A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: implications for groundwater resource management

I. P. Holman · D. Tascone · T. M. Hess

Abstract Groundwater resource estimates require the calculation of recharge using a daily time step. Within climate-change impact studies, this inevitably necessitates temporal downscaling of global or regional climate model outputs. This paper compares future estimates of potential groundwater recharge calculated using a daily soil-water balance model and climate-change weather time series derived using change factor (deterministic) and weather generator (stochastic) methods for Coltishall, UK. The uncertainty in the results for a given climate-change scenario arising from the choice of downscaling method is greater than the uncertainty due to the emissions scenario within a 30-year time slice. Robust estimates of the impact of climate change on groundwater resources require stochastic modelling of potential recharge, but this has implications for groundwater model runtimes. It is recommended that stochastic modelling of potential recharge is used in vulnerable or sensitive groundwater systems, and that the multiple recharge time series are sampled according to the distribution of contextually important time series variables, e.g. recharge drought severity and persistence (for water resource management) or high recharge years (for groundwater flooding). Such an approach will underpin an improved understanding of climate change impacts on sustainable groundwater resource management based on adaptive management and risk-based frameworks.

Keywords Groundwater recharge · Climate change · Soil-water balance · Downscaling · UK

Received: 9 May 2008 / Accepted: 10 March 2009
Published online: 7 April 2009

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Introduction

The recent Fourth Assessment Report of the Inter Governmental Panel on Climate Change (IPCC 2007) demonstrated that our climate is changing and that a significant part of it is due to man's activities. We are committed to a degree of climate change even if major emission reductions of greenhouse gases occur tomorrow. Although the size and long residence times of many groundwater systems provide a buffering function to short-term climatic variability (Winter 2000), many groundwater systems are potentially vulnerable to the direct and indirect effects of climate change on recharge (Holman 2006). Globally, as many as 2 billion people depend directly upon aquifers for drinking water—over half of the 23 megacities rely upon, or make significant use of, local groundwater; almost one-third of Asia's drinking water supply comes from groundwater, and more than 95% of the rural population of the USA depend on aquifers to provide their drinking water (Morris et al. 2003). Despite both this importance and vulnerability, there has been comparatively little research relating to the impacts of climate change on groundwater (Kundzewicz et al. 2007).

The sustainable future management of groundwater resources requires a quantified understanding of the impacts of climate change, primarily through changed temperature and precipitation, on recharge (Jyrkama and Sykes 2007). Rushton and Ward (1979) demonstrated that accurate estimation of groundwater recharge depends on the use of daily, as opposed to weekly or monthly calculations. However, global climate model (GCM) output is not directly suitable for use by hydrogeological impact modellers, because it is often provided as monthly time series or monthly averages, there is uncertainty in the

 DOI 10.1007/s10040-009-0457-8

output at a daily scale, particularly for precipitation (Semenov 2007; Rivington et al. 2008) and because of the coarse spatial resolution of the GCM. These limitations necessitate the use of some form of downscaling technique. Two fundamental approaches exist for downscaling of GCM output:

- Dynamical downscaling: the use of regional climate models (RCM) or limited-area models which use the lateral boundary conditions from a GCM to produce high resolution outputs (Mearns et al. 2003)
- Statistical downscaling: a range of methods which rely on the fundamental concept that regional climate is related to the large-scale atmospheric state, expressed as a deterministic and/or stochastic function between the large-scale atmospheric variables (predictors) and local or regional climate variables (predictands; Wilby et al. 2004). These methods range from simple methods such as Loaiciga et al. (2000) and the change factor (also known as the 'perturbation' or 'delta-change') method (Prudhomme et al. 2002) to more sophisticated methods such as regression models (e.g. Giorgi et al. 2001), weather typing schemes (e.g. Hewitson and Crane 2002) and weather generators (e.g. Semenov 2007; Wilks and Wilby 1999).

It is not the intention of this paper to review the many downscaling methods; the reader is referred to reviews by Prudhomme et al. (2002) and Fowler et al. (2007) and guidance on the use of statistical (Wilby et al. 2004) and dynamical (Mearns et al. 2003) downscaling methods. However, whilst a range of modelling techniques such as soil-water balance models (e.g. Kruger et al. 2001; Holman 2006; Jyrkama and Sykes 2007), empirical models (e.g. Chen et al. 2002), conceptual models (e.g. Cooper et al. 1995; Arnell 2004) and more complex distributed models (e.g. Croley and Luukkonen 2003; Kirshen 2002; Yusoff et al. 2002; van Roosmalen et al. 2007; Woldeamlak et al. 2007; Jyrkama and Sykes 2007) have been used to look at climate change impacts on groundwater under alternative emissions scenarios (Nakicenovic and Swart 2000), the choice of downscaling methods applied in hydrogeological studies have been limited. In understanding the likely consequences of possible future climate changes on groundwater systems and the regional hydrological cycle, an important (but not exclusive) component to understand is the influence that the downscaling technique exerts on estimates of potential recharge. Potential recharge is that water which has infiltrated through the root zone but which may or may not reach the water table because of unsaturated-zone processes or the ability of the saturated zone to accept recharge, as opposed to actual recharge which reaches the water table (Scanlon et al. 2002).

