



Research papers

The impact of climate change on groundwater recharge: National-scale assessment for the British mainland

A. Hughes^{a,*}, M. Mansour^a, R. Ward^a, N Kieboom^b, S. Allen^b, D Seccombe^b, M. Charlton^b, C Prudhomme^c

^a British Geological Survey, Keyworth, Nottinghamshire, NG12 5GG, UK

^b Environment Agency, Bristol, BS1 5AH, UK

^c European Centre for Medium-range Weather Forecasting (ECWMF), Reading, RG2 9AX, UK



ARTICLE INFO

This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Zhang Wen, Associate Editor

Keywords:

Recharge
Model
Climate Change
British mainland

ABSTRACT

Groundwater systems provide an important source of water supply as well as contributing baseflow to rivers, lakes and dependent ecosystems and so the impact of climate change on these systems needs to be understood. Calculating recharge to groundwater systems is, therefore, necessary to quantify what is typically one of the largest components of the groundwater balance. This study uses the national-scale recharge model developed for the British mainland and the 11 ensemble members from the Hadley Centre for rainfall and potential evaporation created by the Future Flows and Groundwater Levels (FFGWL) project to investigate the impact of future climate on groundwater resources. Changes to seasonal and monthly recharge for the 2050s and 2080s time slices have been produced for the whole modelled area and for river basin districts for England and Wales. Areal summaries and monthly time series of recharge values show a generally consistent trend of increased recharge in winter, decreased recharge in summer, and mixed pattern in autumn and spring. The work shows that increased winter rainfall is the main factor in increasing recharge. Water balance calculations reveal that over the 2050s and 2080s, the climate change “signal” predominates over the annual variability, which results in a clearer pattern of more recharge being concentrated in fewer months. This finding should prove useful for water resources planners to assess the resilience of groundwater resources to climate change. Further work is recommended to understand the sequencing of flooding and drought events and to the effects of soil health and land cover changes in the future analysis.

1. Introduction

Groundwater is a hidden asset that contributes significantly to maintaining the overall quality of our environment and is a globally important source of water (Taylor et al., 2012). In the UK, groundwater provides over 75 percent of water for drinking and industrial use, particularly in southern England (Lerner and Harris, 2009). The main issues for groundwater in Britain include the ability to provide groundwater supplies under drought conditions (e.g. Foster and Sage (2017)), ensuring groundwater-fed rivers and streams are kept flowing during periods of low rainfall (e.g. Marsh (2006)). In addition, there is a need to understand the occurrence, extent and frequency of groundwater (Clearwater) flooding (Hughes et al., 2011). All these processes occur in groundwater systems that are largely driven by rainfall recharge as their main input. Rainfall recharge (Lerner et al., 1990) is

defined here as recharge occurring from rainfall directly from where it lands on the ground surface. In the UK, rainfall recharge occurs typically between October and March when actual evaporation is lower than rainfall (and the soil moisture deficit is zero). Further, recharge is defined either as potential recharge (the amount of water leaving the soil zone) or as actual recharge (reaching the water table). Typically, recharge replenishes aquifers during the autumn, winter and early spring and storage allows groundwater abstraction to be undertaken all year round.

Rainfall recharge, is a function of rainfall and evaporation, itself dependant on temperature. In the UK, under conditions of climate change, by 2050 summer and winter temperatures are forecast to increase by 2.5 °C and 2.1 °C on average respectively, while rainfall totals are forecast to increase by an average of 13% in winter whereas summer totals are set to decrease by 16% on average (UKCP09; Special Report on

* Corresponding author.

E-mail address: aghug@bgs.ac.uk (A. Hughes).

<https://doi.org/10.1016/j.jhydrol.2021.126336>

Received 27 November 2020; Received in revised form 12 March 2021; Accepted 12 April 2021

Available online 19 April 2021

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Table 1
Models and data used to assess the impact of climate change on recharge values internationally.

Reference	Model code used	Emission scenarios	Location
Brouyere et al. (2003); Goderniaux et al. (2011)	ANSWERS	SRES A2, PRUDENCE	the Geer basin Belgium
Beigi and Tsai (2015)	HELP3	B1, A2 and A1F1 and two GCMs (PCM and GFDL)	the Southern Hills, Mississippi,
Jyrkama and Sykes (2007)	HELP3	100 year IPCC	Grand River watershed
Kurylyk and MacQuarrie (2013)	HELP3	multiple emission scenarios in conjunction with five GCMs	Otter Brook, New Brunswick
Scibek and Allen (2006)	HELP3	A1 emission scenario with the CGCM1 GCM with SDSM downscaling and linked to a stochastic weather generator (LARS-WG)	Grand Forks, British Columbia,
Pholkern et al. (2018)	HELP3	RCP 4.5 & 8.5 for CanESM2 in conjunction with the SEACAM (HadCM3Q3, HadCM3Q10, HadCM3Q11, and HadCM3Q13) / CanESM2 GCMs	Central Huai Luang Basin, Thailand
Touhami et al. (2015)	HYDROBAL	SRES A2/B2, PRUDENCE ensembles	Alicante, south-eastern Spain
Newcomer et al. (2014)	HYDRUS1D	A1F1 emission scenario with the NOAA GFDL combined with delta change downscaling	San Francisco, US
Farjad et al. (2017)	MIKE SHE/ MIKE 11	B2 and A1B emission scenarios with the CGCM2 and NACARPCM GCMs	Elbow river, Alberta
Luoma and Okkonen (2014)	MODFLOW	SRES A1B/B1, CLN World Data Centre for Climate	Hanko peninsula in Finland
Mileham et al. (2009)	SMBM	A2 scenario and PRECIS	River Mitano, Uganda
Raposo et al. (2012)	SWAT	SRES A2/B2 of the PRUDENCE GCMs	Galacia-Costa region, Spain
Gemitzi et al. (2017)	SWAT	different GCMs	Vosvozis river catchment in north-eastern Greece
Ng et al. (2010)	SWAT	A1B emission with five GCMs (ECHO-G, BCCR-BCM2.0, CGCM3.1, MIROC3.2 and IPSL-CM4)	Southern High Plains US
Eckhardt and Ulbrich (2003)	SWAT	SRES B1/A2; GCMs derived from ACACIA	Dill catchment in Germany
Tillman et al. (2016)	SWB	4 RCPs: v. high/2 medium, low and 97 GCMs & DCSD downscaling	Upper Colorado River Basin.
Niraula et al. (2017)	VIC	PCP 6.6; 11 GCMs	Western US
Crosbie et al. (2013)	WAVES	use three warming scenarios with 16 GCMs	High plains aquifer US
Crosbie et al. (2012)	WAVES	16 GCMs for a range of SRES temperatures	continental Australia
Nyenje and Batelaan (2009)	WetSpa	B2 and A2 emission scenarios of HadCM3 downscaled in SDSM	Upper Ssezibwa basin in Uganda

Emissions Scenarios (SRES) medium emission (A1B) see Table 3 in Arnell et al. (2015)). The A1B is a medium emission projection which has now been superseded by Representative Concentration Pathways (RCP), with RCP8.5 seen as the most likely future outcome. Further, the latest (UKCP18) projections from the UK Met Office bear these figures out, showing increases of winter rainfall of 4% and decreases of summer rainfall of 12% (both median values) for SRES A1B which is comparable with the results for RCP8.5 (7% increase in winter and 15% decrease in summer, both median values) (Lowe et al., 2018). These changes in climatic conditions (wetter winters, drier summers, increase in temperature all year round) are likely to lead to greater soil moisture deficits during summer, which will recover at a later stage in the year, i.e. progressing through the autumn months. All of these predictions are associated with uncertainty and are regionally variable over the British Isles.

Climate change can alter the timing and magnitude of potential recharge resulting in modification of risks to water availability, droughts and flooding. This is clearly demonstrated by the various studies, summarised in Table 1, that have been undertaken to assess the likely future change in recharge at the basin and national scale¹. For example, Luoma and Okkonen (2014) present work in the Hanko peninsula in Finland for different emissions scenarios (SRES; medium emissions: B1 & A1B) which showed that temperature is predicted to rise over most months of the year, but rainfall shows greater rises in autumn and winter. This combined effect leads to future recharge seasons starting earlier by one month. In the Dill catchment, Germany, Eckhardt and Ulbrich (2003) show that whilst changes to rainfall and evaporation are not presented mean annual recharge had been forecast to be unchanged in 2050s, but reduced monthly totals overall and increases are likely for January and February. Raposo et al. (2012) calculated that river flows in Galacia-Costa region, Spain, decrease all year round with greatest decreases in autumn and winter. This change is reflected in significant percentage decrease in summer recharge but absolute differences in May and November are countered by increases of recharge in November. Farjad

et al. (2017) present work in the Elbow river catchment, Alberta, showing that for emission scenarios A1B rainfall increases and B2 (medium emissions) showing modest increases apart from decreases in summer, with Potential Evaporation (PE) increases in winter and mixed signals for the rest of year. This leads to increases in recharge for winter and spring and reductions in summer but the results for autumn are more mixed. Mileham et al. (2009) studied the River Mitano catchment in Uganda and showed that runoff increased markedly from observed but that reduced recharge values were predicted to occur from January to June but are counterbalanced with increased recharge values over August to December.

