Analysis of the impact of hydraulic properties and climate change on estimations of borehole yields

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Abstract

Understanding the impact of climate change on borehole yields from fractured aquifers is essential for future water resources planning and management. Although variation in hydraulic conductivity with depth (VKD) in fractured aquifers is a well-known phenomenon, the relative significance of climate change and VKD on borehole yield estimates is poorly understood. We hypothesize that VKD exerts a significant additional control on borehole yields under climate change that has not been considered in yield assessments to date. We developed a simple two-layered radial groundwater flow model of an idealised pumping borehole in the fractured Chalk aquifer of south-east England, and applied 11 VKD profiles based on a simple conceptual representation of variability in hydraulic conductivity with depth in the Chalk. For each time step, the transmissivity is calculated by integrating the hydraulic conductivity VKD profile over the saturated depth calculated at the previous time step. For each VKD and resulting transmissivity, we applied 20 climate scenarios and six constant pumping rates for the period 1962 – 2014. We then estimated borehole yields based on the derived lowest pumping water levels during key drought years (e.g. 1976). We show that the hydraulic properties of the aquifer are more significant ($p < 0.001$) than changes in climate ($p > 0.1$) in controlling lowest pumping groundwater levels when abstraction rates are < 9000 m^3/day, and that both are significant when abstraction ≥ 9000 m^3/day. Hydraulic conductivity is as significant a control as climate on borehole yields, although responses are non-linear associated with whether pumping water level-pumping rate curves intersect key yield constraints (e.g. pump intake depth, major inflow horizons). It is recommended that variations in hydraulic conductivity with depth are taken into consideration in future assessments of borehole yields under climate change. The approach presented is generic and can be applied across different aquifers where vertical heterogeneity is present and affects transmissivity.

Keywords

Climate change, groundwater management, heterogeneity, water supply, Chalk

1 Introduction

Fractured rocks cover over 20% of the earth surface and groundwater from aquifers in these rocks forms a significant component of global water supply (Sharp and Krasny, 2007). Estimation of reliable yields of boreholes in fractured rock aquifers under drought conditions is essential for water resources planning and management. Anthropogenic climate change is now beyond refute (IPCC, 2013), and decreases in groundwater recharge of > 10% are estimated to affect up to 19% of the world's population in the 2050s (Döll, 2009). Consequently, understanding the impacts of climate change on yields from boreholes in fractured aquifers during droughts is also critical.

Published approaches to quantifying individual borehole yields in fractured rocks during drought periods are scant. Individual case studies have been reported in the USA (Hammond, 2018), UK (Beeson et al., 1997), South Africa (van Tonder et al., 2001), Italy (Piscopo and Summa, 2007) and Kenya (Boak, 2016), but only the UK provides detailed methods and guidelines for borehole yield assessment under drought and climate change impacts (UK Water Industry Research Ltd, 2014). Even in countries with well-developed water resources management practices, estimates of borehole yields during droughts have been shown to be substantially overestimated (Hammond, 2018). Methods for estimating groundwater yields are often not reported and in areas of conjunctive water distribution borehole yields are combined with surface water yields to derive a total yield for the water resource system (UK Water Industry Research Ltd, 2014).

The dearth of published methodologies for assessment of borehole yields during droughts means that this research builds on approaches reported in the UK. In the UK, borehole yields are estimated using the approach outlined by Beeson et al. (1997) and Misstear and Beeson (2000) and shown in Figure 1. In brief, observed step-drawdown test data are used to derive the shape of a yield-drawdown curve. Operational data for borehole water level and pumping rate during drought events are then plotted and the yield-drawdown curve shifted downwards to "bound" the drought data. If the drought-shifted yield-drawdown curve intersects a critical groundwater level constraint (termed "deepest advisable pumping water level (DAPWL)") such as the pump intake or the top of a major inflow horizon, then the rate at the intersection point defines the recommended drought yield. Quantifying impacts of climate change on borehole yields typically involves further shifting of the drought curve. Simple lumped parameter models (e.g. Mackay et al (2014)) or regional groundwater models (e.g. MODFLOW, Harbaugh et al (2000)) are used to estimate groundwater level changes in observation boreholes under various climate scenarios. A statistical relationship between groundwater levels in observation boreholes and pumping boreholes is then developed (UK Water Industry Research Ltd, 2014) and used to shift the pumping borehole drought curve to account for the likely impacts of climate change.

Curve shifting offers a rapid and simple approach to the estimation of climate change impacts on borehole yields during drought periods. However, the approach is subject to significant uncertainty (Besien and Perkins, 2000; Environment Agency, 2012; UK Water Industry Research Ltd, 2014). Applying a linear vertical shift of the drought curve beyond the lowest observed pumping water level (as illustrated in Figure 1) assumes that aquifer properties (hydraulic conductivity, storage) below this water level do not change with depth. Reductions in permeability and storage with depth have been reported in fractured aquifers across the world (Boisson et al., 2015; Gleeson and Ingebritsen, 2016; Guihéneuf et al., 2014; Sanford, 2017), one particular example being the Chalk aquifer, which is found across significant parts of southern England and northern Europe (Allen et al., 1997; Downing et al., 1993). In such aquifers, where the hydraulic properties vary with depth, borehole yields often decrease non-linearly with declining groundwater levels (Butler et al., 2009; Mansour et al, 2011; Upton et al., 2019). Climate change curve shifting to estimate borehole yields in fractured aquifers during droughts therefore represents a best-case scenario where aquifer properties are constant with depth. To date no work has quantified the relative influence of climate change and aquifer properties on borehole yields.

Assessing borehole yields in complex fractured aquifers is challenging. Yields are influenced by a range of processes operating at different scales. At the regional-scale, processes such as recharge and large-scale aquifer transmissivity and storage are important, while at the local-scale the nature and distribution of fractures around the borehole, the position of the pumped water level relative to these, and features of the borehole itself exert major controls on borehole yields. The groundwater level response in a pumped borehole within an unconfined fractured aquifer can be highly non-linear, with significant reductions in yield often observed due to dewatering of major fractures or inflow horizons. This geological heterogeneity, which leads to variations in aquifer properties with depth, can be incorporated in a numerical groundwater model with the use of multiple layers. However, this often causes numerical instabilities when layers dewater and rewet. An alternative approach is the use of a single layer in which hydraulic conductivity varies with depth according to a user-defined vertical profile. Transmissivity is calculated by integrating the hydraulic conductivity over the saturated thickness of the layer at each time-step in the model run. This method avoids the numerical issues of solving multiple layers, while still allowing transmissivity to vary non-linearly due to changes in water level and variations in hydraulic conductivity with depth. The variation of hydraulic conductivity with depth (VKD) mechanism has been implemented in several groundwater models to improve the representation of the groundwater response in vertically heterogeneous aquifers, including the Chalk (Jackson, 2002; Soley et al., 2012; Taylor et al., 2001).

In this study we hypothesized that hydraulic properties, and in particular variations in transmissivity related to different depth profiles of hydraulic conductivity (referred to as VKD herein), in fractured aquifers significantly affect pumping groundwater levels and estimates of borehole yields under climate change. Applied to the Chalk of south-east England, we developed a radial groundwater flow model centred on an idealised pumping borehole. The Chalk is a principal aquifer for water supply and, like many fractured aquifers, it has a distinct VKD profile where hydraulic conductivity reduces with depth. We apply a series of pumping rates, climate scenarios and VKD profiles to derive estimates of borehole yield. We show that VKD through varying transmissivity exerts a more significant control than climate change for the range of scenarios modelled on pumping water levels and that both are significant controls on borehole yield estimates.