This paper compares the results of using two statistical downscaling techniques, the deterministic change factor method and a stochastic weather generator, in estimating potential groundwater recharge at Coltishall in East Anglia, UK (Fig. 1), and further considers the implications of the resultant uncertainties for future recharge assessment and groundwater modelling studies. These two techniques have been selected because of their practicality to the hydrogeological community, owing to the simplicity and familiarity of the change factor method and to the public availability of weather generators (e.g. Kilsby et al. 2007). Although the study relates specifically to an area of the UK, the findings will have wider significance to the hydrogeological community as the need to employ daily climate change scenarios for impact modelling increases.

Fig. 1 Locations of the Coltishall study site (*triangle*) and East Anglia (*grey shading*) in Great Britain

Study area

The study was performed at Coltishall (latitude 52.77°, longitude 1.35°) in East Anglia (Fig. 1), the flattest part of the UK. The climate of the region is influenced by its low relief and proximity to the continent, with average annual rainfall of 550–750 mm. Norfolk is largely underlain by Cretaceous (chalk and greensand) or Pleistocene (crag) aquifers. As such it is highly dependent on groundwater, which provides much of the public water supply and irrigation needs and supports river flows and internationally important wetland areas such as The Broads.

Within the UKCIP02 scenarios, annual precipitation for this area is expected to decrease by less than 10% by the 2050s, although winters are likely to be wetter and summers drier (Hulme et al. 2002). Annual average

 DOI 10.1007/s10040-009-0457-8

temperature will rise by between 1–2.5°C by the 2050s, with increases in all seasons.

Methodology

A conventional climate impact assessment methodology was followed to assess the influence of the choice of downscaling approach on simulation of future potential groundwater recharge for a site in East Anglia, UK. Firstly, the change factor method and a weather generator were each used to generate local precipitation and potential evapotranspiration daily time series under future (2020s and 2050s) climate scenarios. Secondly a daily soil-water balance model (WaSim; Hess and Counsell 2000) was used to simulate daily potential recharge under baseline (1961–1990) and each scenario for a loamy sand and loam soil under permanent grass, which were finally compared with those simulated for the baseline.

Climate change scenarios

The climate change scenarios used have been developed on behalf of the United Kingdom Climate Impacts Programme (UKCIP), known as the UKCIP02 scenarios (Hulme et al. 2002). The UKCIP02 climate change scenarios have become the standard reference for climate change in the UK since their release in 2002 (Gawith et al. 2008). The output from the coupled ocean-atmosphere HadCM3 model provided the boundary conditions to drive the high resolution (~120 km) HadAM3H global atmosphere model, whose outputs in turn provided the boundary conditions to drive the high resolution (~50 km) HadRM3 regional climate model. This 'double-nesting' approach improves the quality of the simulated European climate and provides greater spatial detail.

A high and a low emissions climate change scenario, equivalent to the A1F1 and B1 SRES scenarios (Nakicenovic and Swart 2000) for the period 2040–2069 (termed the 2050s Low and High scenarios, respectively), have been used in this study to characterise the lower and upper ends of the expected temperature and precipitation changes, whilst the 2020s High scenario was also simulated to investigate the evolution of change within a single emissions scenario.

Change factor method

The change factor method is the simplest statistical downscaling method, which applies coarse-scale climate change projections to a high-resolution observed climate baseline. A 'change factor' is calculated for precipitation and potential evapotranspiration for each month according to the percentage change in the period monthly means of the variable between the baseline (1961–1990) and the 30-year future simulations centred on the 2020s and 2050s. This series of twelve monthly change factors was then applied to a time series of daily baseline precipitation and potential evapo-transpiration. So for example, if the period monthly mean January rainfall was 10% higher in the 2050s High UKCIP02 simulation compared to the UKCIP02 simulated baseline (i.e. a change factor of +10%), each daily value of precipitation in January in the baseline precipitation time series was increased by 10%.

To enable the true effects of the downscaling technique to be observed, the change factors were applied to the baseline time series of precipitation and potential evapotranspiration calculated by the weather generator, rather than to the observed weather data recorded at Coltishall.

Climatic Research Unit daily weather generator

The Climatic Research Unit (CRU) daily weather generator was initially developed by Jones and Salmon (1995) and modified by Watts et al. (2004a) during the "Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes" (BETWIXT) project in order to construct climate scenarios. Part of the aim on the BETWIXT project was to provide high-resolution scenarios for eleven case study sites (including Coltishall) in order to overcome some of the limitations of the UKCIP02 data such as coarse spatial resolution, deficiencies in grid square information, lack of climatic variables for future scenarios and poor representation of extreme events (Watts et al. 2004b; Herrera-Pantoja and Hiscock 2008).

Measurements of past meteorological observations at Coltishall were used by Watts et al. (2004a) to estimate the precipitation distribution functions and the regression weights for the weather generator. The observed precipitation and temperature data were divided by Watts et al. (2004a) into half-monthly blocks so that any seasonal variation of the distribution functions and the regression weights between the previous and the current day could be allowed for. In addition, data for four transition types (dry day–dry day; wet day–wet day; dry day–wet day; wet day–dry day) are treated separately, as the correlation of temperature between successive dry days is, for example, distinctly different from successive wet days. Once precipitation has been generated using a first-order Markov chain model (Richardson 1981), the daily mean temperature and temperature range are stochastically generated using the seasonal and transition type regression relationships. The remaining secondary variables (vapour pressure, wind speed and sunshine duration) are determined by regression analyses based on the previous day's value and the current day's precipitation, mean temperature and temperature range. Finally, relative humidity and reference potential evapotranspiration using the FAO (Food and Agricultural Organization) Penman-Monteith method (Allen et al. 1998) are calculated from the generated variables. Further detail on the CRU weather generator is provided in Watts et al. (2004a) and Kilsby et al. (2007).