However, climate change studies show conflicting conclusions regarding changes in projected recharge values over time. For example, Touhami et al. (2015) showed decreasing recharge from the 2050s in Alicante, south-eastern Spain, resulting from rainfall total reducing whilst actual evaporation reduces but to a lesser extent. Gemitzi et al. (2017) showed increasing recharge by 2035–2045 in the Vosvozis river catchment in north-eastern Greece due to rainfall remaining similar or slightly decreasing despite temperature and therefore PE increasing. In the High plains aquifer of the Central United States (US), Crosbie et al. (2013) showed that in the 2050 s there is a north–south gradient in recharge change driven by variability in future rainfall and differences in the gradient of temperature increases. For the Western US as whole, Niraula et al. (2017) examined the impact of different Global Climate Models (GCMs) and their spatial variability of predicted changes in rainfall and temperature. Whilst temperature is consistently forecast to be higher, with a greater temperature increase in the far future, the change in rainfall signal is more mixed with equal decreases observed in the west and increases in the Northern Rockies and Plains. This spatial and temporal variability feeds through to a variability in recharge signal with a reduction in the western and south-western region in the near future (2021–2050) and south in the far future (2071–2100); whereas there is likely to be an increase in the Northern part of the Rocky Mountains for both near and far future.

Different climate models also produced different pictures of recharge estimates. The use of the National Center for Atmospheric Research's Parallel Climate Model 1 (PCM) Global Climate Model (GCM) by Beigi and Tsai (2015) in the Southern Hills, Mississippi resulted in

¹ The model codes used in the referenced research together with the data used to drive these models are presented in Table 1.

precipitation generally increasing until “tipping point” is reached in the 2050 s when first two and then a third GCMs show a decrease in rainfall. Temperature is always rising to a greater or lesser extent for all the GCMs, however, solar radiation is bimodal with half increasing and the other half decreasing. This change in solar radiation is reflected in the PE, which is bimodal. The factors combined then produced an increase of recharge for the 2020 s and 2050 s and a decrease in the 2080 s, whereas National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Lab’s (GFDL) showed increase of recharge in the 2020 s and decrease in the 2050 s and 2080 s. [Jyrkama and Sykes \(2007\)](#) in the Grand River watershed, Canada used the 100 year International Panel on Climate Change (IPCC) assessment and drove their models by a combination of runoff and PE scenarios: the runoff changed both positively and negatively over time whilst PE scenarios increased over time, leading to increasing recharge into the future. It was found that whilst all scenarios showed increasing recharge over the next 40 years with the main increases occurring in October to December and January to April. In the Otter Brook, New Brunswick, [Kurylyk and MacQuarrie \(2013\)](#) used multiple emission scenarios in conjunction with five GCMs, which all had increasing temperature, but the majority of the scenarios showed a decrease in rainfall, apart from two showing an increase. This work showed that recharge changes between 2046 and 2065 were mixed with three GCMs giving lower future recharge values and two giving higher recharge values but in terms of the monthly distribution this is largely unchanged apart from increases in December and March. [Nyenje and Batelaan \(2009\)](#) present work in the Upper Ssezibwa basin, Uganda using the B2 (low) and A2 (high) emission scenarios of Hadley Centre Climate Model3 (HadCM3; [Gordon et al. \(2000\)](#)) downscaled in the Statistical Downscaling Model (SDSM). Climate data were used to drive the WetSpa Geographical Information System (GIS)-based distributed catchment model, with monthly temperature always increasing for the 2050 s and 2080 s and rainfall increasing for all months, apart from September. They showed increasing recharge from the 2020 s to 2080 s through the 2050 s.

In some studies, consistent conclusions can be drawn from the use of multiple climate models. In a study to calculate recharge for continental Australia by [Crosbie et al. \(2012\)](#), the WAVES code ([Zhang and Daws, 1998](#)) was used with 16 GCMs for a range of SRES temperature increases: Low (+1°C), medium (+1.7 °C) and high (+2.4 °C). They applied recharge scaling factors (RSF) in conjunction with probability of exceedance for the three warming scenarios and found that the likelihood of increased recharge is higher for north and eastern Australia whereas recharge in the central and west of Australia is likely to decrease. [Pholkern et al. \(2018\)](#) report a study in the Central Huai Luang Basin, Thailand. They showed that most of the GCMs produced increase in infiltration, but HadCM3Q10 (dry) somewhat unsurprisingly demonstrated a decrease.

In Britain, [Herrera-Pantoja and Hiscock \(2008\)](#) drove point recharge models at Coltishall, East Anglia, Gatwick, southern England, and Paisley, Glasgow, with outputs from UKCIP02 ([Hulme et al., 2002](#)). There are relatively small positive or negative percentage changes for rainfall for the 20 s, 50 s and 80 s. These are counter balanced by significant increases in PE and subsequently Actual Evaporation (AE). The combination of stable rainfall with significant increase of AE leads to decrease of the Hydrological Effective Rainfall (HER) which has a greater magnitude further into the future, although Paisley in Scotland is temporally stable, and also greater increases occur in the south of the country, i.e. Gatwick compared to Paisley.

[Holman et al. \(2009\)](#) extended the studies in East Anglia to examine the uncertainty associated with the choice of emission scenarios, GCMs and downscaling methods. They used the UKCIP02 results from the HadRM3 RCM to investigate the effect of the SRES medium emission (A1F1 and B1) scenarios and combine this with both change factor approach and using outputs from the Climate Research Unit (CRU) weather generator. The median value of annual rainfall is forecast to decrease by a relatively small amount (10 s mm), whilst PE is predicted

to increase markedly (100 s mm). These results are used to drive the WaSim soil–water balance model, see [Holman et al. \(2011\)](#), for loamy and sandy soils. Potential recharge is predicted to decrease for both these soils for all scenarios for the 2020 s as well as the 2050 s.

At a larger scale, [Yusoff et al. \(2002\)](#) applied two Hadley Centre GCMs to a groundwater model in west Norfolk (eastern England). They find a strong monthly signal with reduction of precipitation in July, August and September offset by increases in October to March; PE increases all year round, with the greatest increases in August / September and December / January. All these changes lead to decreased recharge in October, November and December, modest increases in January and February followed by decreases in April and May. For the periods 2020–2035 and 2050–2065 the changes in precipitation produced longer summer and drier autumns resulted in a decrease in groundwater heads in summer and reduced baseflow in autumn in the modelled rivers. Extending this approach to the whole of the east Anglian peninsula, [Holman \(2005\)](#) determined Hydrologically Effective Rainfall (HER) for 5 km grid squares in this area for the high emission scenario for the 2050 s. The potential recharge season was found to increase by up to 10 weeks, although the most likely change is 5 weeks’ reduction. Further, when plotting the ranked changes of HER, winter shows the most number of positive changes with the changes for the summer months all negative.

To date, no studies have used the probabilistic projections or related UKCP09 products to assess recharge for the whole of the UK. UKCP09, a climate product that has been developed based on the Hadley Centre GCM climate models ([Murphy et al., 2009](#)). [Pritchard et al. \(2015\)](#) used the probabilistic output from UKCP09 to simulate how climate change may affect soil moisture and in turn modify the swell-shrink characteristics of clay. This approach is suitable for determining the impact of climate change on building foundations, but falls short of quantifying recharge. In the Marlborough and Berkshire Downs, southern England, [Jackson et al. \(2011\)](#) applied multiple GCMs for the 2080 s under the medium (A2) scenario to a recharge and groundwater flow model of the chalk aquifer. The results from these various GCMs, 13 in total, show that there isn’t much consistency between the different outputs. For example, the greatest variation in recharge occurred over the catchments to the west of the area (Pang, Lambourn and Kennet catchments). Modelled recharge generally increased between November and February and to the east of the area for December to February. This is in contrast for recharge calculated for the whole model and for all the other months, where recharge was demonstrated to decrease particularly for September and October.

Given that no national assessment for the UK has been undertaken for the impact of climate change on recharge for the UK, then this work seeks to fill the gap. Further the causes of any changes to recharge from forecast rainfall and Actual Evaporation needs to be examined. This paper details the assessment of potential recharge under future climate scenarios at the UK scale with reference to groundwater resources, focussed on an understanding of the impact at the national scale and River Basin Management District scale. To provide for a range of climate conditions, the Future Flow and Groundwater Levels (FFGWL) based on UKCP09, SRES A1B with 11 ensemble members (described more fully below) have been applied to a national recharge model of Britain to produce potential recharge ([Mansour et al., 2018](#)). The output from this model has been analysed for the 2050 s and 2080 s to understand how potential recharge may be affected by climate change.

1.1. Study area

The British mainland (BM) is defined by the coastlines of England, Wales and Scotland including the major islands that are close to the coastline (e.g. Isle of Wight, Anglesey and the Inner Hebrides) ([Fig. 1a](#)). Over the area of interest the landscape is varied, with higher ground in Wales (1000 m in Snowdonia) and the north of England (900 m). Most of the rest of England consists of gently rolling hills with isolated areas of

high ground and low-lying coastal areas, especially in the east and south of England. The climate also varies spatially with England having slightly higher maximum temperatures than Wales with average maximum temperature of 20.6 °C and 19.1 °C in England and Wales respectively. Given the predominant west-east rainfall gradient, then rainfall is lower in England (840 mm year⁻¹) compared to 1435 mm year⁻¹ in Wales (UK Met Office, www.metoffice.gov.uk). Land use is predominantly agricultural, occupying about 70% (16,025,000 ha) of the British landmass (c. 19% crops and bare fallow, 52% grasses and rough grazing). Forest and woodland covers c. 12% of the land area (2,750,000 ha), and the remaining 18% of the land (4,120,000 ha) is urbanised or parkland (Bibby, 2009).