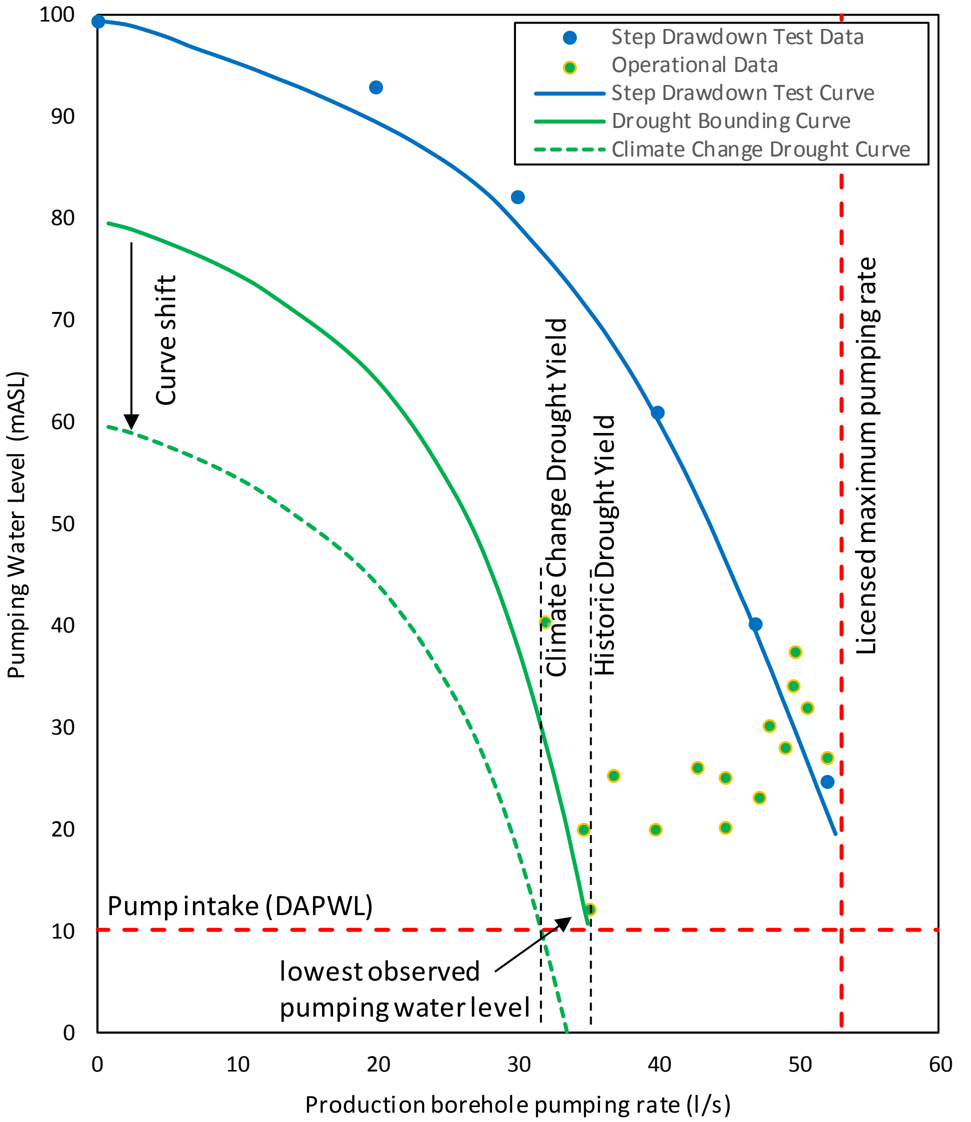

Figure 1: Yield-drawdown plot used for deriving borehole yields under historic conditions and for future climate scenarios based on the approaches of Beeson et al. (1997) and Misstear and Beeson (2000). Adapted after Foster and Sage (2017) with permission of Springer.

2 Materials and Methods

2.1 Study area

This study used an idealised borehole in the Chalk of south-east England (Figure 2). Previous work has shown that in England climate change has already increased the frequency and intensity of groundwater droughts (Bloomfield et al., 2019) and is likely to result in future reductions in recharge and groundwater levels both on an annual basis and during seasonal minima (Jackson et al., 2015; Jackson et al., 2011; Watts et al., 2015). An idealised site was chosen as (1) the purpose of this research is to illustrate the methodology, and this ensures the approach is generic and can be applied across a range of future real-world examples from different types of fractured aquifers, and (2) detailed pumping water level and pumping rate data for public water supply boreholes are not publically available in the UK. The Chalk underlies large parts of England, Belgium, northwest France and the Netherlands. It is a dual porosity soft white microporous limestone in which groundwater flow occurs primarily through the fracture network, although some matrix flow is also present (MacDonald and Allen, 2001). The Chalk is a highly productive aquifer, contributing up to 70% of the public water supply in south-east England. In comparison to aquifers with significant intergranular flow (e.g Permo-Triassic sandstones (Allen et al., 1997)), groundwater resources in the Chalk are susceptible to extremes of both floods (Ascott et al., 2017; Hughes et al., 2011; Macdonald et al., 2008) and droughts (Bloomfield et al., 2015; Bloomfield et al., 2019; Marchant and Bloomfield, 2018). Heterogeneity in the Chalk has been extensively characterised. Laterally, permeability varies substantially between river valleys and interfluves, with additional regional controls associated with Chalk structure and lithology, and superficial deposits and erosion processes. The Chalk exhibits significant reduction in permeability with depth associated with decreasing frequency and aperture of fractures with increasing overburden (Allen et al., 1997; Bloomfield, 1996).

In this research, the idealised borehole is located in the Kennet catchment (Figure 2). Groundwater flow in the Chalk of the Kennet catchment has been extensively characterised (Environment Agency, 2003; Rushton et al., 1989). Rushton et al. (1989) developed a simple model to characterise variation in permeability with depth in the Kennet catchment, describing the permeability variations as a "cocktail glass". This approach, which is adopted in this research (see section 2.3) is illustrated in Figure 3. A minimum hydraulic conductivity, K_{min} (m/day) is defined for the Chalk between the base of the aquifer, D (m), and breakpoint, d_u (m). The slope parameter, c defined as $\frac{(K_{max}-K_{min})/k_{min}}{d_u}$ (m^{-1}), is used to calculate increases in hydraulic conductivity relative to K_{min} above d_u. The transmissivity, T (m^2/day), of the total profile is estimated using Equation 1 below, where d_{wt} (m) is the depth of the time-variant water table:

$$T = \begin{cases} K_{min}(D - d_{wt}) + K_{min} c \dfrac{(d_u - d_{wt})^2}{2}, & d_{wt} < d_u \\ K_{min}(D - d_{wt}), & d_{wt} \geq d_u \end{cases} \# \tag{1}$$

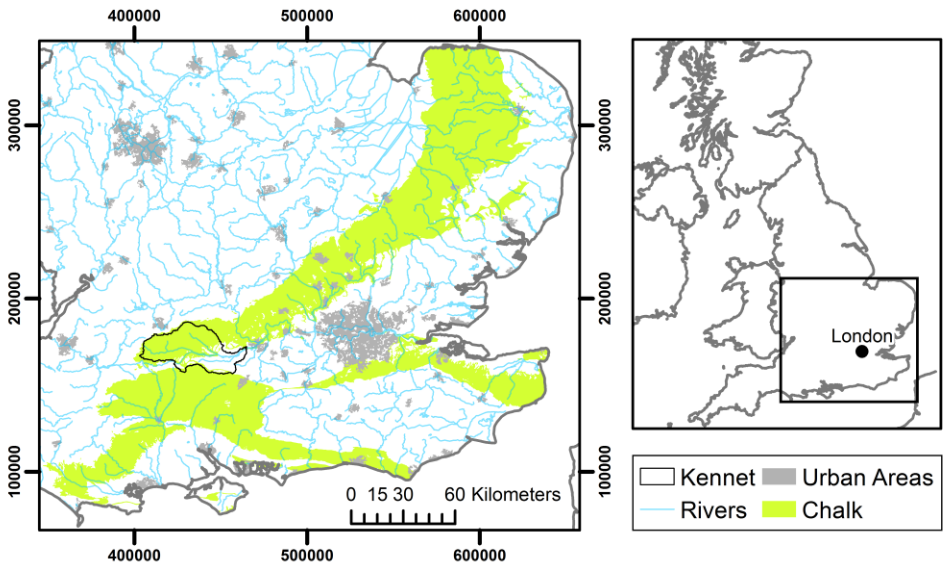

Figure 2 Location of the River Kennet catchment and the Chalk in south-east England (left) in the context of the UK (right). Contains Ordnance Survey data © crown copyright and database right (2018)

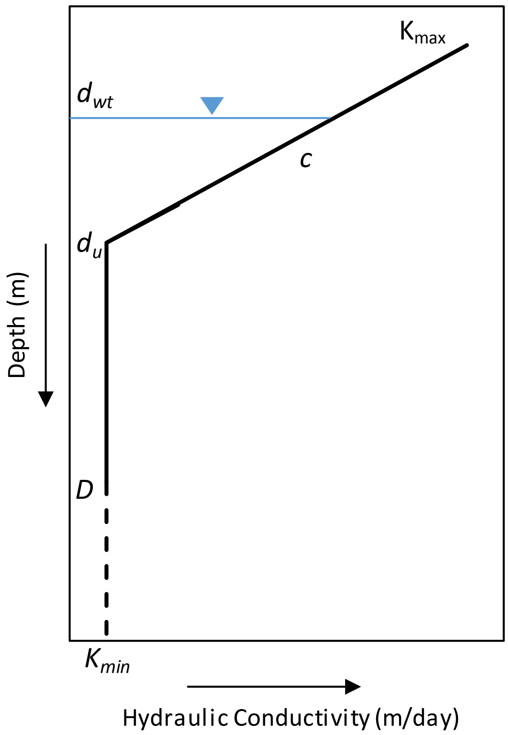

Figure 3 The "cocktail glass" model of decreases in hydraulic conductivity with depth. Reproduced after Rushton et al. (1989) with permission from the Geological Society of London.

2.2 Conceptual and Numerical Groundwater Flow Model

In order to quantify the relative significance of climate change and hydraulic properties on borehole yields, the finite difference radial flow model COOMPuTe (Cylindrical grid Object Oriented Model for Pumping Test analysis (Mansour et al., 2007; Tamayo-Mas et al., 2018)) was used to simulate pumping water level values at a pumped borehole at the idealised site in the Kennet catchment. This model solves the implicit numerical form of the 3-D governing flow equation in porous media, which is expressed in cylindrical coordinates as (Mansour et al., 2007):

$$\frac{K_r}{r}\frac{\partial h}{\partial r} + \frac{\partial}{\partial r}\left(K_r \frac{\partial h}{\partial}\right) + \frac{1}{r}\frac{\partial}{\partial \theta}\left(K_\theta \frac{\partial h}{r \partial \theta}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) + N = S_s \frac{\partial h}{\partial t} \qquad (1)$$

where $h(r, \theta, z)$ is the hydraulic head [L] at a point at cylindrical coordinates (r, θ, z), S_s is the volumetric specific storage [L^{-1}], N is a sink-source per unit volume term that is positive for recharge and negative for withdrawal [T^{-1}], and K_r, K_θ and K_z represent the hydraulic conductivity values [L T^{-1}] along the respective cylindrical coordinate directions. In this model, the pumped borehole occupies the centre of the domain and each defined hydraulic layer is discretised using a numerical grid in cylindrical coordinates. Grid nodes are spaced logarithmically along the radial dimension (r) providing greater refinement close to the pumping borehole to improve the curvature of the potentiometric head surface around the pumped borehole. The model consists of two numerical layers: an upper layer representing a moving water table surface and a lower layer representing the aquifer. Nodes are vertically connected using a conductance term leading to a deforming numerical grid (Figure 4) that represents the spatial and temporal variation of the saturated thickness of the domain. .