Validation by Watts et al. (2004b) during the BETWIXT project has shown the performance of the CRU daily weather generator to be very satisfactory, and robust across the range of UK climate regimes for which it has been tested (i.e. from wet northern sites in Scotland to dryer/warmer sites in southern and eastern England. The derivation and application

 DOI 10.1007/s10040-009-0457-8

of the monthly change factors for the UKCIP02 climate change scenarios for daily precipitation (mean, variance and skewness of daily rainfall and proportion of dry days) and temperature (mean and variance) for use in the weather generator are described in Kilsby et al. (2007). The regression weights within the weather generator were assumed not to change.

WaSim soil-water balance model

Model description

WaSim is a one-dimensional daily soil-water balance model that simulates the soil-water storage and rates of input (infiltration) and output (evapotranspiration, runoff and drainage) of water in response to weather. Although developed as a teaching and learning tool (Hess and Counsell 2000), its value as a research tool has been demonstrated (e.g. Hirekhan et al. 2007). The unsaturated zone is divided into three compartments, the upper 0.15-m layer, the active root zone and layer below the root zone. The thickness of the latter two layers varies as the active root zone changes. The root development is assumed to increase from the planting depth to the maximum depth following a sigmoidal root growth curve between the planting date and the date of maximum root depth (Borg and Grimes 1986). The crop cover fraction on a particular day is determined by linear interpolation between the specified dates of emergence, 20% cover, maximum cover, maturity and harvest. Senescence is simulated by a linear reduction in crop cover fraction between maximum cover at maturity and zero at harvest.

Surface runoff is comprised of two components; runoff due to intense rainfall (infiltration excess) and runoff due to saturated soil. As the rainfall data used to drive the water balance model is only available on a daily time step, daily surface runoff due to the intensity of rainfall is estimated using the curve number method (Conservation Engineering 1986) and any rain falling on saturated soil is assumed to run off.

Any precipitation that does not run off is assumed to infiltrate. Actual evapotranspiration from the soil is taken as the area-weighted average of crop transpiration, soil evaporation and evaporation of intercepted water from the mulch cover (if present). Plant transpiration is assumed to occur at a rate proportional to the reference evapotranspiration (Allen et al. 1998) depending on the plant type and soil-water content, but does not take into account the effect of raised atmospheric CO_2 concentrations (Gedney et al. 2006). It occurs at the potential rate whilst the root-zone soil-water content is between field capacity (here defined as the soil-water content at a suction of 5 kPa) and the limit of easily available water capacity (defined as the soil-water content at a suction of 200 kPa). Under restricted water supply, it decreases linearly to permanent wilting point (defined as the soil-water content at a suction of 1,500 kPa) and remains zero thereafter (Brisson 1998). For soil-water contents above field capacity, it decreases linearly to zero when the root-zone soil-water content reaches saturation (0 kPa). Soil evaporation is estimated using the method of Ritchie (1972).

Soil water moves from one layer to the layer below only when its water content exceeds field capacity. The rate of drainage is a function of the relative saturation of the layer (Raes and van Aelst 1985) and the hydraulic properties of the soil. Water draining out of the lower layer is taken to be potential recharge.

WaSim model set-up

Freely draining loamy sand and loam-textured soils are the dominant soil types in the area (Hodge et al. 1984) and were selected for simulation by WaSim. These are classified as being in ‘soil hydrological groups A’ (low runoff potential and high infiltration rates even when thoroughly wetted) and B (moderate infiltration rates when thoroughly wetted), respectively, based on their ‘Hydrology of Soil Types’ class (Boorman et al. 1995). Both soils have been assumed to be in ‘fair soil condition’ (Conservation Engineering 1986). Hydraulic conductivity and volumetric water contents at suctions of 0, 5, 200 and 1,500 kPa were taken from Smedema et al. (2004).

Permanent grass was represented, with a crop coefficient representing the ratio of crop potential evapotranspiration to reference potential evapotranspiration of 1. A typical rooting depth of 0.7 m was used. Based on the permanent grass land cover and assumed fair soil condition, the loamy sand and loam soils were assigned ‘curve numbers’ of 49 and 69, respectively, as given by Conservation Engineering Division Conservation Engineering (1986) for ‘antecedent moisture condition II’.

Results

Weather time series

The CRU weather generator was previously set-up by Watts et al. (2004a) using data from the Coltishall weather station. The 30 years of simulated baseline weather data (parameterised using 17 years of observed weather data) were used as the current weather, as the simulated time series have the same distribution and statistical characteristics as the training period (Fig. 2), but the simulated years do not correspond to a ‘real’ calendar year, i.e. there is no day-by-day or year-by-year correspondence between the observed and simulated time series. For each climate change scenario, 100 realizations of 30 years of daily data were created by the CRU weather generator, using ‘change factors’ calculated from the same HadRM3H simulations as used to produce the UKCIP02 spatial patterns parameters. Sensitivity studies by Watts et al. (2004b) have indicated that similar variability is obtained across 100 runs as across 1,000 runs. Overall, the future weather time series show little change in the distribution of annual average precipitation within the 100 runs, but significant progressive increases in ‘potential (reference) evapotranspiration’ (Fig. 3).