There are four primary aquifers identified in Britain: Cretaceous Chalk (Fig. 1), Permo-Triassic Sandstone, Jurassic Limestone and Devonian/Carboniferous older cover. Cretaceous chalk is a white microporous limestone with fracture development, which enhances flow and can exhibit karst behaviour. It outcrops predominantly in the south and east of England. The Permo-Triassic sandstone is a pinkish-red sandstone of Aeolian, fluvial and marine origin which has a high porosity and moderate transmissivity. Jurassic age limestones, which outcrop from south-west to eastern central England are fractured limestones of marine origin, which are moderately productive. The Devonian/Carboniferous rocks are mainly limestones and sandstones of marine origin, are moderately productive and predominantly support groundwater abstraction in Wales and Scotland. Given the glacial history in Britain, then there are extensive Quaternary deposits, which range from clays to large boulders and can prevent potential recharge (soil drainage) from reaching the aquifers.

In the present-day climate over a typical year, monthly rainfall totals are relatively constant, however potential evaporation (PE) peaks in the meteorological summer (June, July and August) and is lowest in winter (December, January and February). Recharge is the result of the soil moisture deficit being met, which requires rainfall to be greater than PE over a sustained period. This leads to a recharge season, defined as when the majority of recharge occurs, which typically starts in September and goes through to April the following year. Any changes to the distribution of rainfall over the year as well as factors which control PE will affect the magnitude and timing of recharge. This will also be influenced by changes in the land use and subsequent land cover resulting in modification to cropping patterns and runoff characteristics. There is, however, an inherent feedback as changes in temperature and CO₂ levels will affect plant behaviour and therefore have the potential to decrease evaporation.

2. Materials and methods

Potential groundwater recharge calculations have been undertaken using the zooming object oriented distributed recharge model ZOODRM (Mansour and Hughes, 2004), consisting of laterally connected nodes within grids which in turn form a number of layers which are vertically connected. ZOODRM has been developed by the British Geological Survey (BGS) as part of the ZOOM (zooming object oriented model) suite of model code (e.g. Jackson and Spink (2004)) and provides a water balance model platform where different recharge methodologies can be applied and hydrological processes can be investigated. It is a distributed recharge model that simulates runoff and recharge processes and provides the output in a gridded form for use with groundwater flow models or on a catchment basis for water balance purposes. It has been applied in both the UK (Mansour et al., 2011; Mansour et al., 2018) and overseas (e.g. West Bank: Hughes et al. (2008), Mansour et al. (2019) and China: Ó Dochartaigh et al. (2010)).

Based on the FAO Drainage and Irrigation Paper 56 (FAO, 1998) the recharge approach used here calculates the capacity of the soil zone, from which plants draw water to evaporate. This approach uses the plants characteristics including the root depth (Z_r [L]) and the depletion factor (p [-]), in addition to the soil characteristics including the

moisture content at field capacity (θ_{fc} [$L^3 L^{-3}$]) and at wilting point (θ_{wp} [$L^3 L^{-3}$]). Evaporation is then calculated according to the soil moisture deficit level compared to two parameters, called Readily Available Water (k_{RAW}) and Total Available Water (k_{TAW}), calculated from the plants and soil characteristics. Griffiths et al. (2006) developed a modified EA-FAO method where the number of parameters required to apply the method has been reduced, as follows:

$$k_{TAW} = Z_r (\theta_{fc} - \theta_{wp}) \quad (1)$$

$$k_{TAW} = p \cdot k_{TAW} \quad (2)$$

Griffiths et al. (2006) calculates the evaporation rates as a function of the potential evaporation and an intermediate soil moisture deficit:

$$e_s = e_p \left[\frac{s_s^*}{k_{TAW} - k_{TAW}} \right]^{0.2} \quad s_s^* < k_{RAW} \quad (3)$$

$$e_s = e_p \quad s_s^* \geq k_{RAW}$$

$$e_s = 0 \quad s_s^* \leq k_{TAW}$$

Where e_s [L] is the evapotranspiration rate, e_p [L] is the potential evaporation rate and s_s^* [L] is the intermediate soil moisture deficit given by

$$s_s^* = s_s^{t-1} - r + e_p \quad (4)$$

Where r [L] is the rainfall and s_s^{t-1} [L] is the soil moisture deficit calculated at the previous time step.

The new soil moisture deficit is then calculated from:

$$s_s = s_s^{t-1} - r + e_s \quad (5)$$

Griffiths et al. (2006) proposed that the recharge and overland flow is only generated when the calculated soil moisture deficit becomes zero. The remaining volume of water, the excess water, is then split into recharge and overland flow using a runoff coefficient. While this runoff coefficient is set to a constant at a node, the amount of runoff and recharge generated at every time step depends on both the intensity of rainfall and on the soil moisture deficit, which control the amount of excess water.

ZOODRM has been applied to the British Mainland and calculates potential recharge (soil drainage that may not necessarily reach the water table). It uses a grid with 2 × 2 square kilometre cells over the area described by the following National Grid Reference: Bottom Left (40000, -10000) Top right (680000, 1010000). The model uses gridded datasets of distributed land use, soil type, topography (DEM), geology along with a river network to create the model instance (see Figs. 3 and 4 in Mansour et al. (2018)). The model has been run from 1st January 1962 to 30th of June 2014 and calibrated against the runoff component of river gauged flow (Mansour et al., 2018). It calculates recharge on a daily time step and aggregates the recharge to a monthly value. Given that the model produces potential recharge no account, therefore, is taken of any modification of recharge resulting from the unsaturated zone and other minor aquifers, which may lie above the water table.

The workflow used by this study is illustrated in Fig. 2. Further details are provided in Mansour and Hughes (2017) and a qualitative assessment of uncertainty in Hughes and Mansour (2018). The data used to create the model instance for historical simulation is described in Mansour et al. (2018). To extend this model to undertake climate change simulations, 11 ensemble members from the Future Flows Climate data (Prudhomme et al., 2012) are used to drive the model code, consisting of one unperturbed simulation (afgxc) and ten perturbed (afixa to afixq). These data are 1 km gridded climate time variant projections of rainfall and potential evaporation, and they cover the expected climate variability likely to occur in the UK under a medium emissions scenario (SRES A1B), and allow comparison of results across a range of scales and geographical regions. The data were produced as daily grids from 1st

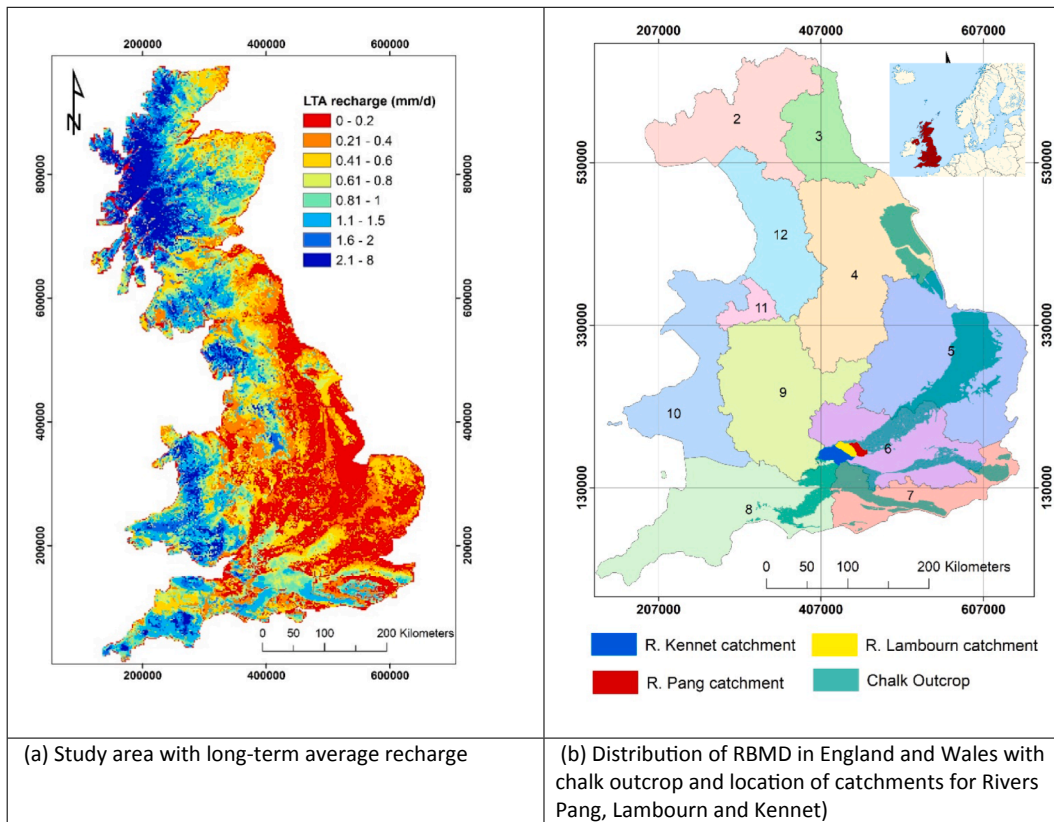


Fig. 1. Geographical extent of recharge model instance (Contains Ordnance Survey data © Crown copyright and database right 2021).