In this case study, we simulate an unconfined aquifer that is uniform and homogeneous in the radial and circumferential directions, but heterogeneous in the vertical direction to represent vertical variations in hydraulic conductivity with depth in the Chalk aquifer (Table 1 and Figure 4). Vertical heterogeneity is incorporated using the variation of hydraulic conductivity with depth (VKD) method developed by Rushton et al. (1989), as described above. The aquifer is represented by two numerical layers: the water table layer and a single aquifer layer in which hydraulic conductivity reduces with depth. This simplified conceptualisation of a complex fractured aquifer includes the vertical flow from the water table but assumes horizontal flows within the aquifer layer are dominant. This is a typical groundwater behaviour in the Chalk where the vertical hydraulic conductivity values are at least one order of magnitude smaller than the horizontal hydraulic conductivity values (Allen et al., 1997), which makes the horizontal groundwater flows more significant than the vertical flows, and with the absence of low permeability layers within the aquifer, a single hydrogeological -layer model approach can be used (Rushton, 2003). For the aquifer layer, the transmissivity between two adjacent nodes is calculated using the mean transmissivity values calculated at these nodes using Equation 1, where d_{wt} is the water table position simulated during the previous time step. Horizontal hydraulic conductivity is defined for each simulation based on the VKD profiles, where the vertical changes in hydraulic conductivity are implicitly considered through an averaged term as described in Section 2.3. Vertical hydraulic conductivity value is calculated as 10% of the calculated horizontal hydraulic conductivity value. Specific storage and specific yield are kept constant for this study at $1x10^{-7}$ m^{-1} and 0.2, respectively (Allen et al., 1997).

The two-layer unconfined model, which has an initial saturated thickness of 80m based on the range of ambient saturated thicknesses in the Kennet catchment reported by Rushton et al. (1989) is pumped from an open, fully-penetrating borehole with a diameter of 0.2m located at the centre of the aquifer. The pumping rate is defined for each simulation as described in Section 2.3. A fixed head boundary, situated 10 km from the centre of the borehole, is specified with an elevation of 40m below the initial position of the water table. The presence of this fixed head node is similar to the presence of a river in a real groundwater system. The model setup generates a groundwater divide the simulated position and elevation of which depends on the pumping rate and the temporally varying recharge rate as illustrated in Figure 4. The location of the groundwater divide is checked at every time-step to confirm that it does not reach the outer boundary. Whilst this ensures that the outer boundary always acts as a discharge point, i.e. does not provide recharge to the borehole, it is acknowledged that the choice of boundary conditions may affect the model results. This is considered further in section 4.2. To overcome the impact of initial conditions on the analysis of groundwater heads, the model is run in a warming up mode for 53 years using the same recharge dataset that is used to produce the groundwater head fluctuations.

Table 1 Model domain properties and discretisation details.

Direction	Hydrogeological properties	Dimension	Discretisation
Radial	Constant hydrogeological properties	Borehole diameter equal 0.2 m. Aquifer radius equal 10000 m.	Six grid intervals every tenfold increase along the radial direction (total of 31 nodes along one radial direction).
Circumferential	Constant hydrogeological properties	Not applicable. Flow simulated using a single slice model.	Not applicable
Vertical	Variable hydraulic conductivity with depth.	Total aquifer thickness equal to 80 m.	Two numerical layers: one representing the aquifer and the other representing the water table.

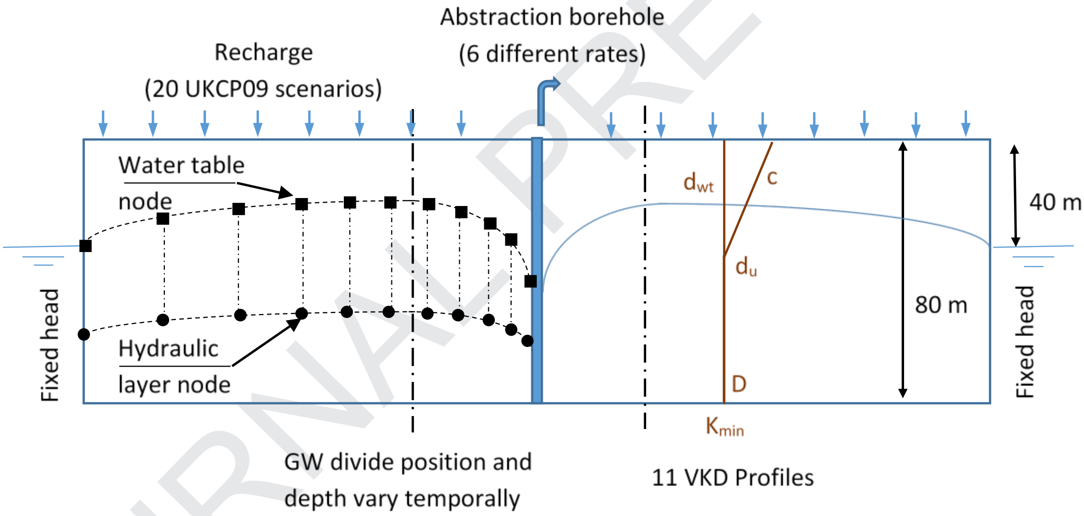

Figure 4 Schematic of the conceptual model developed in this research.

The recharge input to the radial groundwater flow model is calculated using the Zooming Object Oriented Distributed Recharge Model (ZOODRM) (Hughes et al., 2008; Mansour and Hughes, 2004; Mansour et al., 2011). This model uses precipitation, potential evapotranspiration, topography, soil, and land use data to calculate potential recharge. A simplified version of the FAO recharge calculation method (FAO, 1998), referred to as the modified EA-FAO method (Griffiths et al., 2006) is used in this study. This method estimates the actual evaporation based on the soil moisture deficit level and the total available and readily available water in the soil zone. When precipitation is larger than the soil moisture deficit and actual evaporation, the excess water volume is split into potential recharge and runoff volumes using a runoff coefficient. A description of this method is also provided by Mansour and Hughes (2004). The daily time series of historical recharge values calculated at a selected representative location in the Kennet catchment and obtained from the recharge calculation study undertaken over the United Kingdom (Mansour et al., 2018) are used for the reference simulation. These recharge values are then perturbed to create the climate scenarios as explained in Section 2.3. Recharge varies temporally throughout each simulation but is assumed to be spatially uniform across the groundwater model domain. The calculated long term average (LTA) recharge value is approximately 0.6 mm/day. Table 2 shows a water balance produced by the recharge model and Figure 5 illustrates the seasonal variations in the recharge values calculated at the study area.

For each simulation, the radial groundwater flow model, COOMPuTe, is run in time-variant conditions with a daily time-step over the historic period 1962 – 2014. This period was chosen as it covers a number of significant drought events (1976, 1990-1992, 1995-1997, 2004-2006, 2010-2012) which have been used for previous borehole yield assessments (Bloomfield and Marchant, 2013; Folland et al., 2015; Marchant and Bloomfield, 2018) . An equivalent 53 year period is then run using the perturbed recharge time-series to investigate the impacts of climate change.

Table 2 Water balance of the water components calculated over the simulation period from 1962 to 2014

Water component	Inflow (mm/day)	Outflow (mm/day)
Precipitation	1.97	
Actual evaporation		1.34
Runoff		0.03
Recharge		0.6