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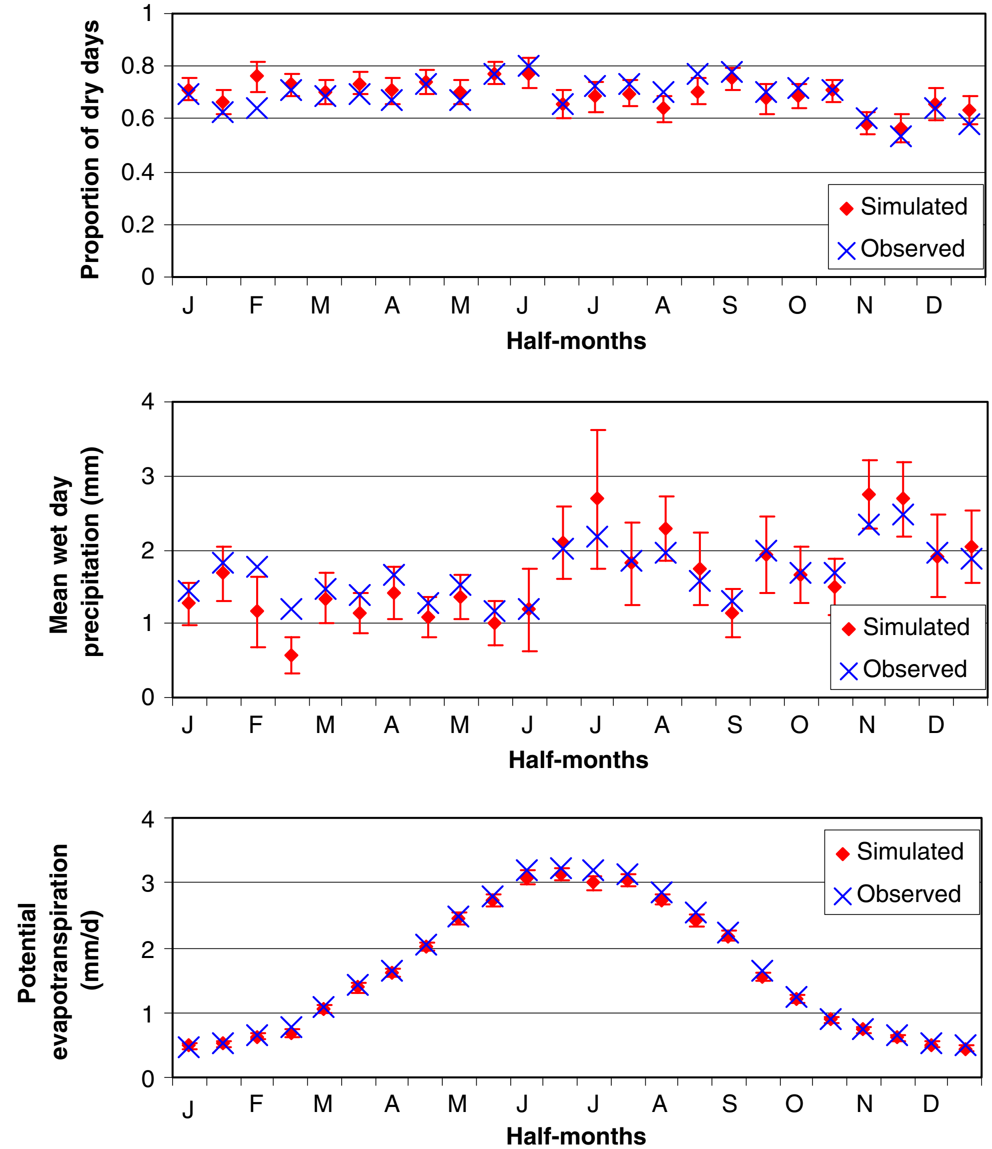

Fig. 2 Comparison of observed and simulated weather variables for Coltishall (mean of 100 30-year weather generator runs ± 2 SD; data provided by the BETWIXT project)

