective in reducing hydrological droughts when
additional surface water imports are available.

The different response to drought management strategies is also related to the different drought characteristics of the ~~high
and low~~ large and small groundwater storage systems. These hydrogeological conditions show a positive relation between
drought duration and ~~groundwater-outflow storage~~ groundwater storage-outflow 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). Hydrological droughts in the ~~high~~ large groundwater storage system are longer and have a longer drought recovery.
In the ~~low~~ small groundwater storage system, mostly short climate-controlled droughts are observed, which 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 component~~ small or large groundwater storage
availability (Bloomfield and Marchant, 2013; Bloomfield et al., 2015).

5.2 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~~ small ground-
water storage system. Scenarios show the potential of integrating both water resources, as management strategy resulting in

485 increased drought resilience (Scanlon et al., 2016; Noorduijn et al., 2019; Holley et al., 2016). However, conjunctive use does not create water, but optimises storage use, particularly in catchments with large reservoir storage (Bredehoeft, 2011). Flexible use of surface water and groundwater aligns the timing problem between water demand and availability (Taylor et al., 2013; Cuthbert et al., 2019). It should also be noted that conjunctive use could also alter the river regime (not tested due to model setup), resulting in adverse impacts on ecohydrology (Rolls et al., 2012). We observed altered groundwater storage patterns in

490 the ~~high~~ large groundwater storage system, resulting in lower groundwater storage with more frequent, but less intense hydrological droughts with potential severe consequences for longer meteorological 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 seems 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

495 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). However, 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).

Maintaining the ecological minimum flow requirements is also very effective in mitigating hydrological droughts, particularly in the ~~high~~ large groundwater storage system. This confirms earlier findings focusing on the protection of ecosystems

500 using trigger level regulations (Werner et al., 2011; Noorduijn et al., 2019). Crucial to the success is the integration of surface water and groundwater use to maintain low flows (Howarth, 2018). However, results show that impact of restricting groundwater use during low flows relies on the defined trigger level (defined ecological minimum flow) and baseflow component, as protecting the minimum flow might not preserve natural or undisturbed river flows (Howarth, 2018). When increasing storage-outflow parameters in the sensitivity analysis and thereby increasing the baseflow component, impact of restricting

505 groundwater use increases. Crucially, hydrological droughts aggravate when the ecological minimum flow is neglected and groundwater use reduces the environmental flow (Gleeson and Richter, 2018; De Graaf et al., 2019). These crucial sensitivities to different ~~groundwater-outflow~~ groundwater storage-outflow parameters show the value of conceptual 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).

510 Combined drought management strategies show primarily the impact of conjunctive use and restricted groundwater use in both systems. The impact of drought mitigation scenarios 1 and 2 (increased water supply and restricted water demand) is mostly noticeable during extreme drought conditions when water demand reduces more than water supply increases. In most extreme drought conditions, water demand reduces by 36% that is similar to extreme water reductions realised in Melbourne during the Millennium Drought (Low et al., 2015), but not as low as water restrictions enforced in some parts of Cape Town

515 during the Day Zero crisis (Rodina, 2019; Garcia et al., 2020).

When introducing a permanent increase in water demand (+5%), the effect on water resources is evident as hydrological droughts increase disproportionally in duration and required additional surface water import to meet the anthropogenic water demand. Further research is required to assess if these volumes of imported water are obtainable during droughts, especially considering the scale of drought events and potentially limited water availability at regional or even national scales.

520   Alternatively, catchment-specific modelling could investigate if storing more surface water during winter in, for example, a small groundwater system, would aid to meet higher surface water demand in summer (Peñuela et al., 2020; Delaney et al., 2020) or as additional groundwater recharge (He et al., 2021). Reducing water demand (-5%) results in shorter hydrological droughts and less imported water, but realising a permanent reduction in water demand can come at high costs for both ~~providers and drinking water providers~~ and/or water users, and might not always be successful (Low et al., 2015; Gonzales and Ajami, 2017;

525   Muller, 2018; Caball and Malekpour, 2019; Simpson et al., 2019). Generating more awareness and reducing water demand 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).

