# METHODS AND MODELS TO QUANTIFY CLIMATE-DRIVEN CHANGES IN GROUNDWATER RESOURCES

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*Understanding climate-driven changes in groundwater resources is essential for future water resources management. In this paper, we review methods and models developed to quantify past, present and future climate-driven changes in groundwater resources, and provide an outlook for future research and practice. The Standardised Groundwater level Index (SGI) has been an effective methodology for quantifying historic groundwater resource status across different sites using observed historical data. However, the paucity of groundwater level data means that modelling groundwater levels may also be required. Lumped parameter models such as AquiMod have been shown to be effective at reconstructing groundwater levels at observation boreholes beyond historic records. These models have also been used for seasonal forecasting of groundwater levels and quantifying impacts of climate change. Major challenges remain in linking indicators of groundwater resource status (i.e. levels) with downstream impacts at both the high and low end of the hydrograph. An example of this is provided by estimating impacts of climate change on yields at abstraction boreholes during drought. As well as linking groundwater levels to impacts, future research should explore the full range of the SGI and apply the latest climate model data to AquiMod models. Access to both live groundwater level observations and high performance computing facilities would allow the methods reviewed here to be applied automatically, providing real-time hydrogeological data services.*

## INTRODUCTION

Understanding climate-driven changes in groundwater resources is essential for water resources management. Quantifying historical changes in groundwater levels can help contextualise current groundwater resource status (Jackson et al., 2016). Assessment of present or near future changes is also beneficial for short-term operational groundwater resource management (Mackay et al., 2015), whilst quantifying impacts of climate change over the next 25-50 years is needed for longer-term strategic planning (Water UK, 2016).

Whether considering groundwater resources in the past, present or future, appropriate methods and models are required to quantify changes. This paper reviews some of these approaches recently developed. The use of the Standardised Groundwater level Index (SGI) to quantify historical changes in groundwater levels at observation boreholes across multiple sites is reviewed. We then review the use of a lumped parameter model, AquiMod, for reconstruction, forecasting and climate change modelling of groundwater levels. Using a case study of quantifying the impacts of climate change on yields at abstraction boreholes during drought, we highlight the challenges of translating changes in groundwater levels to meaningful metrics of impact. Finally, we provide an outlook for future research and practice using these approaches.

## THE STANDARDISED GROUNDWATER LEVEL INDEX (SGI) – A METHOD FOR QUANTIFYING CLIMATE-DRIVEN CHANGES IN HISTORICAL GROUNDWATER LEVELS

Understanding the response in groundwater levels to drought and flood events across multiple sites requires comparisons between standardised groundwater level hydrographs. Whilst there are numerous methods for the development of standardised indices for streamflow and precipitation (Zargar et al., 2011), standardised indices for groundwater levels have only recently been developed. Applied to monthly time series of groundwater levels at 14 boreholes in Great Britain, Bloomfield and Marchant (2013) developed the Standardised Groundwater level Index (SGI). In brief, a normal-scores transform is applied to all groundwater level data for each separate month of a year, and the transformed scores for each month are merged back to form a SGI time series. Values of the SGI below zero are considered to be drier, and above zero wetter, with -1/1 often being used as an arbitrary threshold for drought/flood. Figure 1 shows groundwater level time series and the resultant SGI time series for these sites. By applying the normal-scores transform to each month separately, the SGI is a de-seasonalised time series that shows departures from monthly mean groundwater levels and so enables the quantification of temporally coherent groundwater deficits or excesses between sites.