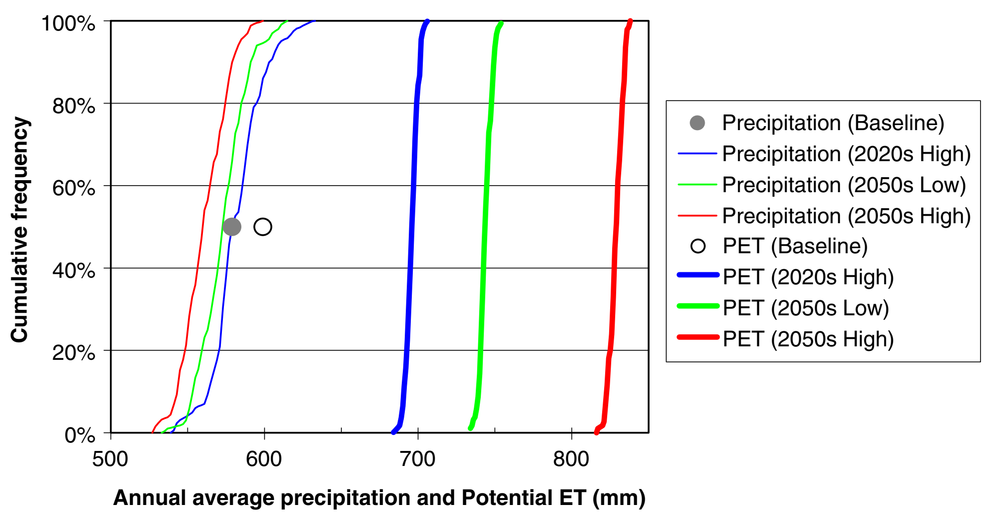

Fig. 3 Cumulative frequency distributions for future annual average precipitation and potential evapotranspiration for Coltishall based on 100 30-year weather generator runs (data provided by the BETWIXT project)

DOI 10.1007/s10040-009-0457-8

Table 1 Median annual potential recharge using change factor and weather generator methods

Scenario	Loamy soil		Sandy soil	
	Change factor[a]	Weather generator[b]	Change factor	Weather generator
Baseline	71		117	
2020s High	63	58	105	100
2050s Low	61	50	99	91
2050s High	51	45	91	87

[a] Based on 29 hydrological years of simulated annual potential recharge

[b] Based on 2,900 hydrological years of simulated annual potential recharge

Groundwater potential recharge results

Baseline

The baseline estimates of average annual hydrologically effective rainfall (AAHER), given as the sum of runoff and potential recharge by WaSim, are 112 mm/year (loamy sand soil of fair condition) and 85 mm/year (loamy soil of fair condition). These agree well with the estimate of AAHER of 102 mm/year given by the UK Meteorological Office Rainfall and Evaporation Calculation System (MORECS, v2.0; Hough and Jones 1997) for the surrounding 40 km×40 km MORECS grid square (cited by Herrera-Pantoja and Hiscock 2008).

Median annual potential recharge

All simulated hydrological (1 October–31 September) years for the weather generator (2,900 model-years from 100 simulations of 29 hydrological years) and change factor (29 model-years from 1 simulation of 29 hydrological years) methods have been separately pooled. A consistent pattern emerges in the overall median annual potential recharge with the two downscaling approaches, as it decreases slightly with time, the decrease being greater for the high emissions scenario (Table 1). Taking the 2,900 model-years of annual potential recharge derived using the weather generator data, the median annual recharge for the loamy soil ranges from 45 mm/year (for the 2050s High) to 58 mm/year (2020s High) compared to the baseline of 71 mm/year. Similar, albeit slightly higher, values are given by the change factor method (based on only the 29 model-years).

Median annual potential recharge of individual simulations

In contrast to Table 1 which pools all of the individual simulations, Fig. 4 shows the distribution in the median annual recharge values (from the 29 hydrological-years) from each of the 100 individual simulations using the weather generator data. There is a significant spread between the lowest and highest median annual potential recharge of individual simulations (Table 2) from, for example, 28–85 mm/year in 2020s High to 19–72 mm/year for 2050s High for the loamy soil. This variability within the individual simulations for a single scenario time slice is much greater than the difference between the overall median annual recharge of the different scenario time slices shown in Table 1, but it cannot be represented by the single value derived using weather data from the change factor method.

Annual potential recharge

Figure 5 shows the distribution of future annual values of potential recharge for each scenario for the loamy and

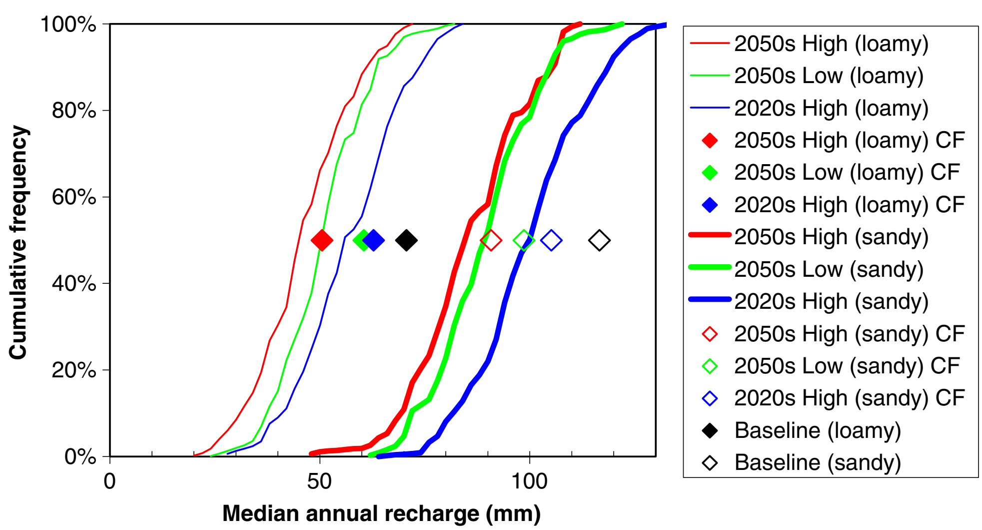

Fig. 4 Cumulative frequency distributions of baseline and future median annual potential recharge at Coltishall for sandy and loamy soils from 100 stochastic and one change factor (*CF*) simulation for each scenario