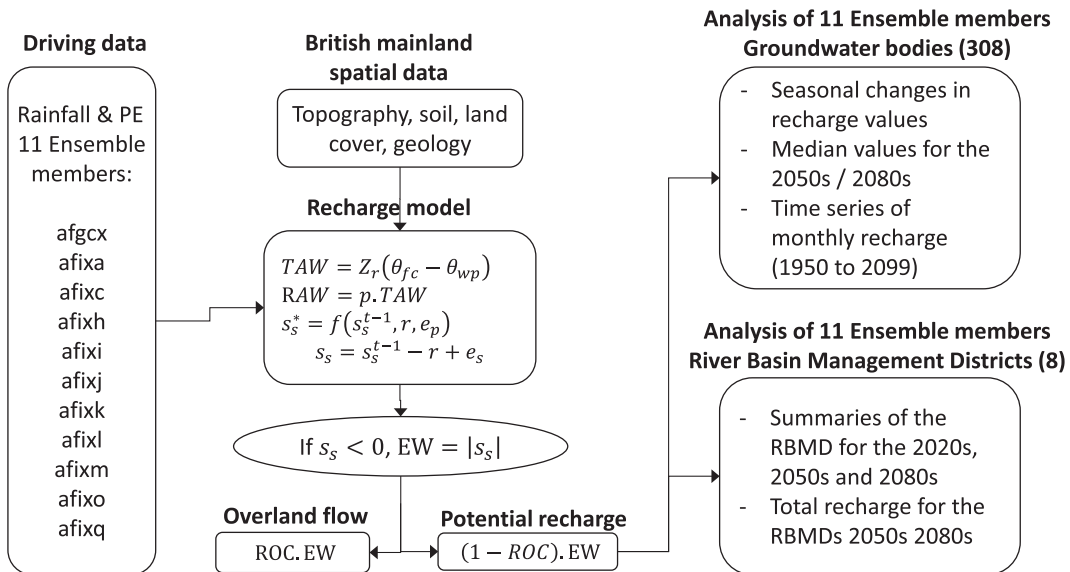


Fig. 2. Flowchart for workflow for recharge model output.

January 1950 to 30th November 2099.

The results from these runs are then separated into two sets: one for England, Wales and Scotland and another for the River Basin Management Districts (RBMDs) (Fig. 1b). Surface water bodies are managed using River Basin Management Districts (RBMDs) which are a requirement of the Water Framework Directive (WFD), e.g. Hering et al. (2010), and are used to report the quantitative status of the basin. A RBMD covers an entire river system, including river, lake, groundwater, estuarine and coastal water bodies. Each RBMD (see Fig. 1b) has a RBMP

(management plan) to protect and improve the quality of the water environment.²

Time series of the mean monthly rainfall, actual evaporation and recharge values are calculated as flows (recharge flux multiplied by model area) from the daily water balance recharge values simulated over the whole area of the model instance (England, Wales and

² www.gov.uk/government/collections/river-basin-management-plans-2015

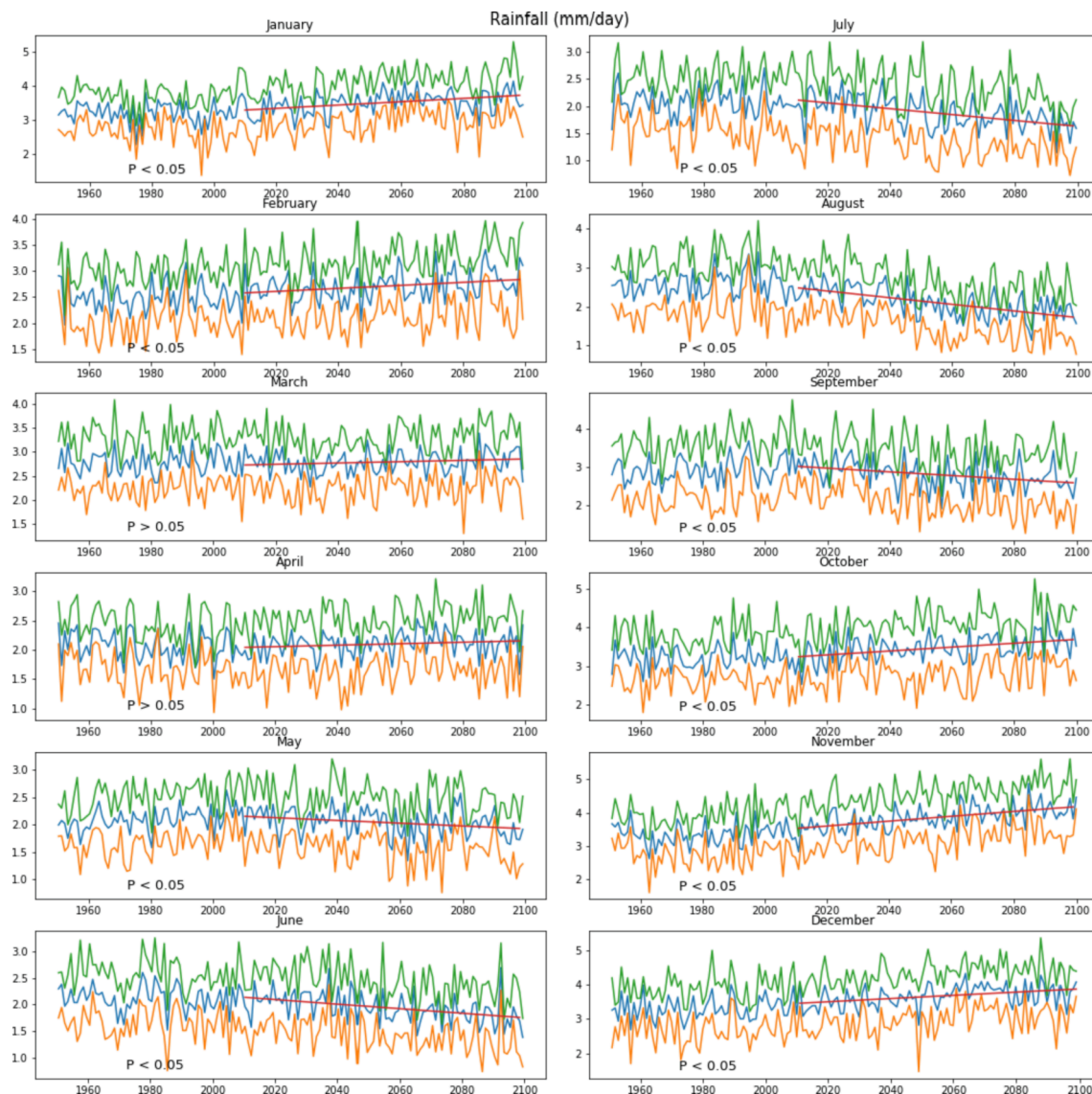


Fig. 3. Monthly time series for rainfall, Actual Evaporation and recharge (75th, mean, and 25th percentile values are presented by the green, blue, and orange lines respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Scotland) for the 11 climate scenarios (Fig. 3). For each month of the year, the mean, the 25th and the 75th percentiles of the recharge values are then calculated using the 11 recharge values produced from each climate scenario. Time series of these three quantities are then produced for each month as shown in Fig. 3 and a linear trend line is fitted for the mean time series over the period starting from 2020 to 2099 for each month. The statistical significance of the linear model fit is tested through the retrieval of the probability p value.

For the River Basin Management Districts two sets of data are produced: Summaries for the RBMD for total volumes of rainfall, actual evaporation, runoff and recharge: historic simulation, 2050 s and 2080 s, and seasonal water balances for autumn, winter, spring and summer. Runoff is not included for the seasonal water balances as it is calculated in the same way as recharge but factored by the runoff coefficient. A daily water balance is also calculated over catchment areas that define the river basin management districts (RBMD) shown in Fig. 1b. Total rainfall, AE and recharge volumes at the 11 RBMD is calculated from the daily water balance values produced by the model over the spatial extents of these basins and for the 11 ensemble members and their percentage differences with respect to the future and historical calculated

(Fig. 4). The selected time horizons for the volumes have been calculated for the periods 1961 to 1990, 1971 to 2000, 2040 to 2069 (the 2050 s), and 2070 to 2099 (the 2080 s). For each climate scenario, the mean seasonal rainfall, AE and recharge values are calculated from the daily recharge values and then the mean of the monthly rainfall, AE and recharge values is produced for each season for the simulated historic, the 2050 s, and 2080 s (Fig. 5). Differences between the projected 2050 s, and 2080 s rainfall, AE and recharge values and the simulated historic values are then calculated for each season.