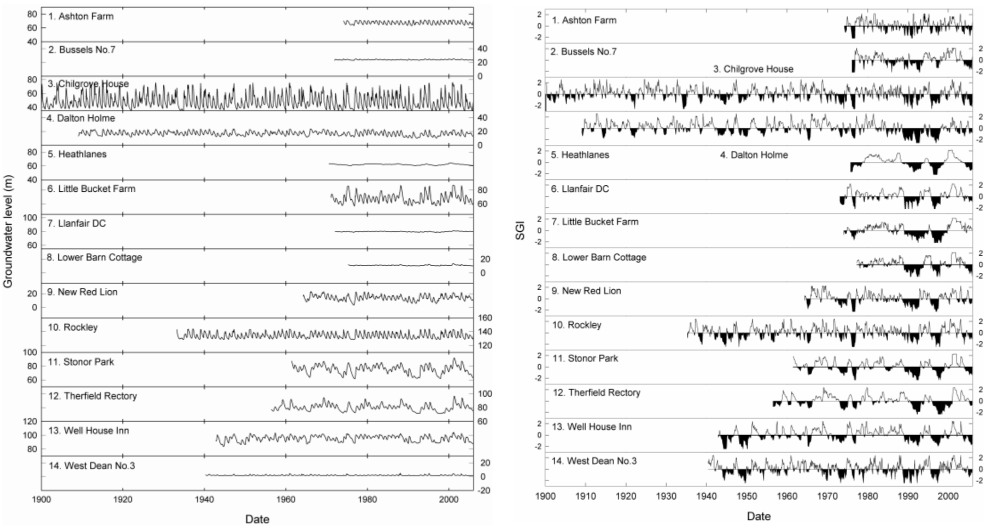


*Figure 1: Groundwater level time series (left) and SGI time series (right) for 14 sites in Great Britain. Reproduced after Bloomfield and Marchant (2013).*

This is particularly evident when presenting SGI values < 0 as a heatmap (Figure 2), where the spatial coherence of droughts in the 1990s is clear. It is also interesting to note that some sites have more persistence and memory in the SGI (e.g. site 5 vs site 1), associated with both different recharge processes and aquifer flow and storage characteristics (Bloomfield and Marchant, 2013).

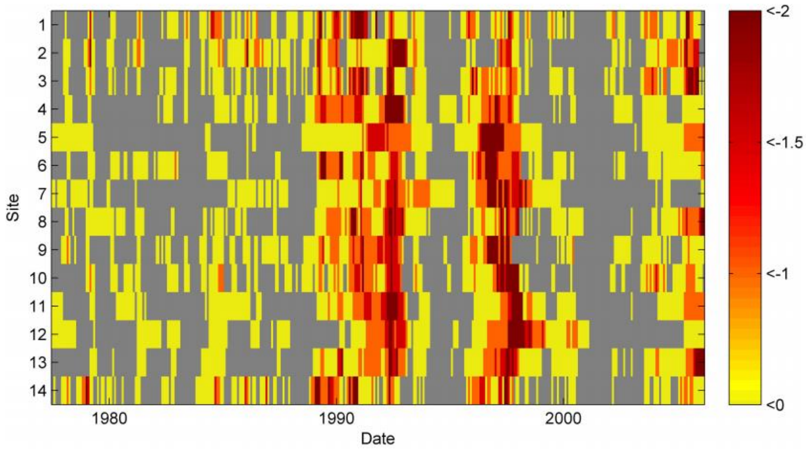


*Figure 2: Heatmap of SGI < 0 for 14 groundwater level time series in Great Britain. Reproduced after Bloomfield and Marchant (2013).*

Application of the SGI to two very long groundwater level time series (Chilgrove House (CH) and Dalton Holme (DH), Figure 1) has revealed changing controls on groundwater drought (Bloomfield et al., 2018). Figure 3 shows the SGI as a function of standardised temperature (STI) and precipitation (SPI) indices for the 2 sites, split over 3 time periods, with notable drought events shown in colours. In 1891-1932, 8% and 10% of groundwater drought events (SGI < -1) occurred when STI > 1 and SPI < -1 for CH and DH respectively. In contrast, in 1974-2015, the number of groundwater drought events when STI > 1 and SPI < -1 increases to 23% and 29% for CH and DH respectively, with notably greater extreme drought events SGI < -2. In the absence of long-term changes in precipitation deficits during drought events, it is inferred that increases in the incidence of monthly groundwater drought is associated with increased temperature associated with anthropogenic warming. It is postulated that this is through impacts of anthropogenic warming on evapotranspiration. Thick capillary fringes at the two sites suggest that evapotranspiration could be supported by groundwater during drought events. Given the large extent of shallow groundwater globally, this may be a significant phenomenon elsewhere (Bloomfield et al., 2018).