 DOI 10.1007/s10040-009-0457-8

Table 2 Range of future median annual potential recharge within 100 simulations using the weather generator method

Scenario	Loamy soil	Sandy soil
2020s High	28–85	64–133
2050s Low	23–81	63–123
2050s High	19–72	49–114

sandy soils from the pooled 2,900 hydrological years (100 stochastic simulations) calculated using the weather generator data and the 29 hydrological years calculated using the change factor method data. It is apparent that there is a slight reduction in annual potential recharge across the whole probability distribution for both soils, although the reduction is greater for the loamy soil for both downscaling methods. The overall distribution is similar for both methods, but smoother for the stochastic method given the much larger number of years simulated (2,900 against 29 model-years). The distribution of annual potential recharge values for both soils for the 2050s Low are between those of the 2020s High and 2050s High scenarios.

At face value, Fig. 5 suggests that the effect of climate change on annual recharge is limited, given the small downward shifts in the distributions of annual potential recharge. However, while the cumulative frequency curves for the stochastic method are based on the 2,900 hydrological years of output (100 x 29 years), each of the 100 individual simulations that make up that distribution are equally probable. Figure 6 shows the 100 individual cumulative frequency distributions (as opposed to the amalgamated or pooled distributions in Fig. 5) produced by the 100 simulations for the loam soil in a 2020s High and 2050s High scenarios, which span a wide range of annual potential recharges for any given probability of exceedance. So whilst the overall distribution in annual potential recharge has shifted evenly downwards by 10–20 mm (depending on scenario) in Fig. 5, individual future simulations within the stochastic output in Fig. 6 can show significant differences of 20 mm to more than 80 mm for a given probability of exceedance which cannot be captured using the change factor method.

Severity and frequency of recharge 'drought' and 'flood' years

To assess how the frequency of potential recharge 'drought' and 'flood' years might change, each of the

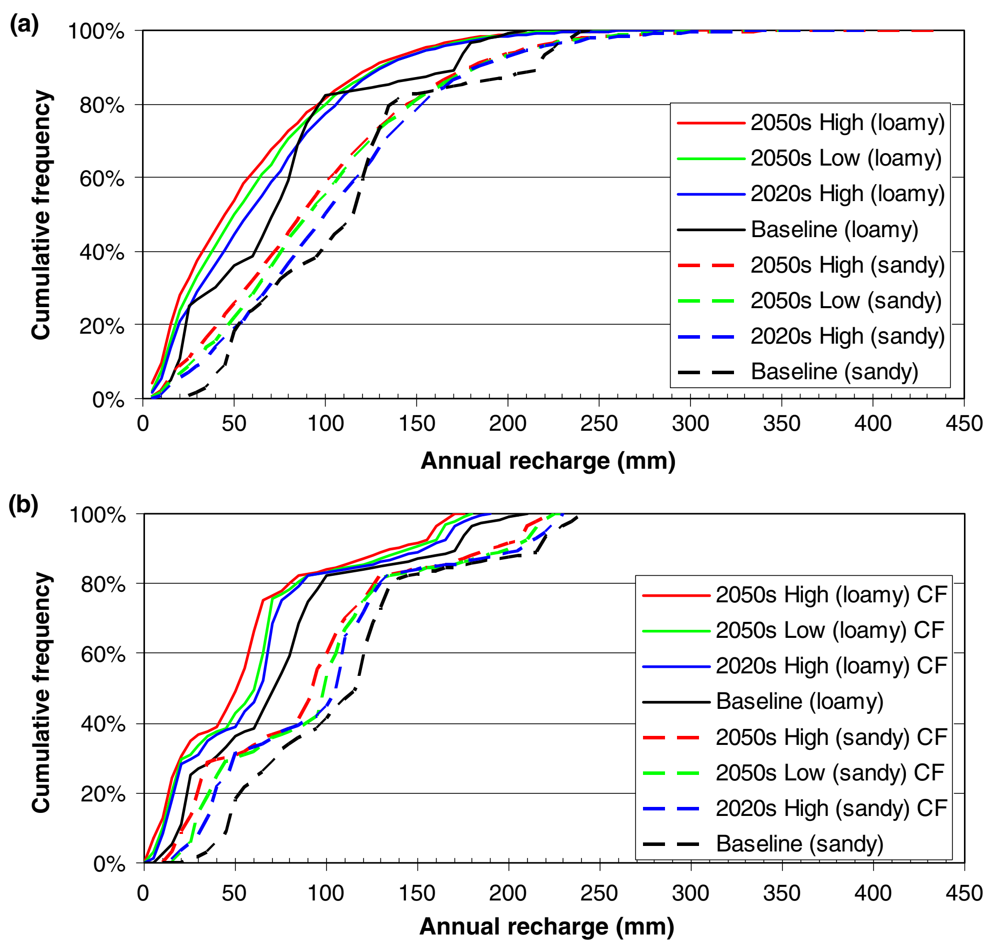

Fig. 5 Cumulative frequency distributions of baseline and future annual potential recharge at Coltishall for loamy and sandy soils using (**a**) stochastic and (**b**) change factor methods