5.3   Model limitations

Limitations of the conceptual socio-hydrological model are related to the overall drawbacks of using a lumped and idealised

530   hydrological model. ~~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 runs to determine water availability and drought impact~~ When determining water availability for specific regions in England~~would therefore require different climate data~~ ~~and additional information regarding~~, the model runs should be revised using less generic, locally-relevant climate data. Moreover, given the range in local water resource availability and drought management

535   practices ~~.~~ (Table 1 and A1), current generic water resource management settings in the baseline might not represent all local water management strategies. Water resource availability in this model is based on annual available surface water and groundwater, implying that actual surface water storage and groundwater storage might be larger than shown here.

    The lumped model structure reduced testing of some drought management strategies that would require a spatially-distributed model. Out of the listed strategies (Table 1), four drought scenarios were tested in this study. Other measures, such as river aug-

540   mentation (groundwater abstraction to supplement river flow or maintain ecological minimum flows during drought), reduction of pressure on the water network, and reuse of urban wastewater could not be modelled. A spatially-distributed setup could further the current analysis, as spatial impact of increased abstractions to the stream could not be included (Gleeson and Richter, 2018) that would be relevant to the estimate the regional impact on hydrological droughts of scenarios applying conjunctive use or maintaining ecological flow requirements. The latter scenarios represents only restricting groundwater abstractions to meet

545   environmental flow requirements that could be extended to a combination of reservoir releases and groundwater restrictions depending on relevant catchment characteristics (Environment Agency, 2019c). A spatially-distributed model setup would also improve the representation of groundwater storage, as lateral groundwater flow is excluded in the lumped model setup. Inflow from deeper aquifer layers is limited to the imported groundwater component in the model.

    If more water demand or water management data were available, current assumptions could be improved. For example, the

550   static water demand could be substituted by a dynamic water demand component or increased awareness of water stress (Garcia et al., 2016), if this would be supported by water resource or drought management plans. Conjunctive use scenarios could also benefit from additional information regarding general water management practices, as practical constrains to flexible water storage can limit the effectiveness of conjunctive use (Holley et al., 2016).

6   Conclusions

This study presents a socio-hydrological model that was used to investigate the impact of water demand and drought management strategies on hydrological droughts. In the socio-hydrological model, different groundwater storage ~~systems were~~ availability was modelled revealing different drought characteristics and impact of drought management strategies on hydrological droughts. Baseline conditions show that hydrological droughts occurred frequently and were mostly climate-driven, although amplified by water use in the ~~low groundwater storage system~~ system with small groundwater storage availability. External water imports were necessary to meet water demand periodically. The ~~high groundwater storage system shows~~ system with large groundwater storage availability has a larger inter-annual ~~storage~~ groundwater storage compared to the small groundwater storage system resulting in fewer, but more intense hydrological droughts amplified by water use.

Introducing drought management strategies to the different groundwater storage systems relieved both streamflow and groundwater droughts in nearly all scenarios. Most hydrological droughts are alleviated when applying conjunctive use and maintaining the ecological flow requirements by restricting groundwater use. The conjunctive use scenario allowed a more optimal use of reservoir storage and delayed response of groundwater storage resulting in reduced and sometimes alleviated streamflow droughts in the ~~low and high~~ small and large groundwater storage systems. These findings encourage further exploration of conjunctive use as a drought mitigation strategy, particularly in ~~low~~ small groundwater storage systems. The impact the restricted groundwater use to maintain ecological flow requirements (hands off flow) was found sensitive to the baseflow component, as hydrological droughts are effectively reduced under a range of storage-outflow parameters and when overall water demand was in/decreased.