3. Results

3.1. Time series of monthly totals for rainfall, AE and recharge

Considering the time series of monthly rainfall, AE and recharge (Fig. 3a-c), all the plots for the period from 1950 to 2009 exhibit stationarity and can be used to compare with the future climate 2010–2099. It is necessary to establish whether the future climate have upwards or downwards trends (decreasing or increasing) to enable the changes observed in the spatial distribution of recharge for the time

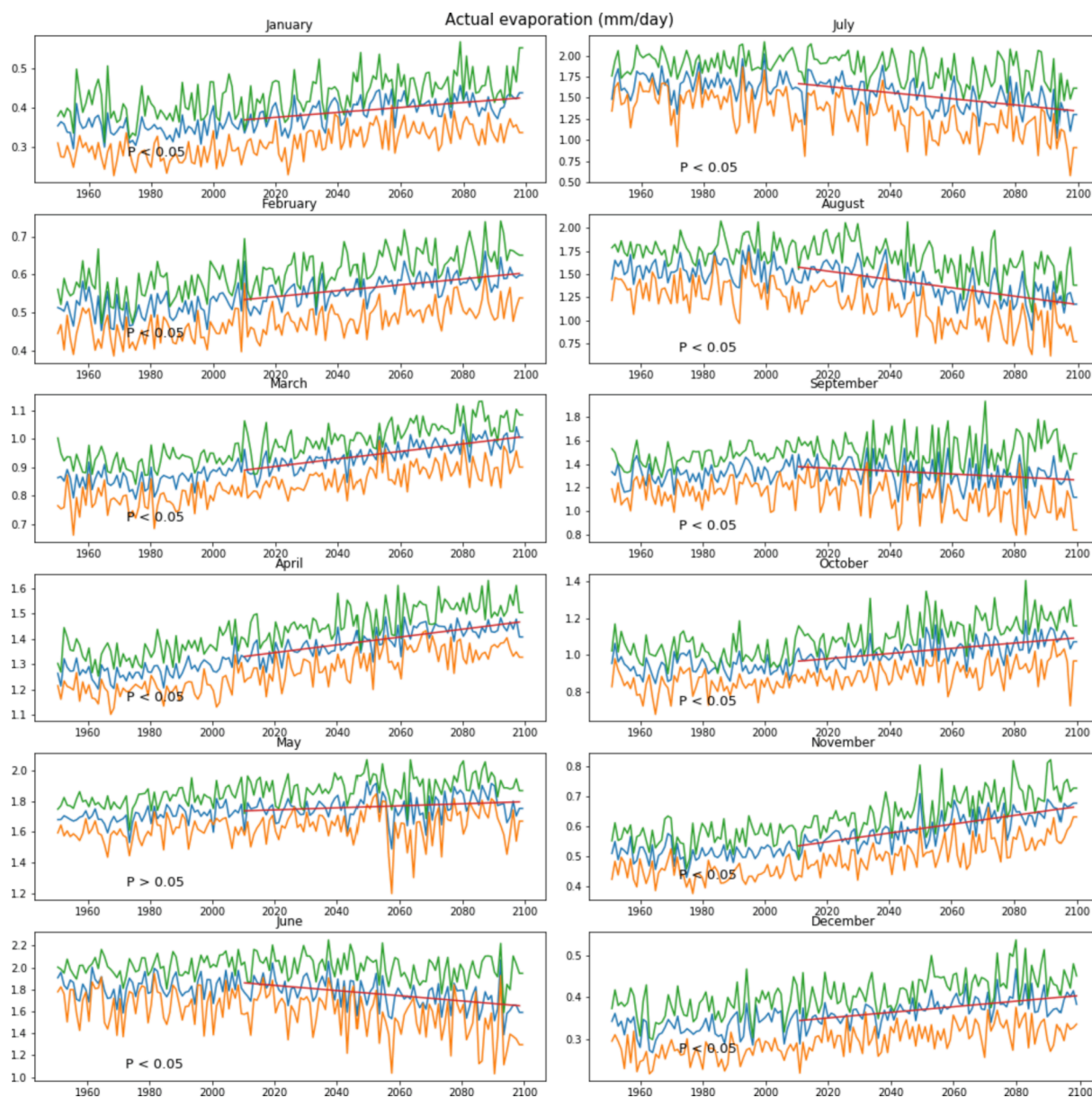


Fig. 3. (continued).

slices (2050 s and 2080 s) to be confirmed.

Rainfall: in keeping with the forecasts of wetter winters and drier summers, in general the summer months (JJA) show decreasing rainfall as opposed to increasing rainfall during winter (DJF). In terms of timing, decreasing trends in average monthly rainfall during the future periods ($p < 0.05$) can be observed for May, June, July, August and September. These months represent both the summer months (JJA) as well as those either side of them. In contrast rainfall in October, November, December, January and February show statistically significant ($p < 0.05$) increases. Again this covers winter (DJF), but importantly for the recharge season (October onwards), rainfall increases in October and November. For the months of March and April, then no significant trend can be detected. The trend for both increases in rainfall for the winter and associated months along with the decreases forecast for summer and associated months continue through-out the future period.

Actual Evaporation: Decreasing trends in average monthly actual evaporation (AE) during the future periods ($p < 0.05$) can be observed for June, July, August and September. Given the projected increases in temperature in the summer months then the decreases in AE during the

summer months are likely to be due to decreases in water availability due to lower rainfall. In contrast AE in October, November, December, January, February, March and April show statistically significant ($p < 0.05$) increases. Again, the increases in rainfall allied with increases in temperature will result in increases in AE. Only for the month of May can no significant trend be detected.

Recharge: The relative amounts of recharge for each month can be seen from the mean values for each month, with the maximum values of recharge occurring in January, February, March, October, November and December. This emphasises the months constituting the recharge season (October through to March).

Decreasing trends in potential recharge during the future periods ($p < 0.05$) can be observed for May, June, July, August and September. In contrast only monthly potential recharge in November, December, January and February show statistically significant ($p < 0.05$) increases. For the months of March, April, October, then no significant trend can be detected. However, more nuanced behaviour occurs during the recharge sequence: March shows a reduction from 2010 to 2070, but an increasing trend thereafter. April shows an increasing trend between

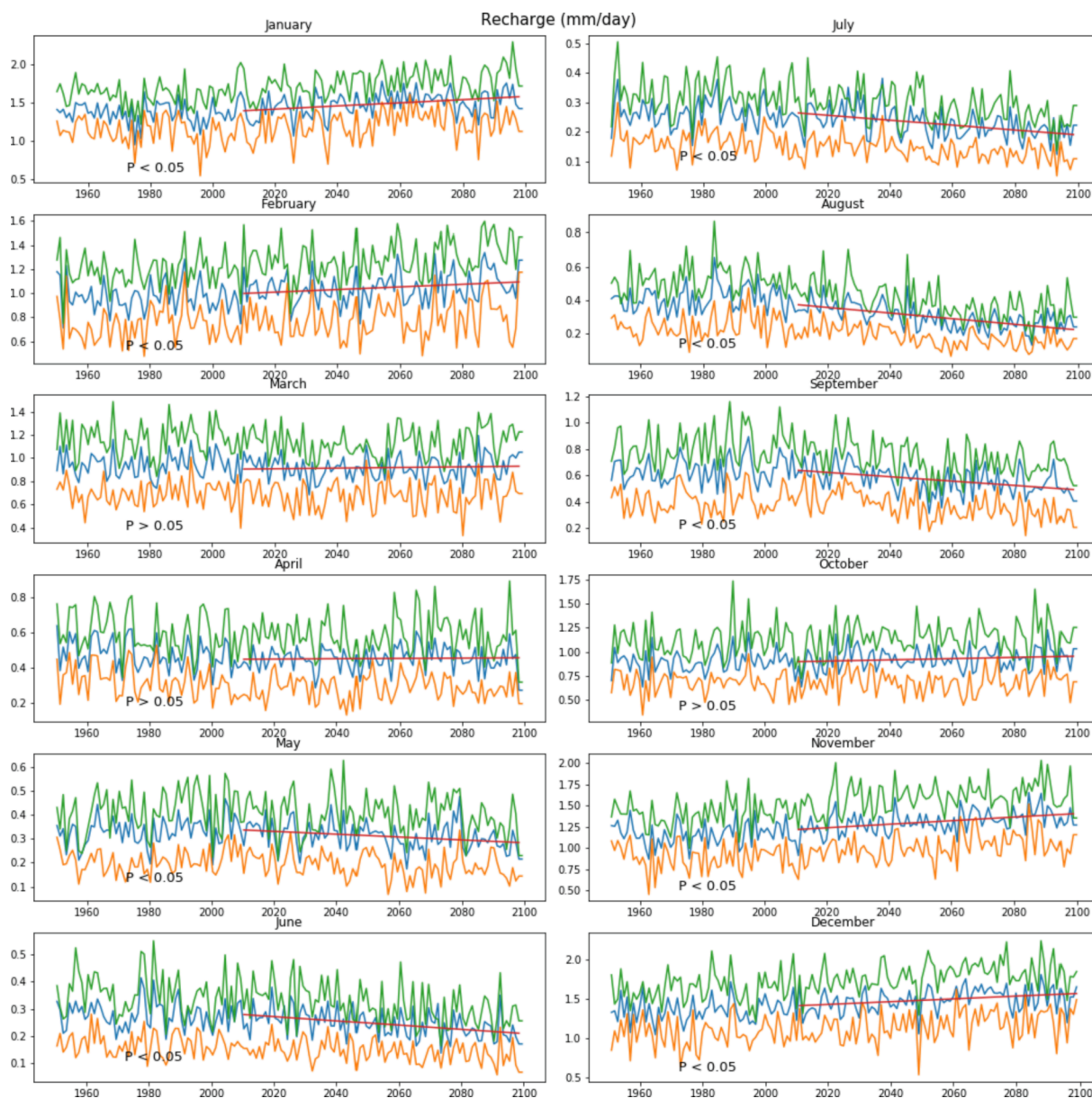


Fig. 3. (continued).

2040 and 2070.

Increases in recharge occur in the months where the increases in rainfall overcome that of actual evaporation. For example, these occur in January and February where increases in rainfall over-rides the increases occurring for AE. Future AE increases in March and April contrast with rainfall showing no predicted change and, therefore, recharge exhibits no change either way. Decreases in rainfall from May through to September occur and despite decreases in AE result in reduced recharge. This changes in October onwards where both rainfall and AE have an increasing trend, and recharge increases from November and December.

Examining the times series indicates wetter winters in combination with drier summers leading to higher recharge in late autumn/winter and will be explored in greater detail for each RBMD.