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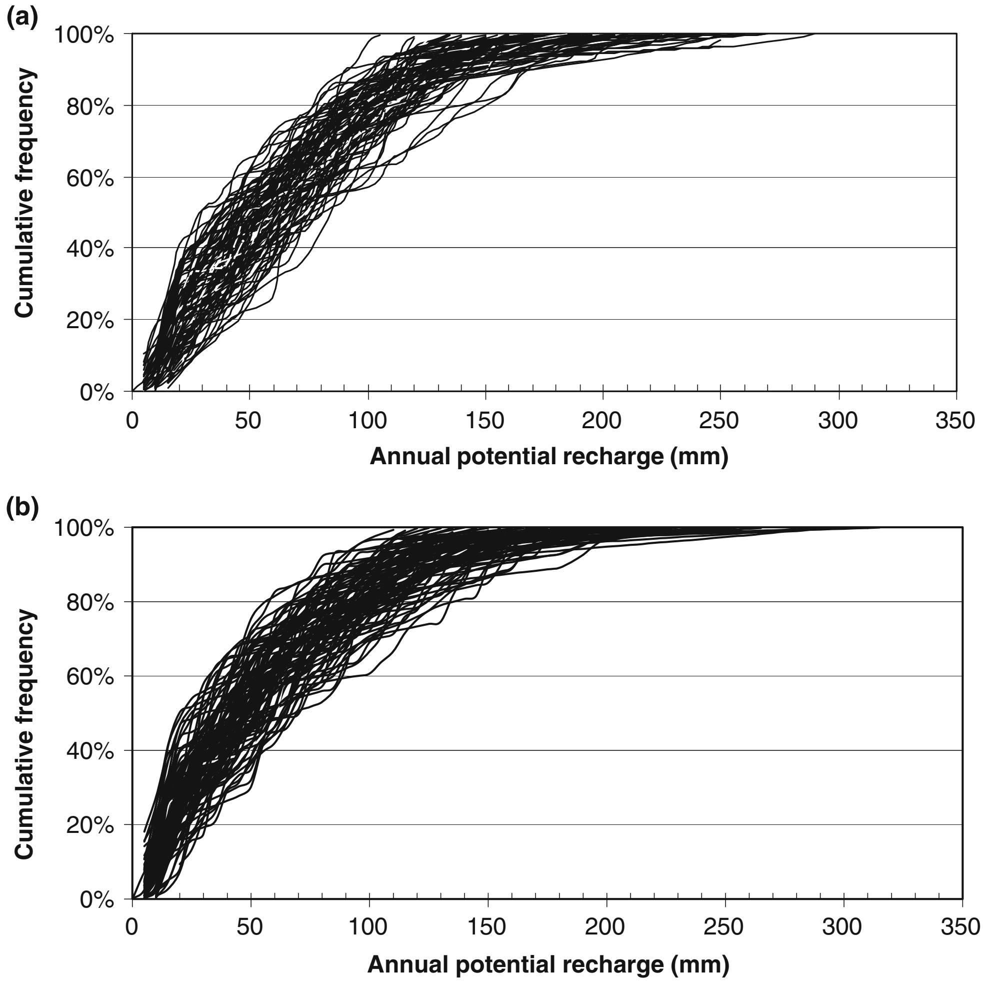

Fig. 6 Cumulative frequency distributions of annual potential recharge for 100 individual simulations of annual recharge for a loam soil under (**a**) 2020s High and (**b**) 2050s High climate change scenarios

hydrological years within the 100 stochastic simulations has been classified as 'very dry' 'dry', 'normal', 'wet' and 'very wet' according to the quintiles of the baseline recharge data. For example, a future 'very dry' year has an annual potential recharge that lies in the lowest 20th percentile of the baseline annual recharge data.

Figure 7 shows the distribution of very wet to very dry years in each of the 100 simulations. It can be seen that the number of each of the 'types' of years varies significantly between each of the equally probable simulations for the same climate change scenario. For example, in the 2050s High, the number of very wet years in a single simulation ranges from 1 to 12, whilst the (more important) very dry years range from 4 to 16.

Persistence of recharge droughts

Because of their great volume and long residence times, groundwater systems have a natural resilience to short duration annual droughts. However, recharge droughts which persist for longer than a single winter, can cause problems for water supply, and lead to increased environmental stress in groundwater dependent ecosystems. The persistence of groundwater recharge droughts in each of the 100 simulations has been assessed based on the sequence of 'very dry' and 'dry' years within each simulation. Figure 8 shows that the persistence of recharge droughts (shown by consecutive horizontal white cells) varies significantly within the simulations for the same climate change scenario. For example there are 44 simulations out of 100 in which annual potential recharge is dry or very dry for more than five consecutive years under the 2050s High scenario, whilst there are also equally probable simulations in which the longest consecutive dry or very dry period is only 2 or 3 years.