The novelty of this study lies in the introduction of the socio-hydrological model to assess of the impact of drought management strategies on both streamflow and groundwater droughts. Results show how strategies as conjunctive use and maintaining ecological flow requirements reduce and alleviate hydrological droughts. The low sensitivity of these drought management strategies to different hydrogeological conditions highlights the wide applicability of results and gives confidence in the tested combined and separate scenarios. However, the considerable pressure on water resources is evident when the overall water demand increased, as drought duration increases disproportionally and additional surface water is required to meet the anthropogenic water demand. Further conceptual modelling could investigate the introduced dependency on imported water with these drought management strategies. The necessity for importing water shows the considerable pressure on water resources and the delicate balance of water-human systems during droughts that calls for sustainability targets within drought policies.

portal (website: https://nrfa.ceh.ac.uk/content/uk-water-resources-portal). Information about water resource and drought management plans
585 is also publicly available and used plans are listed in A2.

Appendix A: Supplementary material

A1 Water use and sources of water supply for drinking water companies in England

Table A1. Summary of characteristics of drinking water company that use both surface water and groundwater in England. Drinking water companies South West and Northumbrian water are therefore excluded form this overview. Data of latest water resource management plans has been used (see A2 for source web-locations). Imported and exported percentages are marked with an asterisk when the source was undefined (or potentially mixed). Thames Water values shown for both London and outer areas in parenthesis. Headroom is calculated taking reported baseline conditions demand: supply (dated in 2019/20) and checked with published data of Environment Agency (2019b).

Drinking water company	Supplies to # million 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

A2 Drought management plans of drinking water companies

Table A2. Locations of drought management plans of twelve 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
Sutton and East Surrey Water	seswater.co.uk/publication-drought	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

Figure A1. 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 on: https://www.gov.uk/government/statistical-data-sets/env15-water-abstraction-tables (Last accessed on 2-09-2020)
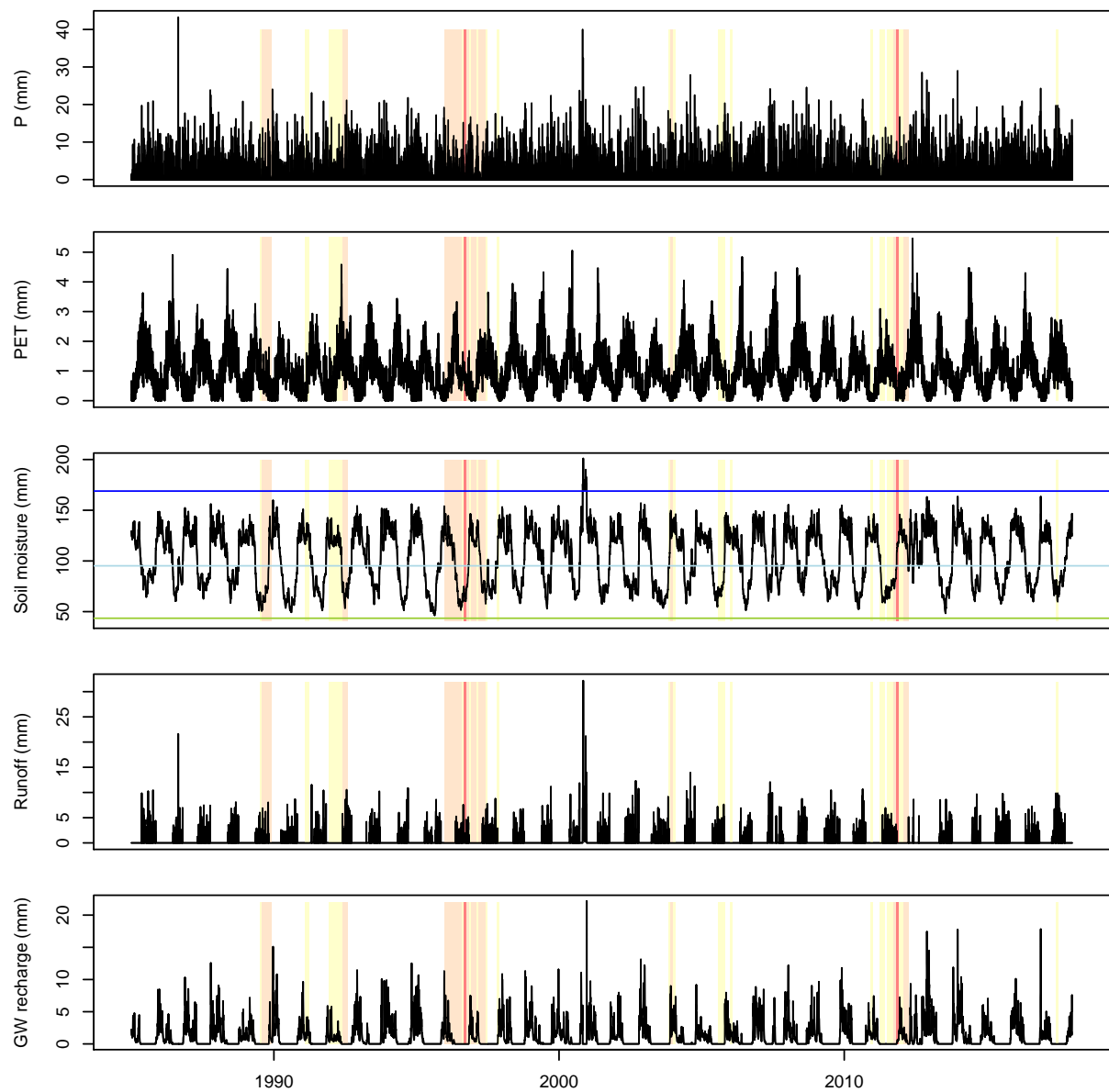
Figure A2. Inter-annual variation of the soil moisture balance in the socio-hydrological model. The five panels show long-term time series of precipitation actual evapotranspiration, soil moisture, runoff, and groundwater recharge (all in mm). ~~The first 5 years are part of~~ In the ~~spin-off period~~soil moisture panel, ~~the remainder (1985-2017)~~ soil moisture levels for field capacity, critical moisture content and wilting point are ~~used~~ indicated in ~~the analysis~~dark blue, light blue and green respectively. Meteorological droughts are indicated in yellow, orange and red for mild, moderate and severe droughts respectively, similar to Figure 2.