3.2. Annual averaged water balances for the RBMD

Changes in the water balances for each 30 year period (2050 s and 2080 s) are presented as percentage changes from baseline (1961–90

and 1971–00) in Fig. 4 with each RBMD coloured to reflect the magnitude of the changes.

Based on this presentation of percentage change for each RBMD, a number of patterns emerge. Rainfall tends to increase for each period in the west of the country (RBMDs 2, 10, 12), decrease elsewhere with exception of the South-east (7) and South-west (8) where a small decrease in the 2050 s becomes a modest increase in the 2080 s. The change in Actual Evaporation has a west-east pattern with the greatest decrease occurring in the south and east of England. Further, the reduction in AE is greater in the 2080 s compared to the 2050 s, with the exception of Solway Firth (2) where the increase reduces between the 2050 s and 2080 s. Recharge has a more mixed spatial response, and tends to reduce in the eastern RBMDs for the 2050 s and then increase in the 2080 s. The increase of recharge in the 2080 s is mainly due to the decrease in Actual Evaporation, allied with a modest decrease in rainfall. The most significant increase in recharge (and runoff) occurs in the south and east of England (RBMDs 5, 6, 7 and 8).

These results fit into the trends observed for forecast rainfall, AE and resulting recharge Fig. 3 – monotonic increases and decreases, but

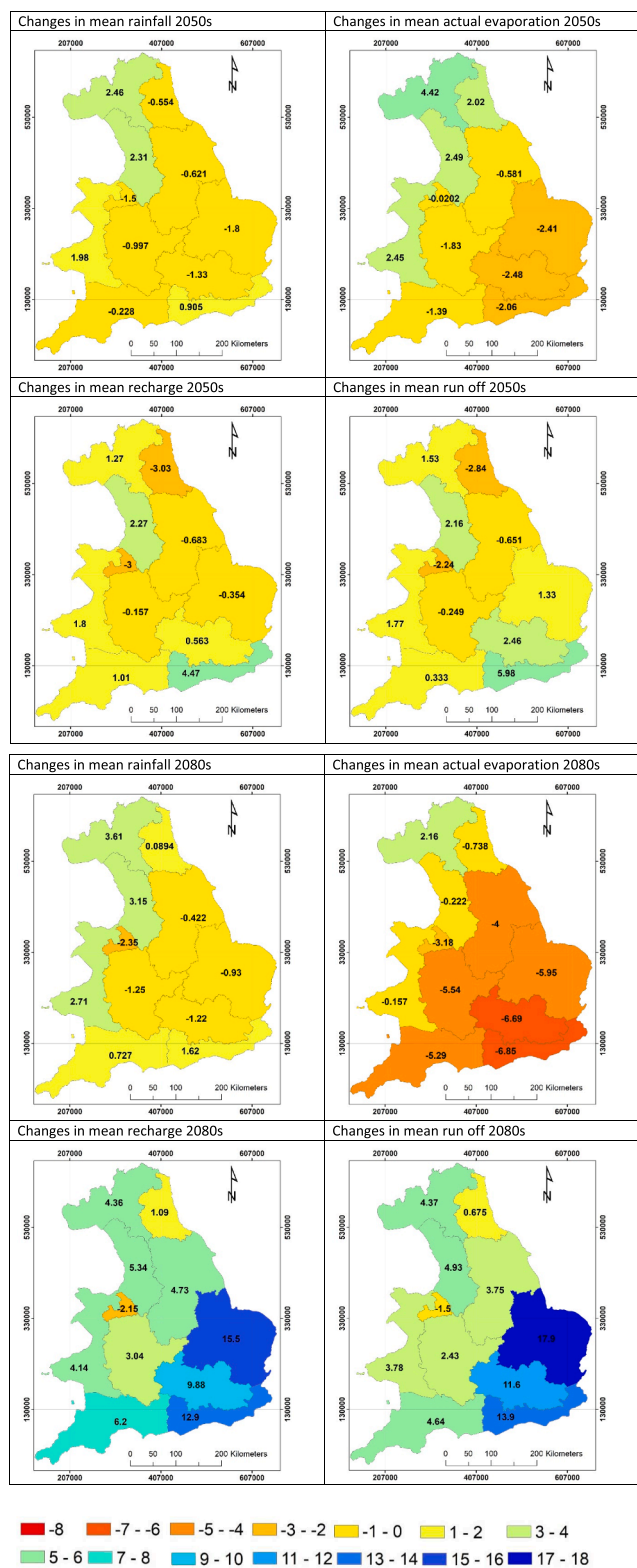


Fig. 4. Spatial distribution of percentage changes to total Rainfall, Actual Evaporation, Recharge and Run off volumes for each River Basin Management District for: (a) 2050s; (b) 2080s. (Contains Ordnance Survey data © Crown copyright and database right 2021)

demonstrate the spatial variation with greater increases in recharge in the south and east of England. These trends are translated into increases in recharge and runoff for 2050 s and the 2080 s – all RBMDs without

exception show an increase in recharge from 2050 s to 2080 s; this is driven by an increase in rainfall, but also a decrease in AE. The greatest percentage increases in potential recharge occur in the south and east of England which also coincides with the outcrops of the main aquifer units (Chalk; see Fig. 1).

3.3. Seasonally averaged water balances for the RBMD

Fig. 5a-c presents the seasonal volumes for rainfall, AE and recharge for RBMD 4 (Humber), 6 (Thames), and 12 (North-west) selected based on their climatic response and location around the country.

Seasonally distributed rainfall is presented in Fig. 5a, for the simulated historic rainfall (1961–90 & 1971–2000) shows that the rainfall totals for each season are not spatially consistent. For the Humber (RBMD 4) they are relatively evenly split between the seasons. However, Thames (RBMD 6) is slightly skewed to winter / autumn and for North-west (RBMD 12) autumn / winter predominates over summer / spring. In general, climate change is predicted to reduce summer rainfall and increases winter rainfall “period on period” for time slices 2050 s and 2080 s. This is confirmed by the seasonal percentage changes: increases in autumn and winter, in contrast to decreases in summer and a mixed response in spring. The percentage changes are similar for each RBMD and each forecast period, with Thames RBMD (6) showing greatest summer reduction.

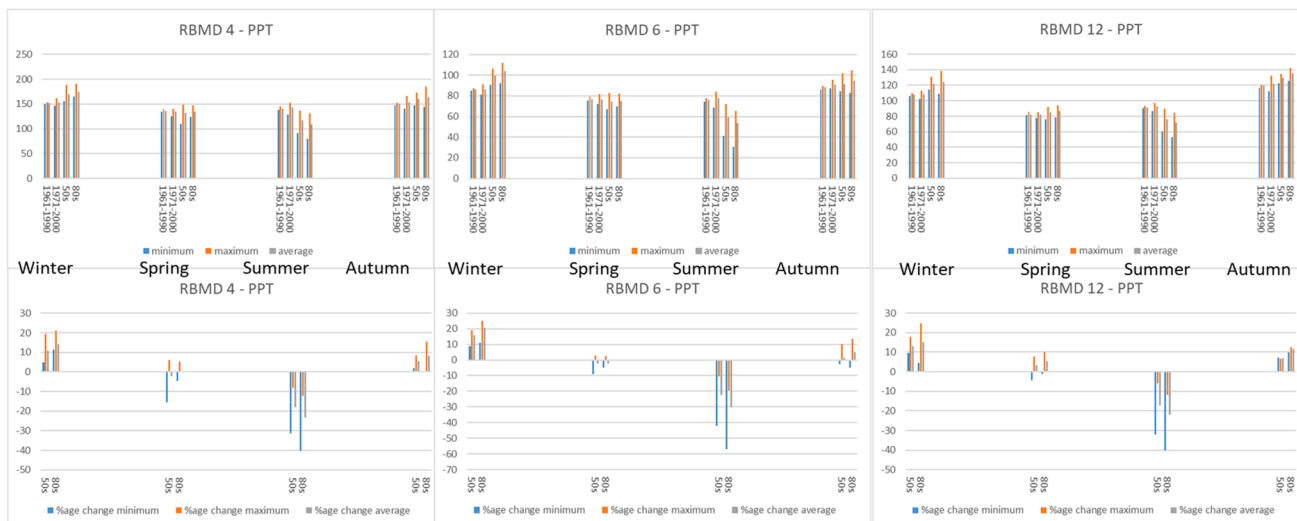
The AE is strongly seasonal as would be expected – as lower autumn and winter potential evaporation results in a defined recharge season. The magnitude is consistent between all RBMDs presented in Fig. 5b, with AE being the greatest in the summer, followed by spring then autumn and winter having the lowest totals. In general, climate change results in an increase of AE in autumn and winter due to higher rainfall and a reduction of AE due to lack of available water in the summer. The ordering of totals stays the same for Humber RBMD (4) and Thames RBMD (6), for these RBMDs AE totals are predicted under future climate to be reduced below that of spring. No change is observed for the ordering of seasonal totals for North-west RBMD (12). Calculating the percentage changes show consistent summer reductions showing the greatest magnitude, followed by increases in winter as well as spring and autumn. Winter exhibits the greatest increases in AE with Thames RBMD (6) and North-west RBMD (12) the highest and lowest magnitudes respectively.