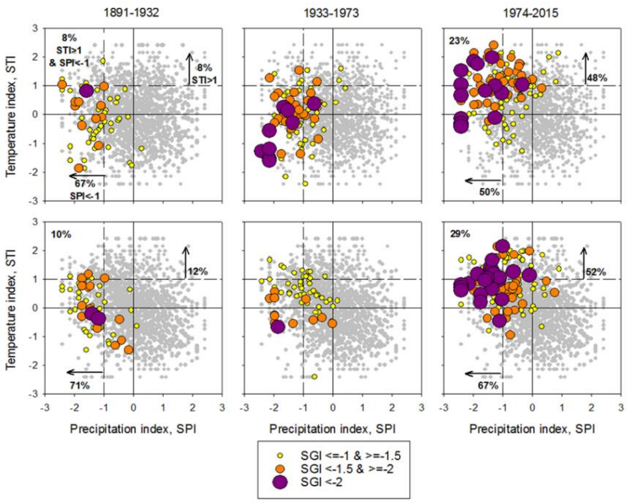


*Figure 3: The SGI as a function of standardised temperature index (STI) and standardised precipitation index (SPI) for Chilgrove House (CH, top panels) and Dalton Holme (DH, bottom panels), split into 3 periods (1891-1932, 1933-1973, 1974-2015, left to right). Colours show notable drought events. Reproduced after Bloomfield et al. (2018).*

## LUMPED PARAMETER MODELS – RECONSTRUCTIONS AND FUTURE PREDICTIONS

Whilst there are a few rare examples of very long groundwater level time series, in general observations of groundwater levels have short durations and often have missing data. In order to reconstruct groundwater levels and infill gaps, groundwater models are required. Such models are also required for any future predictions of groundwater levels associated with seasonal forecasting or long-term climate change. The lumped parameter model AquiMod (Mackay et al., 2014) has been used extensively for these purposes. Figure 4 shows the conceptual structure of AquiMod. AquiMod has a modular structure, with modules for the soil, unsaturated and saturated zones. The soil module calculates a soil moisture balance, drainage from which is routed through the unsaturated zone to become recharge. Changes in groundwater levels are calculated based on an estimate of the aquifer storage coefficient and the mass balance between recharge entering the saturated zone and groundwater discharge calculated using aquifer permeability and discharge elevation. The model permits different structures for the saturated zone, variable time-stepping, Monte-Carlo parameter sampling for calibration and is freely available (British Geological Survey, 2019). The model is run from the command line and requires a time series of rainfall and PET as inputs, and groundwater level observations for calibration.

Figure 4 shows observed and reconstructed groundwater levels for four sites in England developed by Jackson et al. (2016) using AquiMod. Known historic drought events (e.g. 1921/22) are clearly identifiable in the reconstructed record. Operationally, the reconstructed levels are helpful as they can help contextualise current groundwater level status where observed groundwater level time series are short. The reconstructions also have benefits for longer-term strategic planning. For example, in England and Wales water companies have used yields of public water supply boreholes estimated during historic drought events for long-term water resources planning (UK Water Industry Research Ltd, 2014). The groundwater level minima calculated from the reconstructions can give an additional perspective on these yield estimates. AquiMod has also been used for seasonal forecasting groundwater levels one to three months in advance (Mackay et al., 2015) and for quantifying the impacts of climate change on groundwater levels (Prudhomme et al., 2013).