Figure A3. Natural (in black) and human-influenced (in red) conditions of groundwater storage levels in time (1985-2017). The three panels show ~~the high~~modelled systems with large, medium, and ~~low~~ small groundwater storage ~~systems~~availability. Note that y-axis are different due to the large variation in groundwater storage for each system.

A6   Surface water storage with combined scenario in the ~~high~~ large **groundwater storage system and** ~~low~~ small **storage system.**
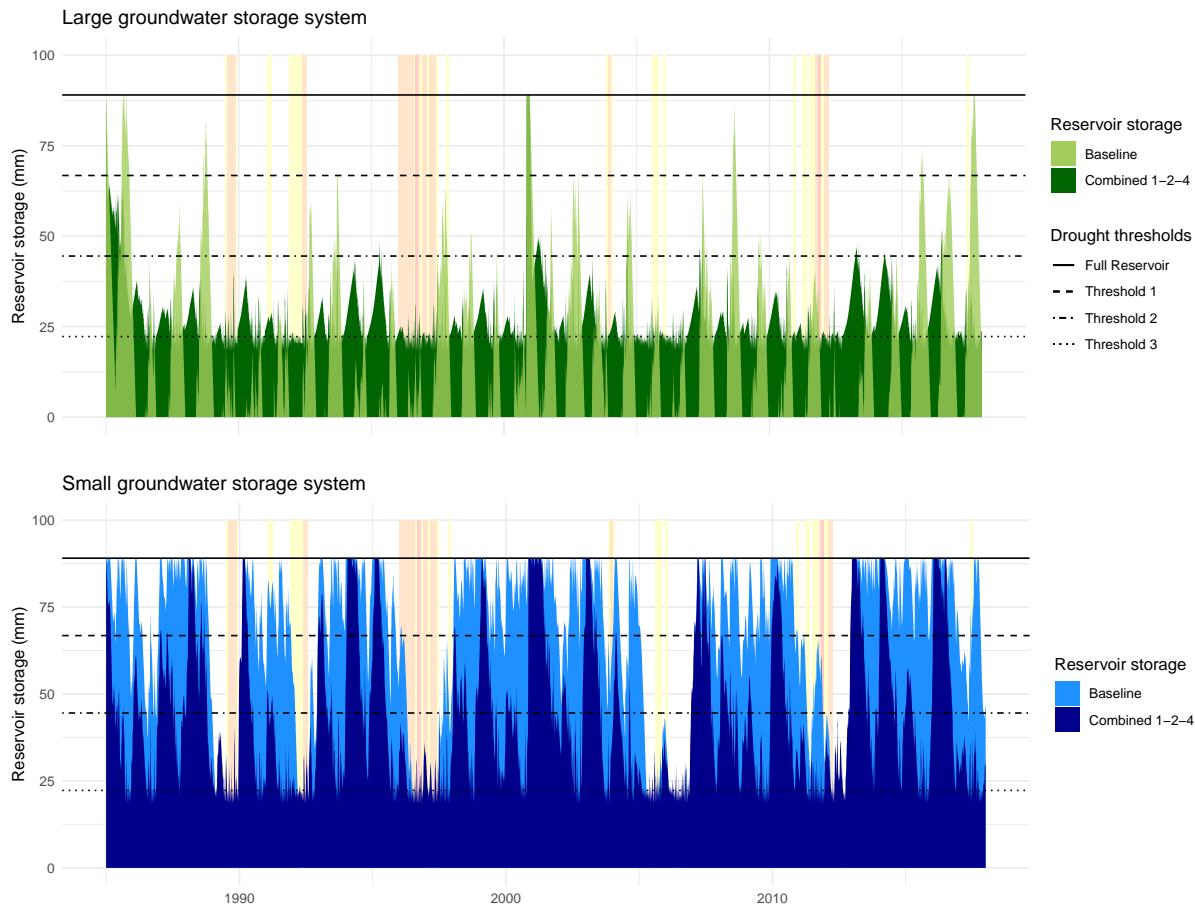
Figure A4. Surface reservoir storage in baseline scenario (no drought measures applied) for ~~high~~ large groundwater storage catchment (first panel, in light green) and ~~low~~ small groundwater storage catchment (second panel, in light blue). Darker green and blue colours indicate the difference in surface water storage as the reservoir is fuller/emptier with the combined scenario (1-2-4; including hands off flow). Coloured surfaces indicate below-normal periods in precipitation (measured in SPI) following Figure 2. Drought thresholds for the surface water reservoir follow the documented range for trigger levels (see Table 1 and Table 3).