Recharge demonstrates a strongly seasonal signal (Fig. 5c) and in general winter recharge is the greatest, followed by autumn and spring with summer exhibiting very small amounts of recharge. For Humber RBMD (4) and Thames RBMD (6) then the spring and autumn have similar totals. For North-west RBMD (12) autumn is much closer to the winter totals. However, there are differences between the RBMDs: Humber RBMD (4) has winter recharge very much greater than either spring or autumn with a very small total for summer. For Thames RBMD (6) the winter recharge totals are again very much greater than autumn and spring with summer having very small totals. For North-west RBMD (12) the seasonal distribution is winter recharge totals greater than autumn followed by spring and then summer.

Forecast climate change does not change the ordering of seasonal recharge magnitudes, but the model output demonstrates definite increases in winter recharge, a mixed response in spring and autumn (with both increases and decreases for different RBMDs and time slices) and significant decreases in summer.

The implications of these changes are that temporal changes to forecast rainfall and PE results in increased winter rainfall which increases winter recharge at the expense of other seasons resulting in a consolidation of winter as the season with the greatest recharge. Recharge does, however, increase (mean and range) in autumn and spring due to increases in rainfall, albeit more modest than those observed for winter. Whilst decreases in recharge are predicted to occur in summer, these are small absolute values and do not affect the overall recharge totals.

(a) Precipitation



(b) Actual Evaporation

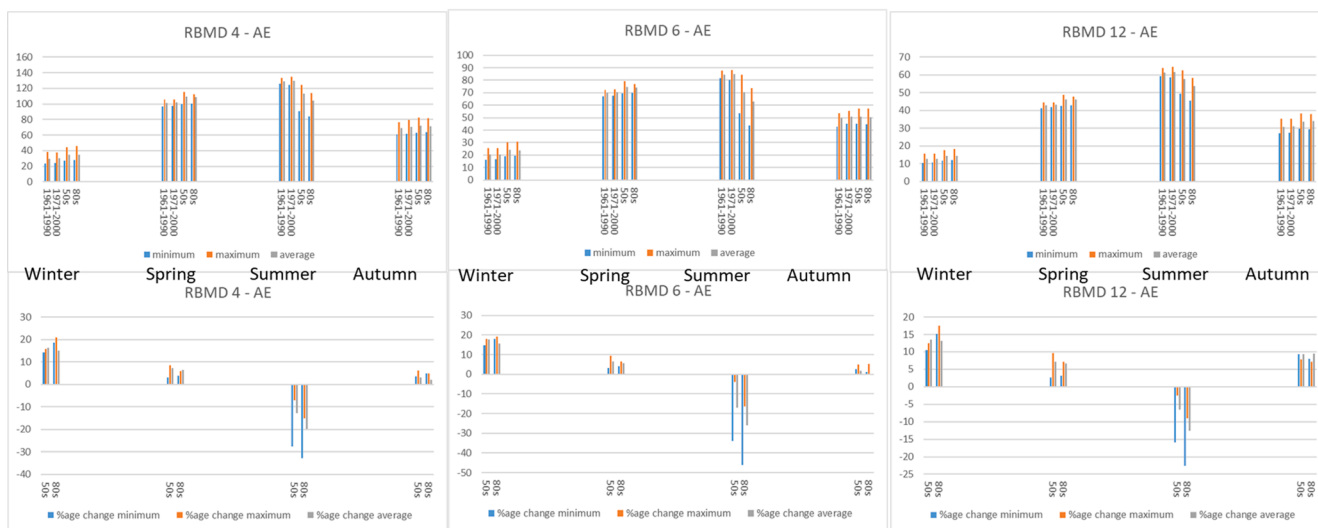


Fig. 5. Volumetric (ML/d) and percentage changes to seasonal Rainfall, Actual Evaporation and Recharge volumes for River Basin Management Districts 4 (Humber), 6 (Thames) and 12 (North-west).

The increases in winter rainfall and to a certain extent autumn rainfall translates through to increased recharge. The strongly seasonal nature of recharge means that the increases in rainfall balance out any increases in AE to produce greater recharge totals. Whilst decreases in summer rainfall along with increasing temperatures result in greater percentage decreases of recharge, these are small totals and do not significant impact the overall recharge volumes. Further the increases observed in 2080 are greater than that of the 2050 s, reinforcing the general trend of increasing recharge totals. The eastern RBMDs (Thames – 6 and Humber 4) demonstrate greater proportion of the total recharge in winter whereas North-west (12) has a comparable autumn contribution to the overall total. This could explain why the Thames and Humber RBMDs show a greater percentage increase in overall recharge compared to the North-west.

4. Discussion

Given the likely changes of drier summers, wetter winters and general increases in temperature (Arnell et al., 2015), this work has investigated how the combination of these impacts will affect potential recharge across England and Wales. The modelling presented here demonstrates that, in general, the annual recharge totals are predicted to increase, but changes to monthly values will vary and are predicted to reduce in September. The latter is a result of drier summers, which have increased soil moisture deficit, and lower rainfall totals in the early months of autumn which mean that it takes long to reduce this deficit and initiate recharge. The results of the modelling suggests that as a result of trends in monthly recharge, the recharge season could change in the 2050 s and, in particular, the 2080 s.

Given the concentration of recharge during winter and autumn months, then wetter winters are predicted to result in an overall increase in recharge totals. The results presented here demonstrate that winter

(c) Potential recharge

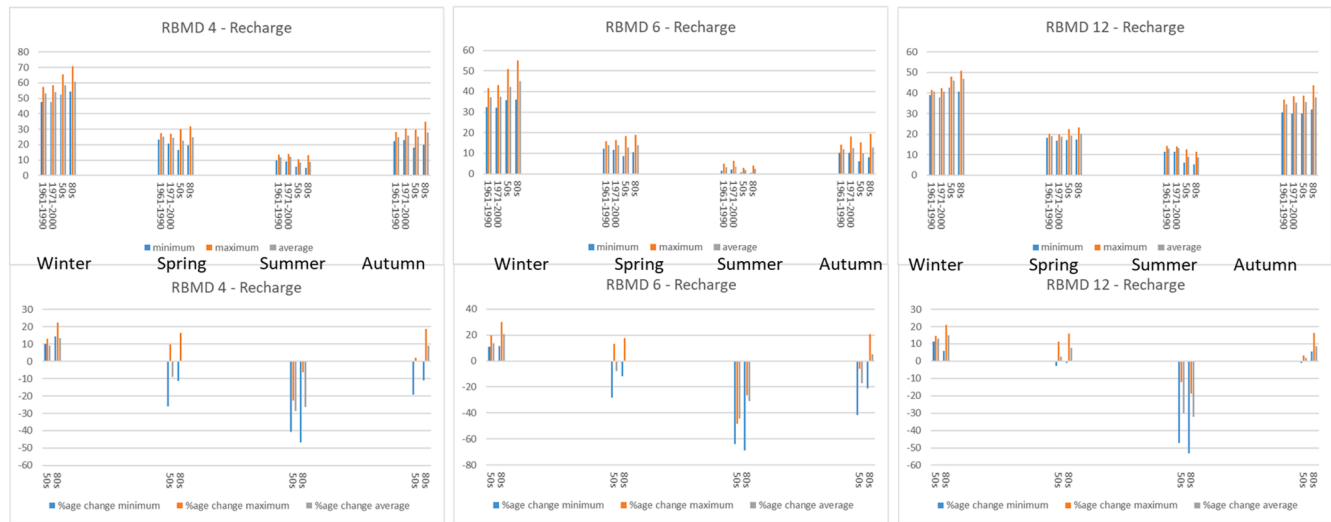


Fig. 5. (continued).

rainfall is forecast to increase from current totals with the associated increase in potential recharge. Whilst increases in rainfall in autumn are predicted, the winter recharge provides the majority of the overall recharge volumes. However there is an east–west split with eastern parts of the country recharge is more concentrated in the winter. Whilst summer rainfall totals are forecast to decrease which results in a significant percentage decrease in recharge, the contribution of summer recharge to the overall totals is limited. These results demonstrate how the recharge processes can “balance” the predicted modification of meteorological conditions associated with climate change, i.e. drier summers and wetter winters. Examining the trends in monthly recharge from 2010 onwards (Fig. 3c) shows that increases are observed for the late autumn and winter (November, December, January and February), decreases in late spring, summer and early autumn (Many, June, July, August and September) with the transition months, i.e. March, April and October showing no statistically reliable change. The results show a clear lack of stationarity in modelled future recharge for November, December January and February and, importantly, demonstrate that increases occur in recharge during what is traditionally thought of as the recharge season (autumn and winter).

There are spatial variations in the change in annual potential recharge with the magnitude of variation greatest in the west of Britain, particularly the north-west of England and Wales. This could be related to either the climate change signal or its attenuation by recharge processes. Arnell et al. (2015) (see Table 3) do report spatial variation with western regions showing greater increases in winter precipitation than their eastern counter-parts. Spatial variability is very important, particularly when the relationship between climate, location, as well as abstraction and aquifer type are taken into account. The spatial distribution of groundwater abstraction is heavily weighted to the south and east of England³ where Water Companies are also the most water stressed⁴. Additionally, the hydrogeological response of the system related to aquifer type may mitigate climate response. This can be related to aquifer diffusivity (Transmissivity / Storage coefficient) with the higher the number the quicker the aquifer responds to any changes.

³ www.bgs.ac.uk/research/groundwater/waterResources/GroundwaterInUK/2015.html

⁴ See Table 1 2013 classification https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/244333/water-stressed-classification-2013.pdf

Chalk is very much higher than sandstone so it would be expected that any climate change signal would be slower to be detected in sandstone aquifers.