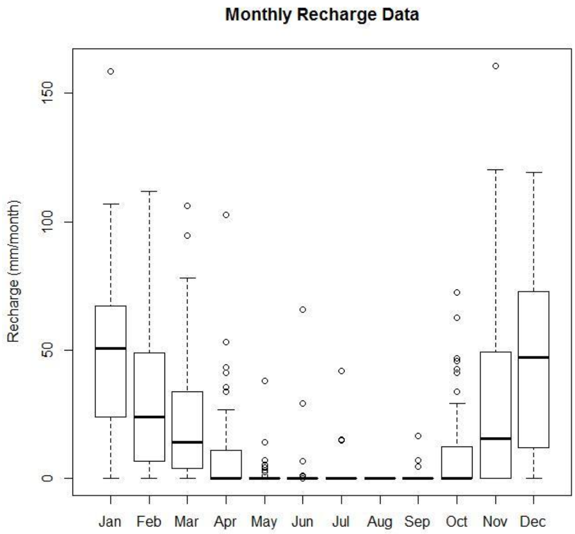

Figure 5 LTA monthly recharge values

2.3 Pumping rates, VKD profiles and climate change scenarios

Six different pumping rates were applied to the numerical groundwater flow model (5000 to 10000 m^3/day in increments of 1000 m^3/day). Each pumping rate was applied constantly for the full length of the simulation. This range of pumping rates is wide enough to include the actual rates for 9 of the 10 main groundwater abstractions for public supply present in the Kennet catchment (Atkins, 1992). Detailed borehole-scale observations and regional modelling studies were used in combination with the "cocktail glass" approach of Rushton et al. (1989) to derive 11 VKD profiles to apply in the numerical model described above. Packer test results reported from the Kennet catchment by Butler et al. (2009) were used to derive the range of values of K_{min} (0.5, 1, 1.5 and 2 m/day). A range of values for c from 0 to 0.8 m^{-1} was used based on sensitivity analyses in previous groundwater modelling studies in the Kennet Valley (Environment Agency, 2003; Rushton et al., 1989). The zone of enhanced permeability in the Chalk is typically associated with the area of seasonal water table fluctuation (Allen et al., 1997), and thus a breakpoint elevation d_u of 10 m below seasonal groundwater level minima was used (Environment Agency, 2003). The range of K_{min} and c values were combined to derive 36 hydraulic conductivity profiles. Assuming the model is fully saturated, we then calculated the equivalent transmissivity for each profile. We then selected 11 of the 36 profiles which had transmissivity values within the interquartile range of values for the Chalk in the Kennet Valley (380 – 1500 m^2/day (MacDonald and Allen, 2001)). Figure 6 shows these profiles and the associated transmissivity when the model is saturated. It should be noted that the VKD “cocktail glass” model has been widely used in Chalk groundwater modelling studies in both the Kennet catchment (Environment Agency, 2003; Rushton et al., 1989) and elsewhere (regional distributed groundwater models in Kent, Hampshire, Wiltshire (Soley et al., 2012) and Hertfordshire, UK (Clark et al., 2017), as well as in lumped parameter (Mackay et al., 2014) and streamflow depletion models (Hulme et al., 2012)). The cocktail glass model is the only generic published model of the distribution of permeability with depth specifically for the Chalk. Consequently, in this idealised example it is appropriate to use this model. However, it should be noted that the “cocktail glass” model is a simplified interpretation of VKD (Butler et al., 2012). There is evidence in some boreholes that large increases in drawdown can occur due to dewatering of discrete flow horizons (the “dog-leg” response to pumping as reported by Allen et al. (1997)), and conversely that other wells may have significant fracture flow at depth (Parker et al., 2019). Further application of the groundwater model developed in this research to real-world case studies should consider different distributions of permeability with depth that are specific to the borehole in question. This is discussed in section 4.2.

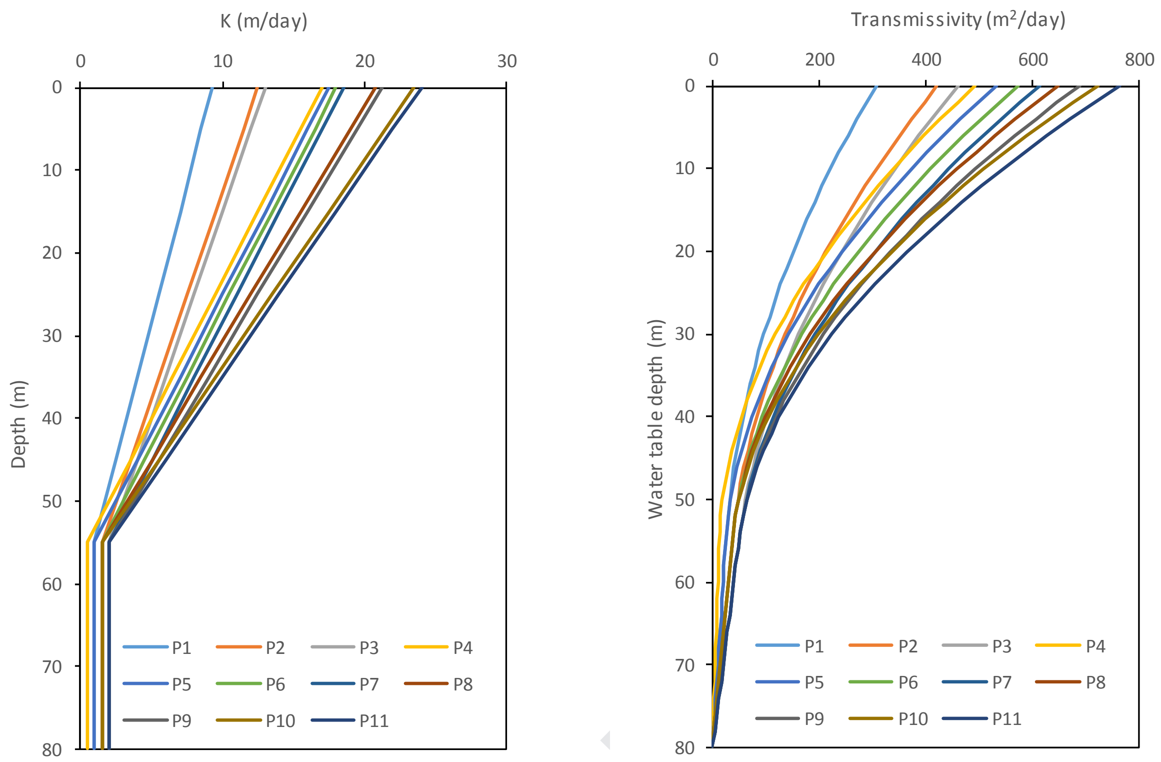

Figure 6 Hydraulic conductivity and transmissivity at saturation of VKD profiles used in the groundwater model

Consistent with current water resource management planning processes in England and Wales, we used climate change scenarios from the United Kingdom Climate Projections 2009 (UKCP09, UK Water Industry Research Ltd (2009)). UKCP09 consists of a sample of 10,000 equally probably climate futures. The approach adopted in this research is analogous to the methodology used by water companies in the UK (Environment Agency, 2012). To ensure that the number of groundwater model runs was manageable, outputs from the Latin hypercube sample approach developed by UK Water Industry Research Ltd (2009) and detailed by Christierson et al. (2012) were used. This approach sub-samples the 10,000 runs down to 20. For each sample, percentage changes in monthly rainfall and potential evapotranspiration for the 2020s (2011-2040, baseline historic period: 1961 – 1990) for the medium emission scenario for the River Thames catchment (in which the Kennet is located) were downloaded. This is the only publically available set of representative multidimensional samples of the UKCP09 climate change factors. We applied the 20 sets of monthly climate change factors to the historic recharge model run to derive "future" groundwater recharge for the 2020s. We then applied this recharge time series to the numerical groundwater flow model for each pumping rate and geological profile.

2.4 Quantifying the relative influence of VKD and climate change on pumping groundwater levels and borehole yields

The six pumping rates, 11 geological profiles and 20 climate scenarios were combined to derive 1320 unique model runs. For each model run, we assessed the impact of both climate change and VKD on pumping groundwater levels using both qualitative and quantitative methods. We examined the response of the minimum pumping water level to changes in mean annual recharge (as perturbed by the climate change scenarios) and the arithmetic mean saturated hydraulic conductivity for each profile for the worst historic hydrological drought in the Kennet, 1976 (National River Flow Archive, 2018). For each pumping rate and drought period (1976, 1990-1992, 1995-1997, 2004-2006, 2010-2012), we then derived Multiple Linear Regression (MLR) models in the form of Equation 3 to determine how much of the simulated minimum pumping groundwater level during the drought (PWL_{MIN}, m) can be explained by climate change-affected recharge and hydraulic conductivity:

$$PWL_{MIN} = a \cdot R + b \cdot K + c \qquad (3)$$

Where *R* (mm/year) is the mean annual recharge over the complete model run (1962-2014) and *K* (m/day) is the saturated hydraulic conductivity when simulated pumping groundwater levels during the drought are lowest. *a*, *b* and c are model coefficients derived using least squares regression. *K* is estimated using calculate model transmissivity and saturated thickness as:

$$K = \frac{T_{PWL_{MIN}}}{PWL_{MIN} - 80} \#(4)$$

Where $T_{PWL_{MIN}}$ (m^2/day) is the calculated model transmissivity at the pumping borehole when pumping water levels are lowest for each drought year, VKD profile and climate scenario. By using mean annual recharge over the complete model run this means that changes in recharge in the MLR models are controlled solely by climate change factors rather than historic climate variability between drought years. We then extracted the MLR model outputs (adjusted R^2, p values for predictor variables *R* and *K*) and plotted these as a function of different drought years and pumping rates. We also extracted the root mean square error (RMSE) for the MLR models in the form of equation 3 and compared this with the RMSE for models using: (1) a constant term (c) only, (2) c + R, (3) c + K.

The methodology used to quantify the relative influence of VKD and climate change on borehole yields is summarised in Figure 7. We derived both flow and groundwater level related yield constraints on the idealised borehole. We defined the maximum licenced pumping rate, Q_{lic}, to be a flow rate of 10000 m^3/day. In order to understand the sensitivity of yield estimates to different groundwater level constraints, we defined deepest advisable pumping water levels (DAPWL), at 20 to 60 m below ground level at intervals of 10 m. DAPWLs correspond to practical constraints on borehole performance such as the vertical location of the pump intake or major inflow horizons. For each climate scenario, VKD profile and drought period, modelled pumping rate-pumping water level data were extracted. We then derived pumping rate-pumping water level curves as presented in Figure 1 by fitting a quadratic equation to the modelled data:

$$Q = a \cdot PWL_{MIN} + b \cdot PWL_{MIN}^{2} + c \quad (5)$$

where Q (m^3/day) is the model pumping rate, PWL_{MIN} (m) is the simulated minimum pumping groundwater level during the drought and *a*, *b* and *c* are empirically derived constants estimated using least squares regression. The quadratic is the simplest form of equation that can match the non-linear response of pumping water levels to changes in abstraction. For DAPWL = 20 to 60 m below ground level, we used equation 6 below to calculate the borehole yield, Y (m^3/day), by predicting Q using equation 5 when $PWL = DAPWL$ and comparing against Q_{lic}:

$$Y = \begin{cases} Q_{lic}, & Q_{DAPWL} > Q_{lic} \\ Q, & Q_{DAPWL} < Q_{lic} \end{cases} \tag{6}$$

The relative influence of climate change and VKD on borehole yield were assessed visually initially by plotting the response of borehole yield to different climate change scenarios and VKD profiles for each drought period and each DAPWL. In a similar manner to equation 3 for pumping groundwater levels, we then used least squares regression to derive a multiple linear regression model (equation 7) to quantify the relative significance of VKD and climate change on Y:

$$Y = a \cdot R + b \cdot K + c \tag{7}$$

We extracted the MLR model outputs and plotted these as a function of different drought years and pumping rates, and compared the RMSE for this model with the RMSE for models using: (1) a constant term (c) only, (2) c + R, (3) c + K.