A7   Baseline conditions for groundwater storage under a range of storage-outflow parameters
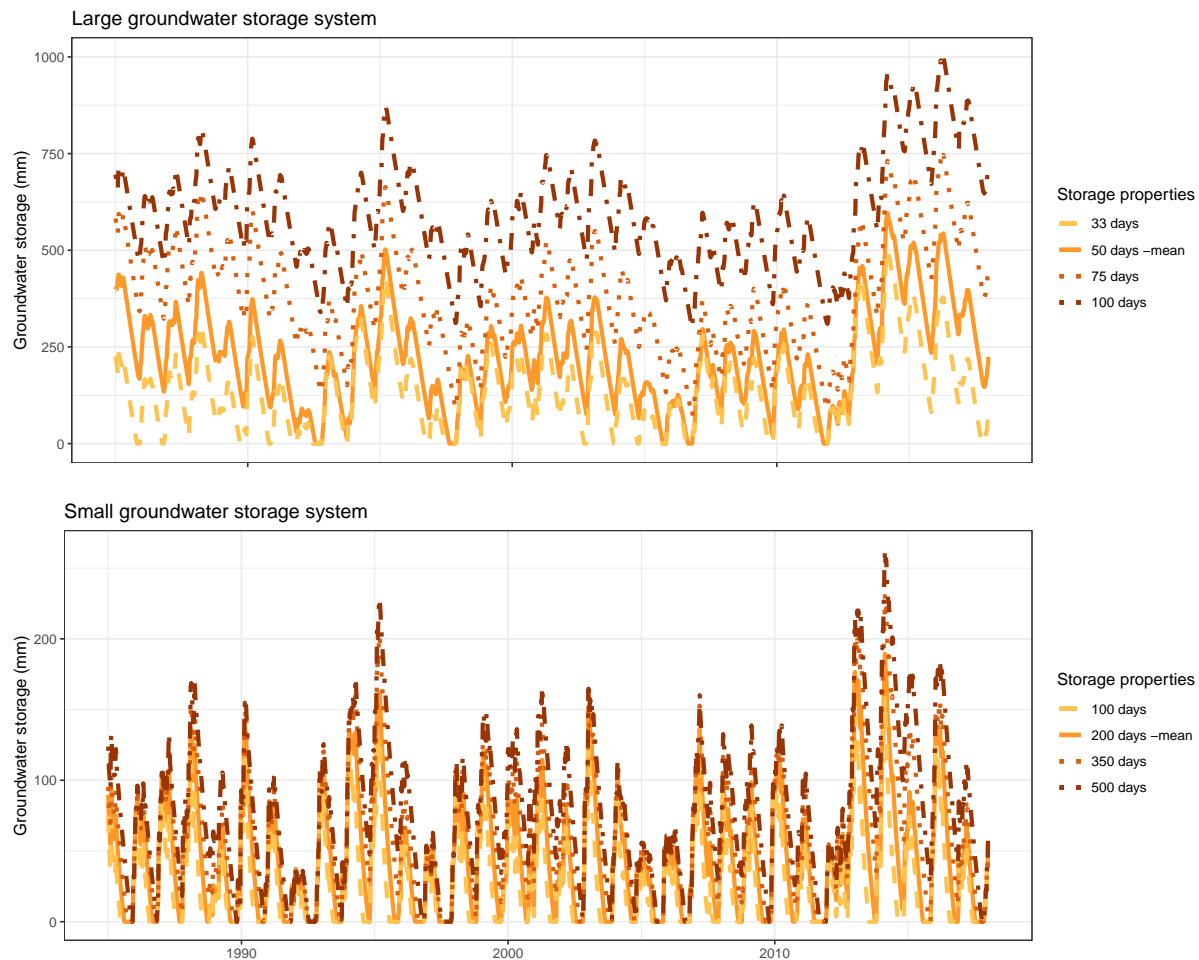
Figure A5. Baseline conditions for groundwater storage modelled using different groundwater storage-outflow parameters, as given in Table 2. The first and second panel represent the high and low groundwater storage system.