Changes to monthly recharge indicated by Fig. 3(c) indicate the shortening of the recharge season and whilst there is likely to be overall greater recharge in volume terms, this could occur over shorter periods with greater individual monthly totals. This shortening will lead to fluctuations in groundwater levels which could be greater in faster responding aquifers i.e. chalk as opposed to slower responding sandstone in relation to the different storages (see Allen et al. (1997)). Given that the UKCP09 driving data used in this study is based on medium emission scenarios (A1B), the likely emission pathway (RCP8.5) could provide for more variability in the climate and associated uncertainty. This could result in winter recharge totals may be affected and could reduce overall recharge volumes.

Given the importance of winter rainfall translated to recharge totals, then the vulnerability of groundwater systems to meteorological drought (related to precipitation deficiency over a large area and for a long time; Van Loon (2015)) could increase in that rainfall totals over fewer months control the delivery of potential recharge. For example, “blocking high pressure” weather systems such as that which occurred in the 2010 drought in the UK (Kendon et al., 2013) could have greater impact by affecting rainfall in the crucial months that control recharge (Winter and to a lesser extent autumn; October to March). Therefore, even relatively short duration blocking high climate events could have proportionally greater impact on recharge totals if synchronised with the winter recharge period, which may be more likely to occur under the RCP8.5 forecast scenarios.

The current understanding of the response of groundwater systems to droughts and how this might change under conditions of climate change requires further study. The issue of drought sequencing in rainfall and PE time series such as provided by FFGWL can be addressed using the scenario neutral approach, used for example to examine the impact of climate change on flood frequency (Prudhomme et al., 2010). This approach could provide information on catchment response regardless of climate change scenario chosen. The twin advantage is of lack of bias in the choice of driving data and providing information on the sensitivity of the catchment to the climate change signal.

The results presented here have potential implications for water resource management, in particular the reliability of using groundwater alongside its resilience under drought conditions. Deployable output for water resources need to be examined under conditions of climate change

in groundwater systems, e.g. [Charlton and Arnell \(2011\)](#). However, further analysis is required to feed through potential recharge to the groundwater systems and subsequently how it impacts water supply systems.

4.1. Assumptions and limitations

Whilst the work has shown that potential recharge totals may indeed increase, the modelling has a number of limiting assumptions. As [Holman et al. \(2011\)](#) state the majority of assessments of Climate Change impacts assume that the physical properties of the landscape do not change. This is the case here in addition, changes to rainfall intensity, changes to soil condition and land use changes are not taken into account.

Daily rainfall is used to drive the model and used in conjunction with a daily time step. This means that diurnal fluctuations and the potential changes to the distribution of rainfall over the day are not taken into account. Further, changes to rainfall intensity (hourly rates) are also not taken into account. However, rainfall is predicted to become more intense under conditions of climate change (e.g. [Kendon et al. \(2014\)](#)), so not taking into account rainfall intensity could be a weakness as rainfall is likely to intensify in the future. The intensification of rainfall events could impact soil erosion which in turn can affect recharge processes ([Burt et al. \(2016\)](#)). Further, land use / land cover will also be modified either by choices made by land owners in response to climate change or by natural response to changing climate. The former are likely to include changes to the distribution of arable land and cropping patterns and increased urbanisation resulting from greenfield development. The latter is related to changing growing season and the response of plant and trees to changing stimuli ([Holman, 2005](#)).

Soil condition are also not included and will be affected by farmer's attitude to soil health. Workability and use of heavy machinery in autumn, particularly if these are wetter can lead to compaction and changes to soils ([Holman, 2005](#)). There may be significant interaction between intensifying rainfall and poorer soil health leading to greater generation of runoff at the expense of recharge.

Land use change is not included in this study because it adds one additional dimension in the complexity of the problem especially considering the uncertainties associated with the climate projections and land use projections. The focus of this research is on the impact of future climate change on groundwater resources only. However, previous work has shown that modelling recharge for gradual land cover change does not produce changes that are significant with respect to climate change, particularly for the UK ([Mansour and Hughes, 2014](#)). However, studies in the Netherlands show this can be the case ([Witte et al., 2019](#)), but this may be due to differing catchment size and topographical effects.

The recharge model outputs are calculating potential recharge and the role of the unsaturated zone along with the quaternary deposits in the UK in mitigating changes to recharge needs to be assessed. Further, the results have not been used to drive groundwater models / water balances and this is required to fully demonstrate the impact of the changes in potential recharge on baseflow to rivers and water resources (groundwater levels and deployable outputs). Further, the FFGWL climate dataset has been produced from a perturbed climate models and drought sequencing is not considered.

In the UK as in many parts of the world, flooding and droughts has been identified as important to study under conditions of climate change, particular examples include changes to flood frequency, particularly in upland Britain (e.g. [Lavers and Villarini \(2013\)](#)) and that droughts may become more prevalent by the 2050 s ([Environment Agency \(2013\)](#)). The reduction of rainfall totals during droughts over the winter and the subsequent response of the groundwater system is important to understand in terms of groundwater availability and needs to be addressed. Additionally changing recharge season / volumes and its impact on flashiness of groundwater response needs addressing. This

has particular relevance to groundwater (Clearwater) flooding.

In terms of the climate change scenarios and their relevance, a revised set of UK predictions have been recently released (UKCP18), which consolidate the changes predicted by UKCP09: wetter winters and drier summers. Presently the datasets are not available in as comprehensive form as for UKCP09, which precludes detailed analysis. However, work ([Kay et al., 2019](#)) has been undertaken to compare the two outputs using monthly change factors to determine the impact on river flow. This work shows that the median change is very similar, but that greater range of response occurs in UKCP18 than UKCP09; this will be explored in future work.

4.2. Relevance of outcomes

Given that there is a concern that climate change in general could lead to a reduction in water resources and in particular groundwater recharge, then the work presented here has shown that potential recharge volumes will not decrease, but could show a modest increase. The increase in winter rainfall outweighs the drier summers and subsequent impact on the soil moisture deficit being reduced and the timing of the start of the recharge season.

In terms of the input to groundwater systems in the UK, then it would appear that groundwater resources have the potential to be maintained. Of course, this is dependent on other factors such as response of the aquifer, river-aquifer interaction as well as outflow to springs. Whilst there is no reason for complacency it is likely that if climate change occurs as predicted then in volume terms the groundwater resources will be maintained. Subject to confirmation by groundwater modelling, it would appear that water resources managers in the UK should, therefore, be encouraged to maximise groundwater for their plans in terms of Public Water Supply (PWS).

The outputs from this work can be used to driving groundwater flow models to fully assess the impact of changes on groundwater resources. For example, Table 3 in [Jackson et al. \(2015\)](#) shows that groundwater response in boreholes situated in the chalk aquifer is more vulnerable to climate change, with median annual values decreasing more than for limestone or sandstone. This could be due to location (south and east of the England) rather than aquifer response, but none the less reflects the lack of storage in the chalk.

This work shows the need to understand the variation of recharge on seasonal basis and how this then related to changes in the driving variables. This is particularly the case in temperate regions where there isn't a defined rainy season, but a dependence on the relationship between rainfall and PE to drive groundwater recharge. For example even if rainfall totals reduced then it is important to examine when rainfall is predicted to change and how this relates to the seasons where recharge is generated.

Finally the results presented here suggest that idea of resilience of groundwater to climate change ([Taylor et al., 2012](#)) is worth pursuing. Recharge to aquifers, particularly in temperate climates, is based on rainfall in defined seasons. Therefore, winter rainfall drives the recharge totals. This dependency on one season allows recharge to be maintained even if rainfall changes at other times of the years. Further, storage in aquifers means that recharge during the winter can be made available for abstraction at others times of the year. This seasonal input allied with storage echoes the message by others, e.g. [Kundzewicz and Döll \(2009\)](#) that groundwater could be a mitigation for climate change in terms of PWS.

5. Conclusions

This work has taken a recharge model instance of the British Mainland (BM) and run through the 11 ensemble members of the FFGWL climate product for the AIB SRES (medium emission scenario). A time series of potential (soil infiltration) for the 1950 – 2099 has been produced. By summarising the changes of future recharge for the 2050 s and

2080 s for both England, Scotland and Wales as a whole as well a River Basin Management District then the likely changes in potential recharge for the BM has been assessed.

Given that the predicted changes are drier summers and wetter winters, then the analysis of seasonal and monthly trends from the historic simulation highlights that summer will become a period of reduced potential recharge. The reduced potential recharge in September (historically the start of the recharge season) suggests that the period of low recharge could be extended by one to two months, thereby shortening the recharge period. However, set against this, winter recharge is forecast to increase, as winter rainfall totals increase at the expense of rainfall at other times of year. Further, whilst the recharge season is likely to shorten, the overall volumes of potential recharge at the RBMD scale for the 2050 s and 2080 s are likely to be at least as much as the present day, if not increase.

However, the work has limiting assumptions and the model is run on an “as-is” basis and the growing season doesn’t change. Further, changes to rainfall patterns (duration and intensity) have not been considered. The FFGWL climate is statistically consistent, but does not address drought behaviour. To address this, further work on response to growing season, rainfall intensity, and drought sequencing is required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The work on this project has been jointly funded by the Environment Agency and the British Geological Survey. The Future Flow and Groundwater Levels project is gratefully acknowledged for providing the driving data for the 11 ensemble members. Hughes, Mansour and Ward publish with the permission of the Executive Director, British Geological Survey (UKRI). Jon Mackay provided an internal review and is gratefully acknowledged. The comments of two reviewers: one anonymous and Willem Zaadnoordijk, which helped in improving the paper are gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2021.126336>.

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