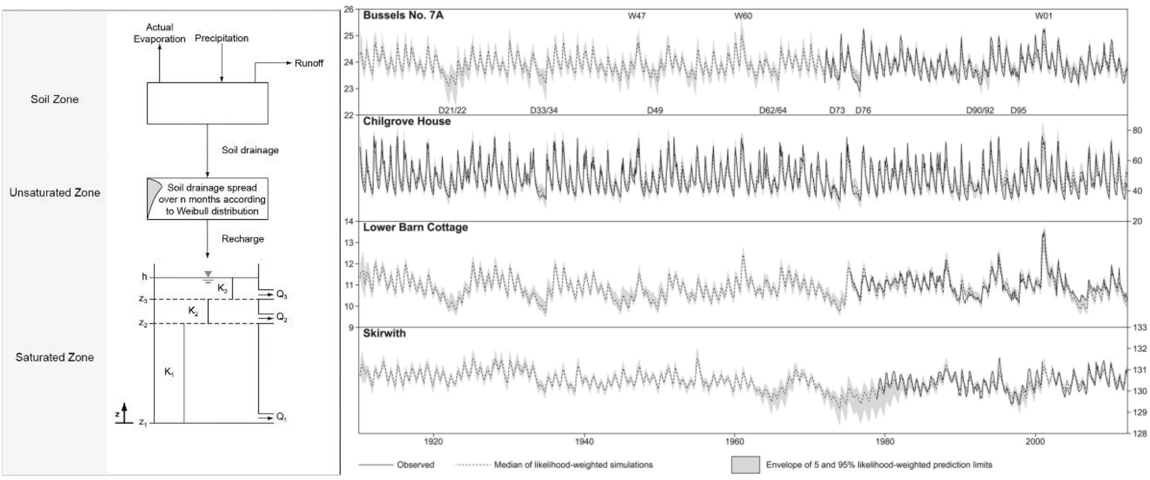


*Figure 4 Conceptual structure of the AquiMod model (left) and groundwater level reconstructions produced by the model (right). Reproduced after Jackson et al. (2016) with permission from Wiley.*

## FROM LEVELS TO IMPACTS

The SGI and lumped parameter models such as AquiMod are useful tools for quantifying historic and future climate-driven changes in groundwater levels in observation boreholes. However, changes in levels in observation boreholes have little intrinsic value in comparison to the benefits and costs of groundwater to society. Benefits are associated with public water supply, providing baseflow to rivers and supporting wetlands, and costs associated with groundwater flooding (UK Groundwater Forum, 2018). The challenge therefore becomes how to relate changes in groundwater levels with impacts (in the examples above; public water supply yields, baseflow and ecological thresholds, groundwater flooding thresholds). In many cases, groundwater levels are one component of the controls on these impacts. In these cases there is a need therefore to understand the interaction between the groundwater system and these other constraints to make meaningful impact predictions. A specific example of this challenge is associated with assessing the yields of public water supply boreholes under a range of future droughts.

In the UK there is a simple, well-established methodology for quantifying impacts of climate change on yields of public water supply boreholes during drought periods (UK Water Industry Research Ltd, 2014). A pumping water level-pumping rate curve during droughts (Figure 5) is developed using step-drawdown test data and operational abstraction-water level data during historic droughts. A statistical relationship between groundwater levels in a pumping borehole and an observation borehole is then used to shift the pumping water level-pumping rate curve, and yields are estimated based on the intersection of the curve and potential yield constraints (e.g. pump intake depth). However, this method doesn't account for variations in hydraulic conductivity with depth (VKD), which is well known to occur in fractured aquifers. Figure 5 shows the typical "cocktail glass" model developed by Rushton et al. (1989) of VKD in the Chalk aquifer, England. The relative significance of both changes in climate and in permeability with depth on estimates of borehole yields during droughts is poorly understood.