A8 **Groundwater drought duration and severity for baseline and combined scenarios applying a range of groundwater storage-outflow parameters**
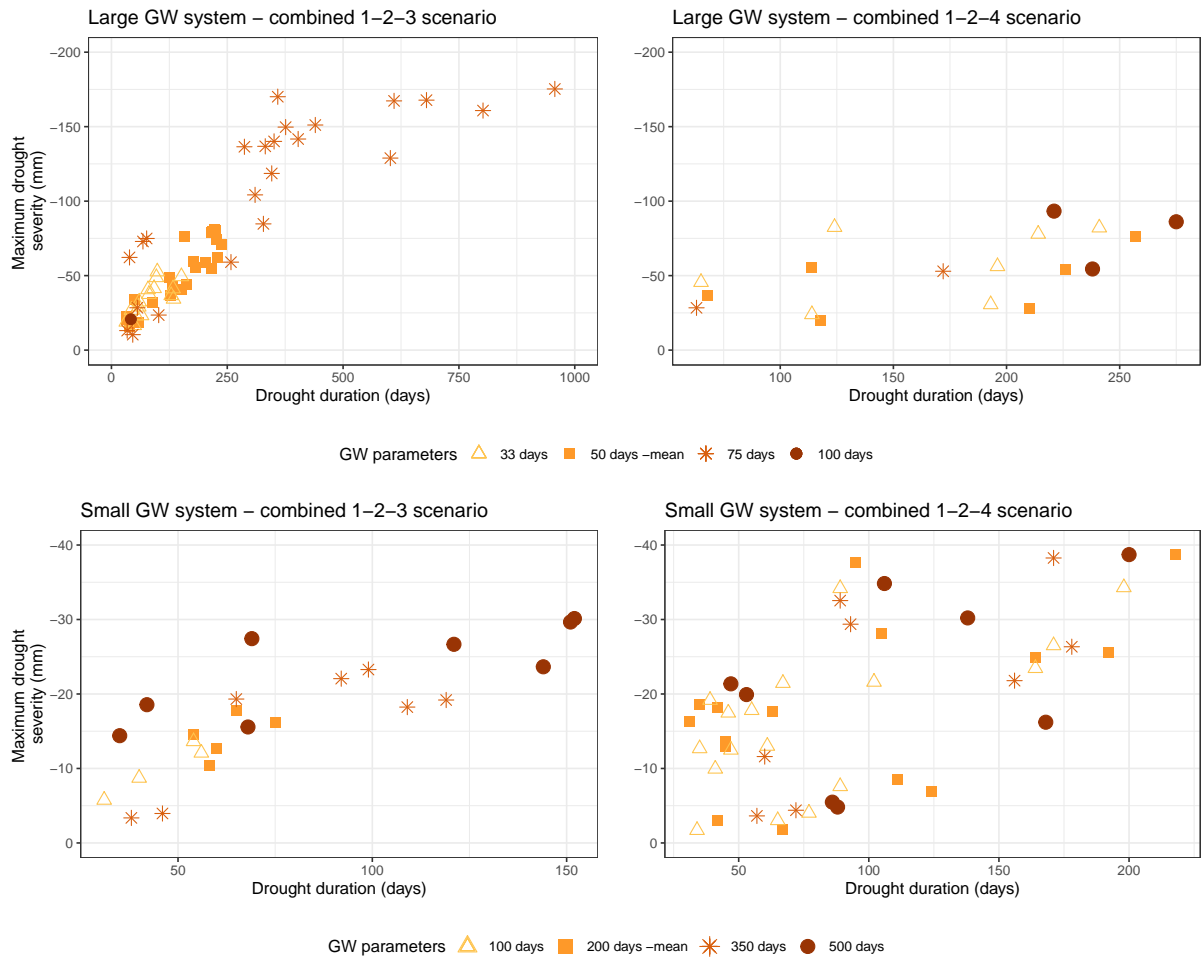

Figure A6. Groundwater drought duration and severity for ~~baseline conditions and~~ the two combined scenarios (1-2-3 and 1-2-4) in the ~~two~~ large and small groundwater storage systems for different groundwater storage-outflow parameters (abbreviated as GW parameters). The full range of groundwater storage-outflow parameters ~~can be found~~ is presented in Table 2. One outlier (a drought of 11528 days) is omitted from the groundwater drought scenarios in the large GW system with 1-2-3 scenario. In this extreme case, two drought occur one of 42 days (shown in figure) and one that last for the remaining modelling period (11528 days). Note that y-axis are kept constant for the large and small groundwater storage systems, x-axis vary due to the large range in drought duration in the scenarios.