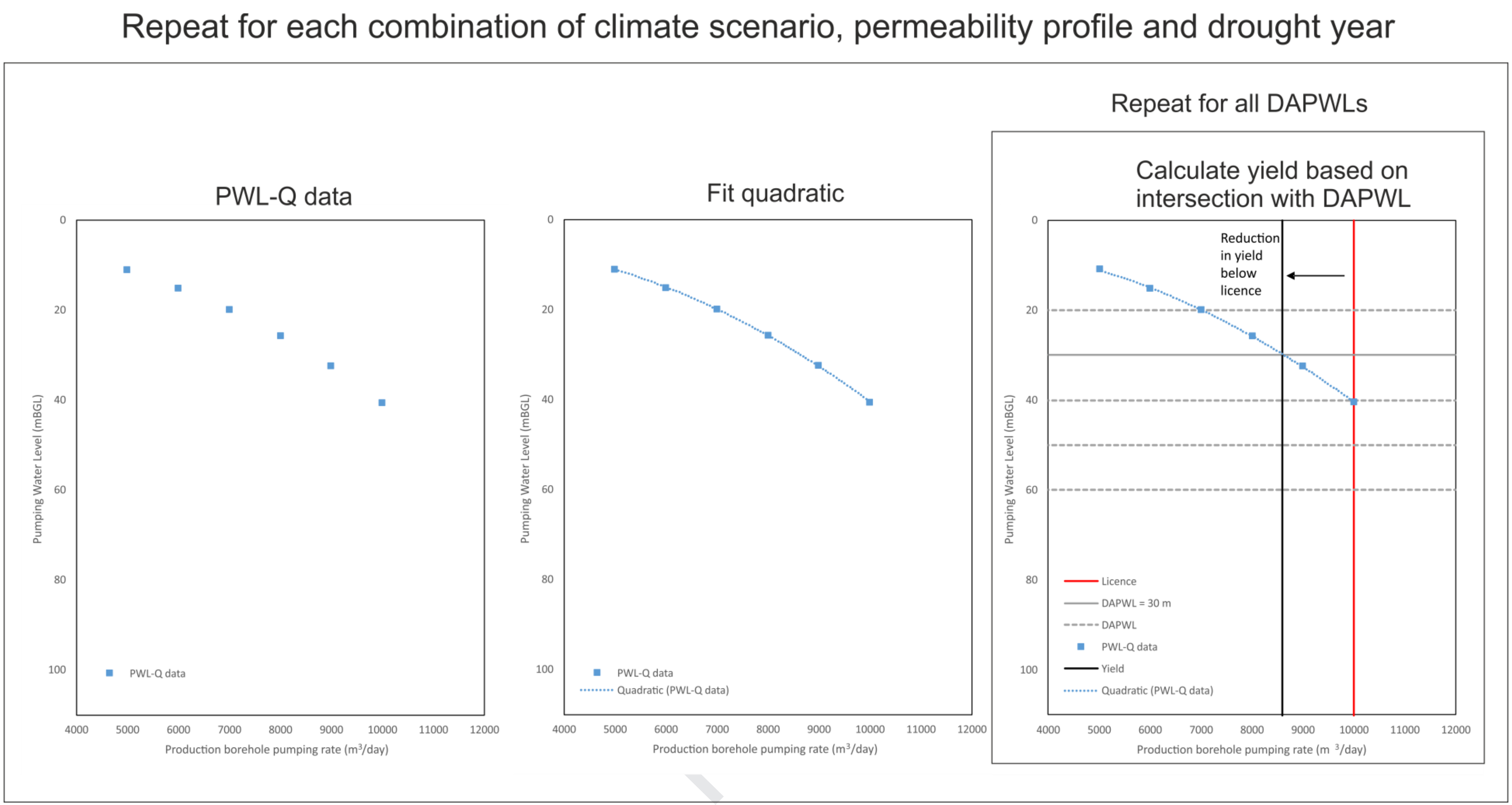

Figure 7 Schematic of the methodology used to calculate changes in borehole yield from model pumping water level (PWL) and discharge (Q) data using different deepest advisable pumping water levels (DAPWLs)

3 Results

3.1 Qualitative and quantitative assessments of the response in pumping water levels to changes in climate and VKD

Figure 8 shows the variation in the simulated minimum groundwater level during 1976 associated with changes in recharge associated with the climate scenarios and hydraulic conductivity associated with the VKD profiles, for pumping rates Q = 5000 to Q = 10000 m^3/day. Pumping water levels decrease substantially more in the y-axis dimension associated with variation in hydraulic conductivity than in the x-axis associated with variation in recharge. This is particularly the case for Q = 5000 m^3/day and Q = 6000 m^3/day, where pumping water level decreases of 40 to 60 m are induced associated with reduced permeability, in comparison to changes in pumping water levels of < 20 m associated with changes in recharge.

The results of the MLR models for 1976 are presented in Table 3. For Q = 5000 to 8000 m^3/day, the models derived for each pumping rate resulted in reasonable model fits (adjusted R^2 = 0.67 – 0.85). Hydraulic conductivity was a more significant explanatory variable ($p < 0.001$) than climate (p = 0.035 – 0.85). Addition of hydraulic conductivity (c + R + K, column 5 in Table 3) to the model against use of a constant term and recharge alone (c + R, column 7 in Table 3) substantially reduced the model RMSE from c. 9.3 to 4.7 m. For Q = 9000 and 10000 m^3/day, the model fit was somewhat worse (R^2 = 0.27 – 0.54) and both climate and hydraulic conductivity were significant explanatory variables ($p < 0.001$). Addition of hydraulic conductivity resulted in a small reduction in RMSE (from c. 8.8 to 7.2 m) At these pumping rates, use of a number of the lower hydraulic conductivity VKD profiles resulted in the model dewatering, resulting in a reduced number of data points as also shown in Figure 8.

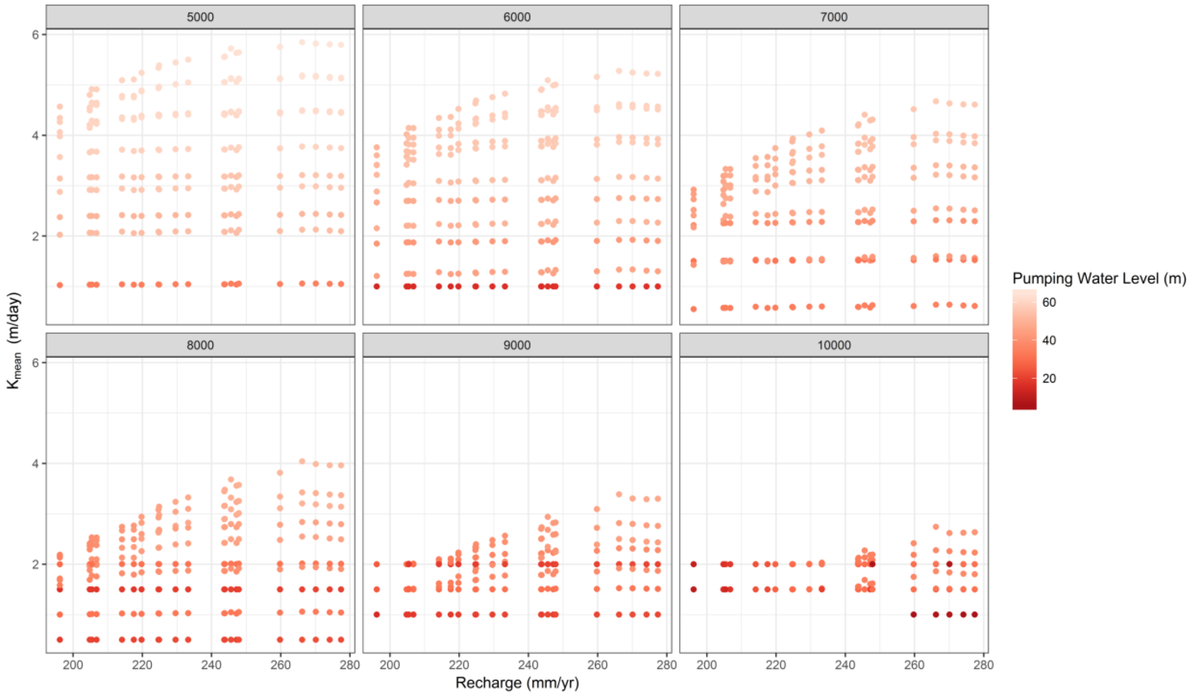

Figure 8 Minimum pumping water level in 1976 (colour of points, m) as a function of recharge (mm/yr) and mean saturated hydraulic conductivity (K_{mean}, m/day) for Q = 5000 – 10000 m^3/day (top left to bottom right panel). For example, a series of dots in the vertical correspond to variations in hydraulic conductivity for a single recharge scenario.

Table 3 R^2 and p values for VKD and climate for different pumping rates for MLR models of the form of equation 3 for lowest pumping groundwater levels during the 1976 drought. RMSE values for MLR models of equation 3, just using a constant (c), c + R, and c + K are also shown.