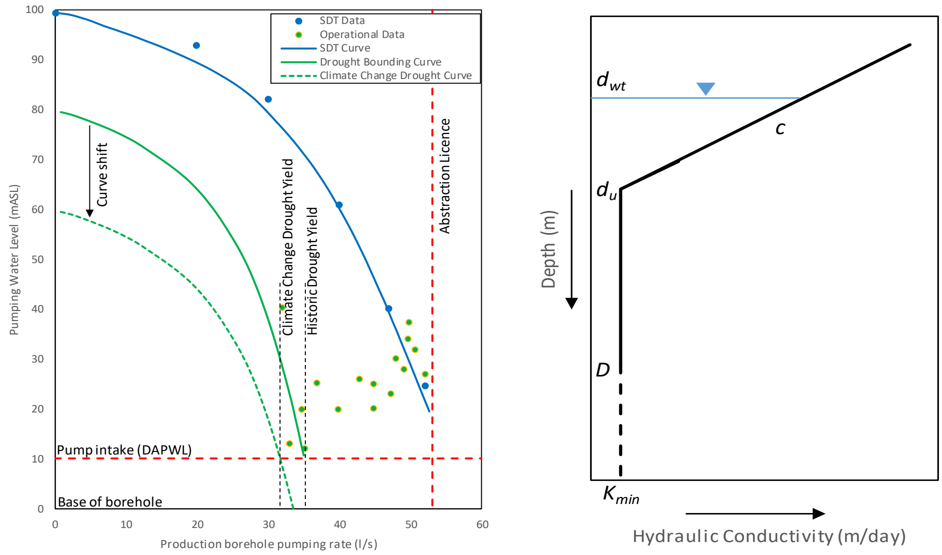


*Figure 5: Yield-drawdown plot for estimating borehole yields under historic and future conditions (left) and the "cocktail glass" model of VKD (right). Adapted after Foster and Sage (2017) with permission of Springer and Rushton et al. (1989) with permission from the Geological Society of London.*

To address this, Ascott et al. (2019) developed a simple radial groundwater flow model of a conceptual site around a pumping borehole. Six abstraction rates, 11 different VKD profiles and 20 different climate scenarios were implemented, resulting in 1320 model runs. For each run, the relative significance of climate and VKD profile on groundwater levels and yield estimates during drought periods was evaluated. Figure 6 shows the drawdown response as a function of the mean permeability of each profile and annual recharge for each climate scenario, for the 1976 drought event. Across all abstraction rates and drought years, VKD is more significant ($P < 0.001$) than with climate change in controlling lowest pumping water levels ($P > 0.1$). Both VKD and climate are significant controls on borehole yields, but responses are non-linear due to pumping water level-pumping rate curves intersecting yield constraints (Figure 5).