A9   Groundwater drought duration and severity for baseline and combined scenarios applying an increase (93%) and decrease (83.5%) in overall water allocation.
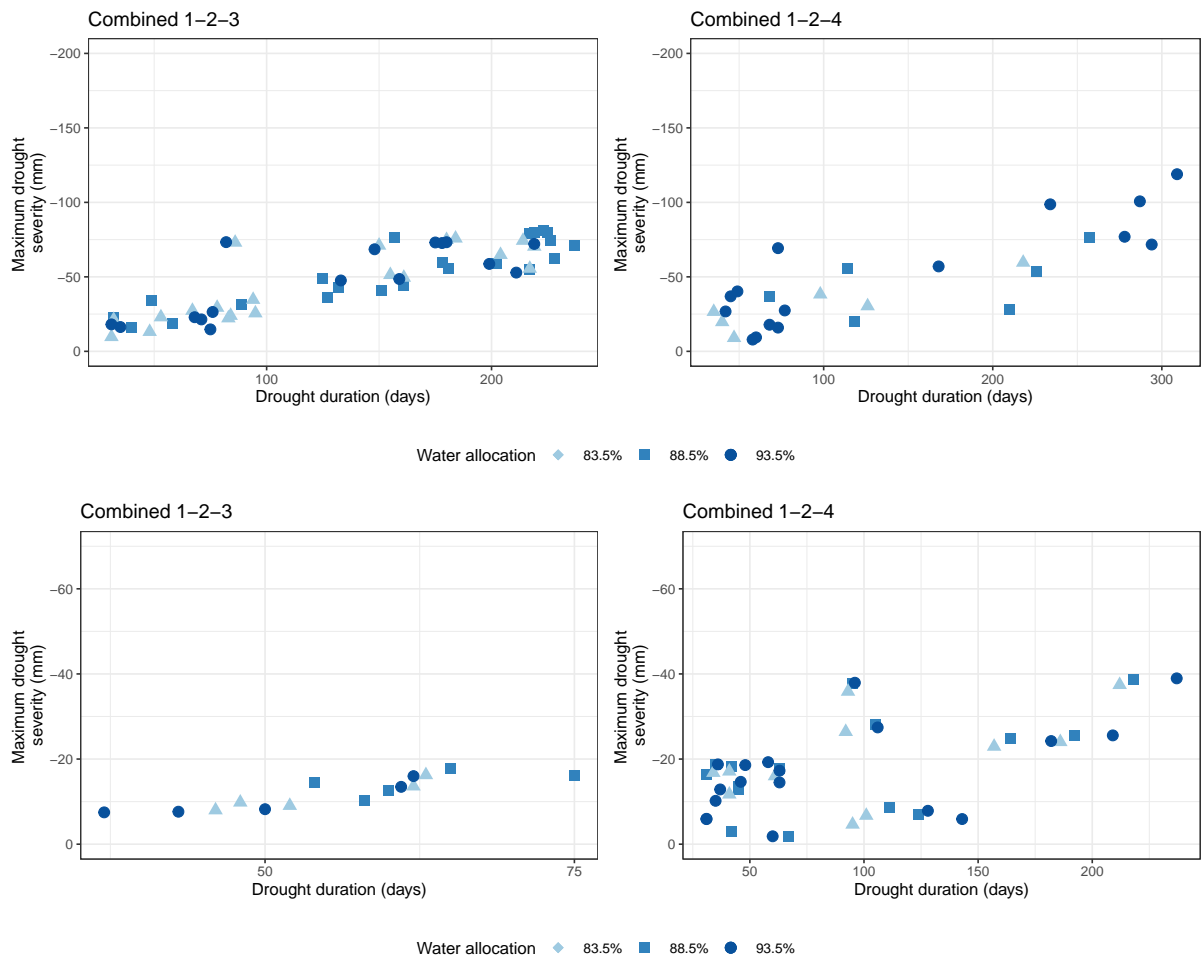

Figure A7. Groundwater drought duration and severity for ~~baseline conditions and~~ two combined scenarios (1-2-3 and 1-2-4) in the ~~two~~ Large and small groundwater storage systems. These tests are part of the sensitivity analysis for which the proportional water allocation was increased and decreased with 5%.

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