Q (m^3/day)	R^2	P_{VKD}	$P_{climate}$	$RMSE_{c+R+K}$	$RMSE_c$	$RMSE_{c+R}$	$RMSE_{c+K}$
5000	0.79	<0.001	0.3479	3.64	8.00	7.97	3.65
6000	0.67	<0.001	0.84741	6.80	11.83	11.79	6.80
7000	0.85	<0.001	0.03223	2.93	7.58	7.43	2.96
8000	0.74	<0.001	0.38996	5.28	10.42	10.20	5.29
9000	0.54	<0.001	<0.001	6.03	8.95	8.22	6.24
10000	0.27	<0.001	<0.001	8.44	9.95	9.33	8.96

Figure 9 shows the outputs of the MLR models in the form of equation 3 for different pumping rates and drought years. For all drought years and where Q < 9000 m^3/day, hydraulic conductivity is a more significant explanatory variable ($p < 0.001$) than recharge ($p > 0.1$) in controlling pumping water levels. Where Q ≥ 9000 m^3/day, both hydraulic conductivity and recharge are significant explanatory variables ($p < 0.001$). Across the range of pumping rates and drought years, the model fit is generally good (Figure 9 (right), R^2 = 0.6 – 0.9). This is expected as permeability and recharge (through the sink/source term *N*) are the primary variables controlling hydraulic heads in the groundwater flow equation (equation 2). Better model fits are found at lower pumping rates where model dewatering was insignificant (Q = 5000 - 8000 m^3/day, R^2 = 0.6 - 0.9; Q = 9000 - 10000 m^3/day, R^2 = 0.3 - 0.5). For all drought years when Q = 5000 – 8000 m^3/day, addition of hydraulic conductivity (c+R+K) to the model against use of a constant term and recharge alone (c + R) substantially reduced the model RMSE from c. 9.3 to 4.7 m. When Q = 9000 – 10000 m^3/day, only small reductions in RMSE were observed (c. 8.8 to 7.2 m, see Supplementary Figure 1).

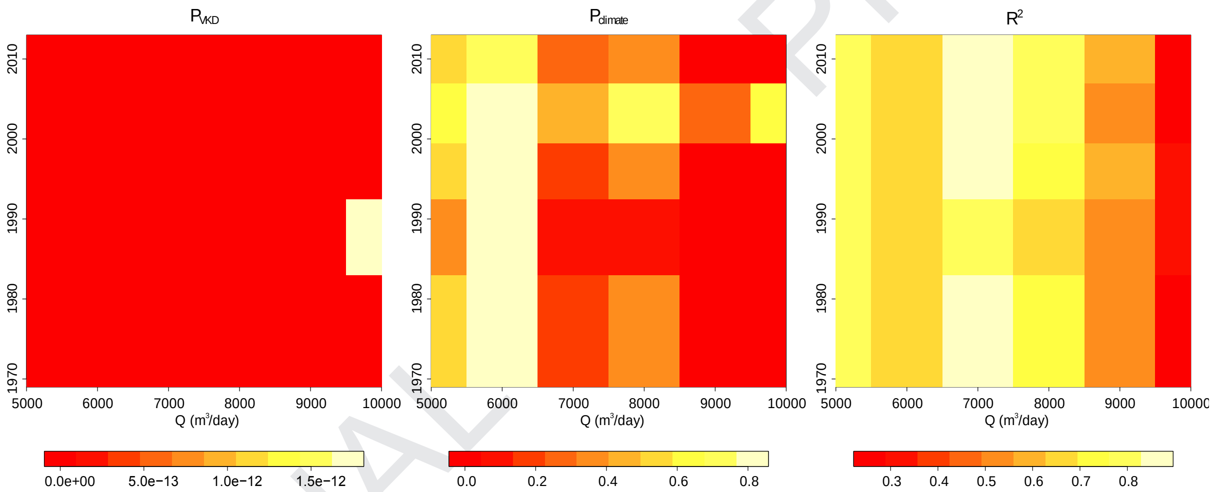

Figure 9 Response surfaces for outputs of multiple linear regression models in the form of equation 3 for different pumping rates (x-axis) and drought years (y-axis). Outputs are p values (for hydraulic conductivity and climate, left and centre) and adjusted R^2 (right).

3.2 Assessments of the response in borehole yield estimates to changes in climate and VKD

Figure 10 shows the relative influence of recharge and VKD on estimates of borehole yield from the idealised borehole based on equations (5) – (7), for different DAPWLs and drought periods. Reductions in borehole yield are more significant in the y-axis associated with VKD than in the x-axis associated with recharge. The impact of climate change and VKD on yield estimates is primarily controlled by the vertical position of the DAPWL (Figure 10, note variation in yield reduction where

DAPWL = 20 m (top row) to when DAPWL = 60 m (bottom row)). This is expected as the vertical position dictates whether the derived pumping rate-pumping groundwater level curve (equation 5) intersects the DAPWL and therefore reduces yield to below Q_{lic} (equation 6).

Quantitative relationships between VKD, climate change and yield are non-linear and highly dependent on the vertical position of the DAPWL (Figure 11). When the DAPWL is relatively shallow (20-30 m below ground level), the derived pumping rate-pumping water level curve (equation 3) always intersects the DAPWL. This results in a moderate relationship between VKD, climate and yield (mean R^2 = 0.2), with both VKD and climate significant explanatory variables ($p < 0.001$) and a relatively small reduction in RMSE when K is added to the MLR models (reduction of 260 m^3/day, see supplementary figure 2). At moderate DAPWLS (40 m below ground level), the relationship between VKD, climate and yield becomes weaker (mean R^2 = 0.07). For a number of geological profiles, the derived pumping rate-pumping water level curve doesn't intersect the DAPWL (note both grey (no yield reduction) and coloured (yield reduction) points in row 3 of Figure 10). Intersection of the curve with the DAPWL only occurs for VKD profiles with relatively low permeability, and hence low pumping water levels, which results in VKD being more important than climate (mean $P_{climate} > 0.1$, mean $P_{VKD} < 0.001$) and a slightly larger reduction in RMSE by addition of K (310 m^3/day). When the DAPWL is deep (50-60 m below groundwater level), the curve almost never intersects the DAPWL and yield is defined as Q_{lic}. When DAPWL = 50 or 60 m below ground level, $Y = Q_{lic}$ for 91% of yield estimates shown in Figure 10. This results in a very poor relationship between VKD, climate and yield (R^2 = 0.03), with both VKD and climate are poor predictor variables for yield (mean $P_{climate} > 0.1$, mean $P_{VKD} > 0.05$). This also causes RMSE values to be small relative to those for when DAPWL = 20 – 40 m, and the reduction in RMSE by addition of K when DAPWL = 50 or 60 m is small (156 m^3/day, see supplementary figure 2).

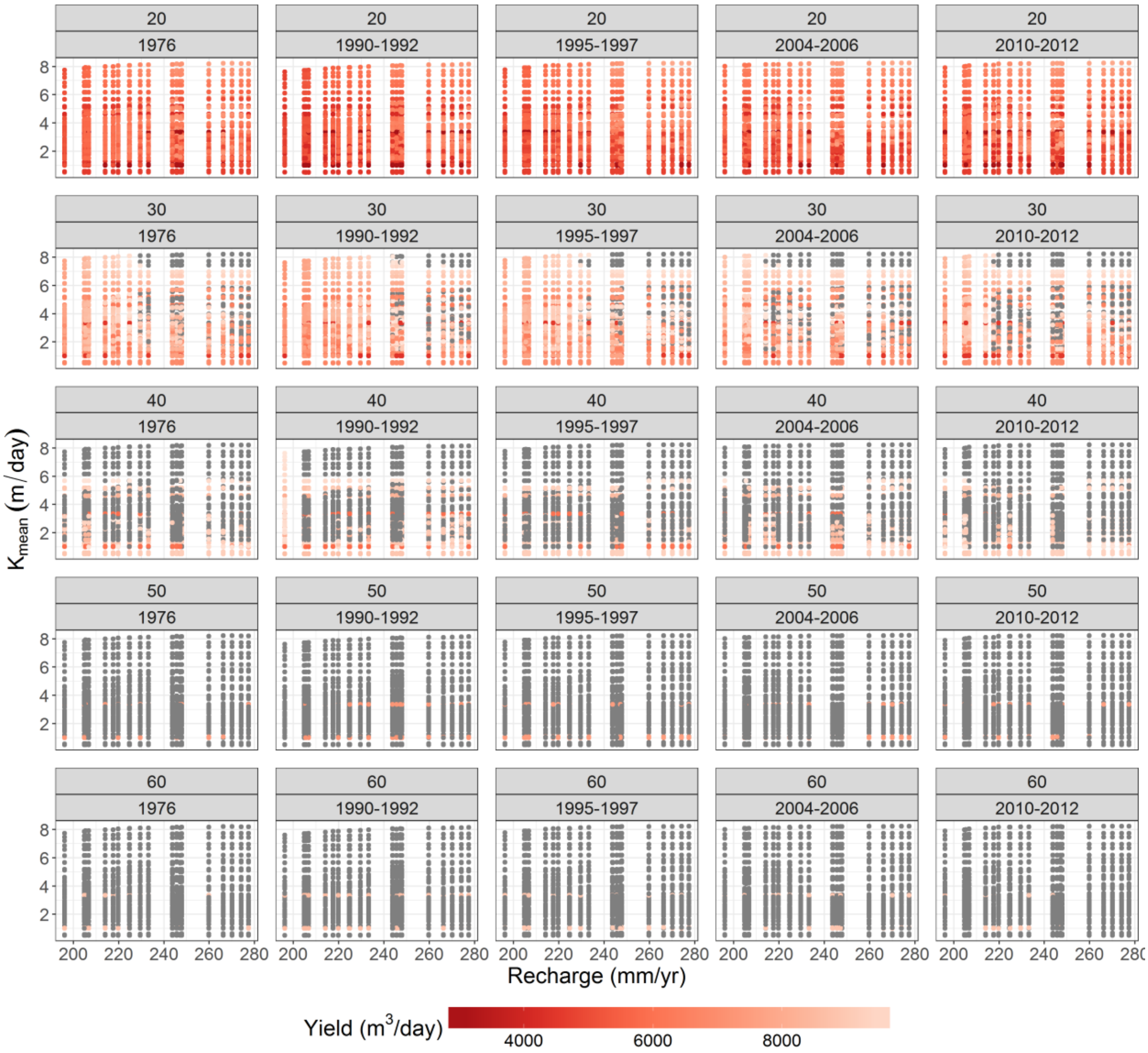

Figure 10 Loss of borehole yield (m^3/day, colour of points) as a function of recharge (mm/year, x-axis) and mean saturated hydraulic conductivity (m/day, y-axis) for different drought years (1976, 1990-1992, 1995-1997, 2004-2006 and 2010-12) and different DAPWLs (20 – 60 m). Grey points indicate no yield loss (i.e. Yield = 10000 m^3/day).