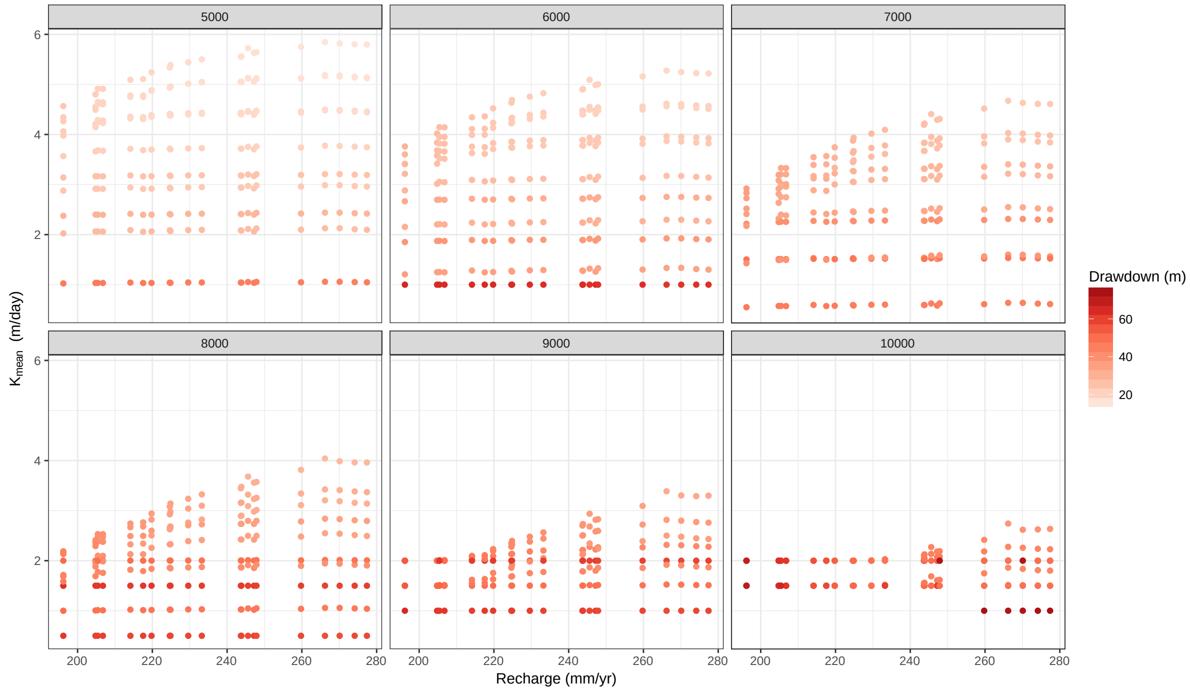


*Figure 6: Maximum drawdown in 1976 (colour of points, m) as a function of recharge (mm/yr) and mean saturated hydraulic conductivity ($K_{mean}$, m/day) for Q = 5000 – 10000 $m^3$/day (top left to bottom right panel). Reproduced after Ascott et al. (2019).*

Ascott et al. (2019) suggest that VKD is taken into consideration into future assessment of impacts of climate change on borehole yields during droughts. This highlights the challenges in translating climate-driven changes in groundwater levels in observation boreholes to changes in impact metrics. In this case, without considering VKD and key yield constraints, estimates of impact (yield loss) associated with climate-driven changes in regional groundwater levels are likely to be underestimates.

## AN OUTLOOK FOR FUTURE RESEARCH AND PRACTICE

There are a number of outstanding research questions related to climate-driven changes in groundwater resources. The empirical hydrograph analysis using the SGI has predominantly focussed on groundwater droughts, with little attention paid to groundwater flood periods (Ascott et al., 2017), or the full extent of the hydrograph. Exploring how the full SGI changes associated with historic changes in rainfall and temperature would be beneficial to understand how climate change is affecting groundwater resources.

Lumped parameter models such as AquiMod are a computationally cheap way of modelling historic and future groundwater level time series. A number of driving climate datasets have been recently developed (Weather@home (Guillod et al., 2018); UKCP18 (Met Office, 2018)). It is suggested that future lumped parameter modelling could explore future changes in groundwater levels associated with these climate datasets.

There remain significant challenges in relating changes in groundwater levels in observation boreholes to impacts. In the context of public water supply, the relative impacts of VKD and climate on borehole yields has been quantified. However, often yield estimates are made conjunctively using water resource system models (UK Water Industry Research Ltd, 2014), and future works should consider integrating climate and VKD into these approaches.

Whilst the SGI and AquiMod have been used extensively in research applications, to date operational use of these tools in practice has been limited. In recent years there has been a significant development of high performance computing facilities. In parallel with this, environmental regulators are increasingly adopting policies for open access to datasets in real-time (Environment Agency, 2019). These trends open up the possibility of automating the SGI and AquiMod to be run in real-time using live groundwater level data. Such “real-time services” have been already been developed for surface water (Environment Agency, 2019), but limited work to date has developed these for groundwater.

## CONCLUSIONS

In this paper, we review methods and models for quantifying climate-driven changes in groundwater resources. The SGI and AquiMod are shown to be powerful tools for quantifying historic and future changes in groundwater levels. However, there remain significant challenges in in relating changes in groundwater levels to impacts across different sectors (e.g yields of public water supply boreholes). Future research should: (1) explore the full extent of the SGI, rather than just drought, (2) apply the latest climate model data to AquiMod models and (3) develop improved links between observation borehole groundwater levels and impacts. Use of live open access datasets and high performance computing facilities will allow the methods and models presented here to be applied as a real-time service.

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