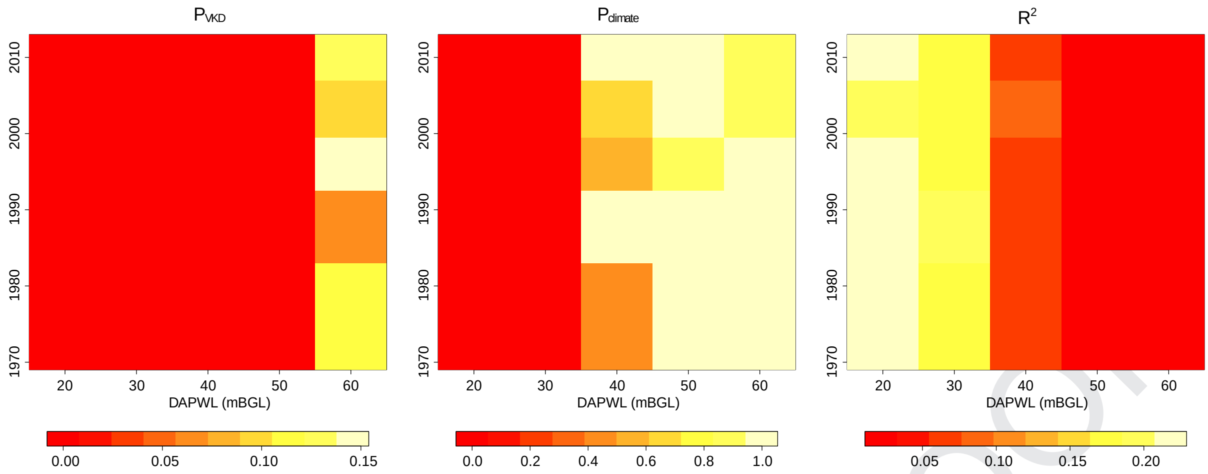

Figure 11 Response surfaces for outputs of multiple linear regression models in the form of equation 7 for different DAPWLs (mBGL, x-axis) and drought years (y-axis). Outputs are p values (for hydraulic conductivity and recharge, left and centre) and adjusted R^2 (right).

4 Discussion

4.1 Implications for yield assessment and groundwater modelling

This research has shown that, for an idealised site, the influence of variations in hydraulic conductivity with depth on mean vertical hydraulic conductivity have a greater influence than climate change when estimating pumping groundwater levels. This is particularly the case where Q < 9000 m^3/day and limited model dewatering occurred. In these cases, the greater influence of VKD compared to climate change reflects the VKD profiles and climate change factors used in this research. We used VKD profiles that reflect the hydrogeological setting of the site, and climate change factors that are consistent with current water resources management practices. Use of climate change data over longer time horizons and temporal variations in drought events may result in climate change being as significant as VKD. This considered further in section 4.2. Where Q ≥ 9000 m^3/day, use of the lower hydraulic conductivity profiles resulted in the model dewatering. The remaining profiles have a relatively high hydraulic conductivity, and combined with the reduced number of data points this resulted in both climate and hydraulic conductivity being significant explanatory variables.

Whilst borehole yields are largely controlled by the vertical position of the DAPWL, VKD is as significant a control as climate change when DAPWLs are shallow and is more significant than climate change when DAPWLs are moderately deep. These results have significant implications for real-world borehole yield assessment. Conventional methods for quantifying the impacts of climate change on borehole yields in the UK use extrapolation and vertical shifting of the drought bounding curve (Figure 1). The curve shift is based on changes in groundwater levels in observation boreholes, which can in turn be derived from simple lumped parameter models. Both curve shifting and lumped parameter models used assume no reduction in permeability with depth beyond the lowest observed groundwater level. As a result, these methods are likely to significantly underestimate the reduction in yield due to climate change in areas with significant vertical heterogeneity.

Whilst the research reported here builds on methodologies published in the UK, there are broader implications for yield assessments worldwide. Future borehole yield assessments should attempt to take into account vertical heterogeneity below the lowest observed groundwater level. This is likely to pose a significant challenge, particularly in countries where reported methodologies for borehole yield assessment are limited. An essential requirement for such improved assessments is accurate pumping water level and pumping rate data during drought periods to add further operational data to borehole yield diagrams such as Figure 1. These data are also required for calibration of numerical models of groundwater flows to pumping boreholes and real-world applications of the idealised example developed in this study. However, obtaining such data can be difficult as water companies prefer to reduce pumping from boreholes when groundwater levels approach DAPWLs to avoid operational issues (pump cut outs, inflow horizon dewatering, turbidity etc). Where there is a tension between the operational needs of water companies and the strategic benefit of an improved understanding of borehole yields and drought resilience, a pragmatic approach building on the curve shifting methodology may be the best approach to refine estimates of borehole yield under climate change. In addition to vertical shifting of the drought curve, the slope of the curve could be steepened to reflect reductions in permeability with depth beyond the lowest observed groundwater level. Given the uncertainty in both shifting and steepening the drought bounding curve, it would be most appropriate for a range of curves and corresponding yield estimates to be reported. Such estimates can then be refined when additional pumping water level data become available.

The approach developed in this study also has broader implications for groundwater modelling in general. Whilst numerical groundwater flow models with multiple layers or VKD implementation explicitly include variations in permeability with depth, a number of lumped parameter models do not consider this (e.g. GARDENIA (Thiery, 1988); CATCHMOD (Wilby et al., 1994)). This is also the case for semidistributed hydrological models which use a simple conceptual representation of groundwater (e.g. SPHY (Terink et al., 2015), SWAT (Arnold et al., 2012)). In areas where permeability is known to decrease with depth, the outputs of these models should be used with caution. When beyond the range of historic observations of groundwater levels during drought periods, model outputs are likely to be “best-case” results and underestimates of actual drought impacts.

4.2 Limitations and outlook for further work

By using an appropriate range of generic VKD profiles associated with the Chalk and the most recent published set of representative multidimensional samples of climate change, this research has shown that VKD is at least as significant as climate change in estimating borehole yields. However, there are a number of limitations of this research that should be addressed by further work before the methodology presented here can be adopted operationally by water companies. The methodology developed in this study has been applied to an idealised borehole and the vertical changes in hydraulic conductivity are implicitly considered through an averaged / integrated term. No pumping water level or pumping data are available to calibrate the model, which limits the direct application of the model results. The generic, idealised methodology developed in this research should be further developed into a real-world case study for a pumping borehole with pumping groundwater level and pumping rate data. As previously discussed in section 2.3, the "cocktail glass" model of VKD is a widely applied simplified interpretation of the distribution of permeability with depth in the Chalk. Previous studies have shown rapid increases in drawdown associated with individual fracture dewatering (Allen et al., 1997), and conversely others have shown that some boreholes have significant fracture flow at depth (Parker et al., 2019). Consequently, direct application of the generic cocktail glass VKD model to such boreholes may result in unrealistic yield estimates. Application of the groundwater model developed in this study to a real-world example would require detailed local information in changes in hydraulic conductivity with depth, obtainable from a range of sources (pumping test and operational data, borehole geophysical, flow and video logs, core data).

In the Chalk, in addition to hydraulic conductivity, the specific yield has been reported to vary with depth (Allen et al., 1997). Whilst variation in the storage coefficient with depth has been shown to be relatively small in comparison to transmissivity variations (Allen et al., 1997; Owen and Robinson, 1978), further model runs should explore the sensitivity of pumping groundwater levels to reduction in storage coefficient with depth. Whilst beyond the scope of this research, borehole depth is also likely to affect yield estimates. Future modelling should investigate the relative influence of borehole depth, VKD and climate change on yield estimates. In this research VKD profiles that represent the full interquartile range of transmissivity values at saturation for the Kennet catchment have been used. Whilst in unconfined aquifers transmissivity changes at every time step due to changing saturated thickness, further work could explore the impact of different VKD profiles which result in the same bulk transmissivity when the model is fully saturated. Simulations should also investigate the impact of aquifer heterogeneity in the radial and circumferential directions and the choice of model boundary conditions, but importantly must consider improving the flow processes near the pumped borehole through the inclusion of the impact of turbulent flows using the Darcy-Forchheimer equation as proposed by Upton et al. (2013) and Upton et al. (2019). In this research, estimates of yield were calculated by deriving modelled pumping water level-pumping rate curves and the calculating the intersection of these curves with DAPWLs. Further work could estimate yield directly from the groundwater model by running the model iteratively to determine the abstraction rate which results in results $PWL_{MIN} = DAPWL$ during a specified drought period.

This research has explored the relative influence of VKD and climate change on the lowest groundwater levels during historic drought periods using a delta change approach, in order to quantify the maximum possible impact of borehole yields. To do this we used the only publically available representative sample of climate change factors, which is between the 2020s and a historical baseline period of 1961 – 1990 (Christierson et al., 2012; UK Water Industry Research Ltd, 2009). Further research should consider a range of different time horizons (e.g. 2050s, in comparison to a baseline period up to 2018), emissions scenarios and new climate model outputs (e.g. the recently published UKCP18 (Met Office, 2018)), where the impacts of climate change on groundwater recharge may be greater. This approach does not consider changes in the temporal variability in drought periods associated with climate change. Application of transient climate change data such as outputs from weather generators may give important further insights into the temporal impacts of climate change on borehole yields.

In this research, we used changes in mean annual recharge for the whole of the model run as a metric for climate change impacts on recharge. This is advantageous as it is simple to calculate and is solely associated with the climate change factors and is not affected by historic climate variability between different drought years. For each combination of abstraction rate, VKD profile and drought year, differences in mean annual recharge (R) correlate well with minimum groundwater levels

(PWL_{MIN}) (mean R^2 = 0.80, standard deviation = 0.13). In practice, however, groundwater levels during droughts are likely to be more strongly correlated with cumulative recharge over a period of time in the build up to a drought. Whilst out of scope of this research, application of standardised indices and/or thresholds (see Van Loon (2015) for a review of approaches) of cumulative recharge to MLR models could be beneficial. This would require derivation of both recharge indices and thresholds, as well as relevant accumulation periods and metrics for groundwater drought severity. Where both VKD and climate change are significant explanatory variables in MLR models, partial correlation analysis may reveal further insights into the relative influence of these two factors. The approach also does not consider increases in demand for water, which are predicted in large areas of the world (Wada and Bierkens, 2014). Further work exploring the relative significance of VKD and climate change on pumping water levels at higher pumping rates associated with increased demand may be useful. Linking the groundwater modelling framework developed in this research to economic models of groundwater yield reductions may also be beneficial (Foster et al., 2017).

Whilst applied to the Chalk of south-east England, the approach developed in this study is generic and can be applied beyond the UK to other aquifers where vertical heterogeneity is present. Globally generic permeability-depth relationships are often modelled using power law or log decay models (Kuang and Jiao, 2014). Exploring the relative significance of climate and VKD associated with these models is likely to be beneficial, although detailed permeability-depth data for a specific borehole should be used when applied to local case studies. Other carbonate aquifers are known to exhibit reductions in permeability with depth (e.g. Jurassic Limestones (Allen et al., 1997)) and comparison with the Chalk would be beneficial to understand the relative sensitivity of different aquifers to climate change impacts. Some aquifers exhibit complex variations in permeability with depth. For example, in weathered crystalline basement aquifers present across much of Africa and the Indian subcontinent (Boisson et al., 2015; Chilton and Foster, 1995), permeability initially increases with depth associated with the weathering profile. As depth increases further, fracture aperture and frequency then decreases, resulting in a decrease in permeability. In comparison to models just considering the low permeability upper layer, incorporation of variations in permeability with depth and the permeable lower layer may potentially buffer, rather than exacerbate, climate change impacts. Whilst this research has focussed on fractured aquifers, the same modelling approach could also be adopted for aquifers which have an intergranular flow mechanism and permeability changes with depth associated with multiple aquifer horizons (e.g. Permo-Triassic sandstones (Allen et al., 1997)). Application of different vertical profiles of hydraulic conductivity (including a homogeneous profile) which have the same transmissivity when the model is fully saturated may also yield important insights into the impact of vertical heterogeneity on borehole yields. Whilst the range of VKD profiles and climate scenarios used in this research are appropriate for the Chalk and UK water resources planning, research exploring different aquifers and different climateologies should consider a broad range of climate futures and VKD uncertainties.

It should be noted that the uncertainty in both VKD and climate change in the assessment of borehole yields considered in this study is just a small component of the total uncertainty in yield estimates. In climate change impact studies, consideration of all the uncertainties in the impact modelling chain from climate models to hydrological models would be beneficial (Clark et al., 2016). In the context of this research, this would mean considering different driving datasets (climate models, emissions scenarios), different recharge calculation schemes, different VKD profiles and subsurface conceptualisations. Such an approach is likely to be challenging and only feasible for research projects. However, such work should support practitioners to identify which parts of the impact modelling chain are (1) subject to the most uncertainty, (2) have greatest impacts on model results, and consequently (3) should be prioritised for further work by both researchers and practitioners. In the context of estimation of borehole yields, this research has made a critical first step towards this by identifying the relative significance of VKD and climate change.

5 Conclusions

This study has quantified the relative influence of climate change and variations in hydraulic conductivity with depth (VKD) on borehole yields for the first time. Applied to an idealised borehole in the Chalk of south-east England, we have shown that VKD (applied in the model using a simplified vertically integrated approach) is more significant than climate change in controlling pumping water levels during drought periods when abstraction rates are < 9000 m^3/day. When abstraction rates are ≥ 9000 m^3/day, both VKD and climate are significant controlling factors. Vertical variations in hydraulic conductivity are at least as significant as climate change in affecting estimates of borehole yields, although yield responses are non-linear and controlled primarily by the vertical position of groundwater level constraints (e.g. pump cut out levels, major inflow horizons etc). It is suggested that variations in permeability with depth beyond the lowest observed groundwater level be taken into account in future assessments of the impacts of climate change on borehole yields. Ideally this should be informed by additional groundwater level monitoring data during drought periods and considering a range of plausible groundwater level-pumping rate drought curves. The approach developed in this research is generic and should be applied to real world examples in the Chalk and other aquifers where variations in permeability with depth are significant.

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8 Supplementary Information

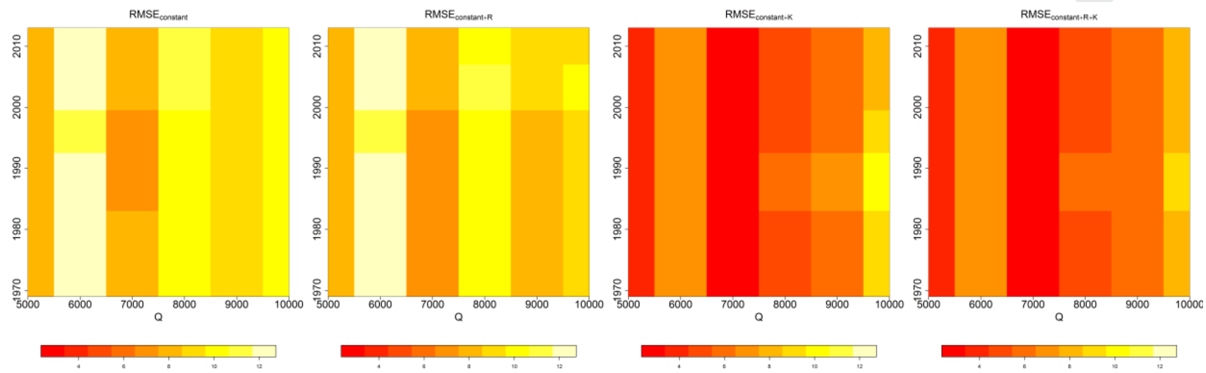

Figure S 1 Root mean squared error values (m, colour flood) as a function of abstraction rate and drought year for MLR models for minimum pumping water levels as a function of (1) a constant term only, (2) constant + R, (3) constant + K, (4) constant + R + K.

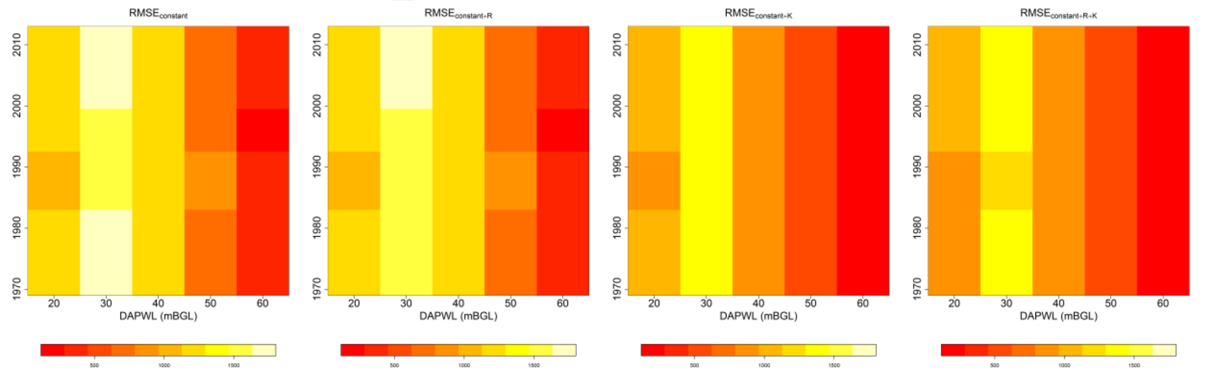

Figure S 2 Root mean squared error values (m, colour flood) as a function of deepest advisable pumping water level and drought year for MLR models for borehole yield reduction as a function of (1) a constant term only, (2) constant + R, (3) constant + K, (4) constant + R + K.

Highlights for Ascott et al. 2019 - Analysis of the impact of hydraulic properties and climate change on estimations of borehole yields

- First study of influence of hydraulic properties and climate on borehole yields
- Variation in hydraulic properties with depth is a significant control on yields
- Future yield assessments should consider variation in hydraulic properties with depth