Discussion

Assessments of hydrologically effective rainfall (Holman 2006; Herrera-Pantoja and Hiscock 2008), potential recharge (Holman et al. 2005) and actual recharge (Yussof et al. 2002) have been previously derived for this part of the UK. In common with many climate change scenarios, the UKCIP02 and their predecessor UKCIP98 scenarios (which were used in all of these studies) are provided as

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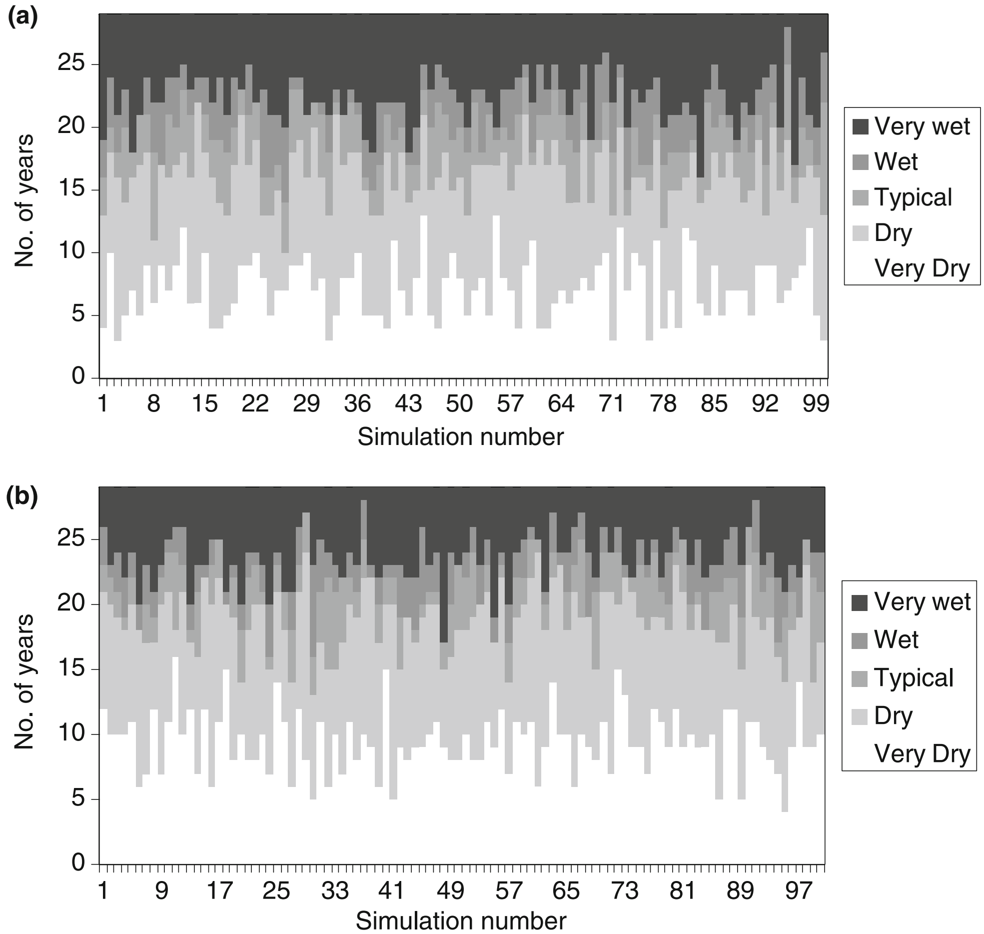

Fig. 7 Frequency of very wet to very dry potential recharge years at Coltishall under (**a**) 2020s High and (**b**) 2050s High for a loamy soil

period means, which require temporal downscaling to the daily time scale needed for recharge estimation. All of the aforementioned studies have been based on a single time series for each 30-years time slice, and all have used the change factor method with the exception of Herrera-Pantoja and Hiscock (2008) who used only a single run from the same CRU weather generator as used in this study.

The commonly used change factor method has the advantage of simplicity but gives the impression of apparent certainty about the nature of future weather (even when different emissions scenarios are used) because only a single time series of future weather with similar natural inter-annual variability is created to represent each given future scenario. The resultant time series maintain the detail of the station record, but the scaled and baseline data differ only in their respective means, maxima and minima. The method ultimately produces only a single deterministic scenario with the variability unchanged, which implicitly assumes that the future climate is a slightly perturbed version of the present with future weather that has the variability characteristics of the baseline weather, albeit slightly wetter/drier and/or warmer/cooler in each month.

However, many studies suggest that the future variance within climate parameters will change. For example, Schär et al. (2004) show that the variance of European summer temperature is expected to increase strongly in the twenty-first century, whilst Vidale et al. (2007) show amplification in surface temperature and precipitation variability. The changed variances within the CRU weather generator (described by Kilsby et al. 2007) aims to address this. However, whilst the single simulation of the weather generator used by Herrera-Pantoja and Hiscock (2008) ensured a different sequencing of wet and dry periods compared to the baseline, they fail to identify where their single time series fits within the distribution of future time series that the weather generator can create. It is not therefore possible to determine whether the single simulation is a representation of unduly dry, typical or particularly wet conditions within the future probability distribution.

The use of a stochastically generated series of weather in this study has allowed a fuller understanding of the consequences of the uncertainty in potential recharge arising from the treatment of natural variability within the choice of temporal downscaling method. It is apparent that the uncertainty in the distribution of annual potential recharge associated with the individual stochastically generated weather time series of a single emissions scenario/time slice (e.g. 2050s High in Fig. 6) are greater

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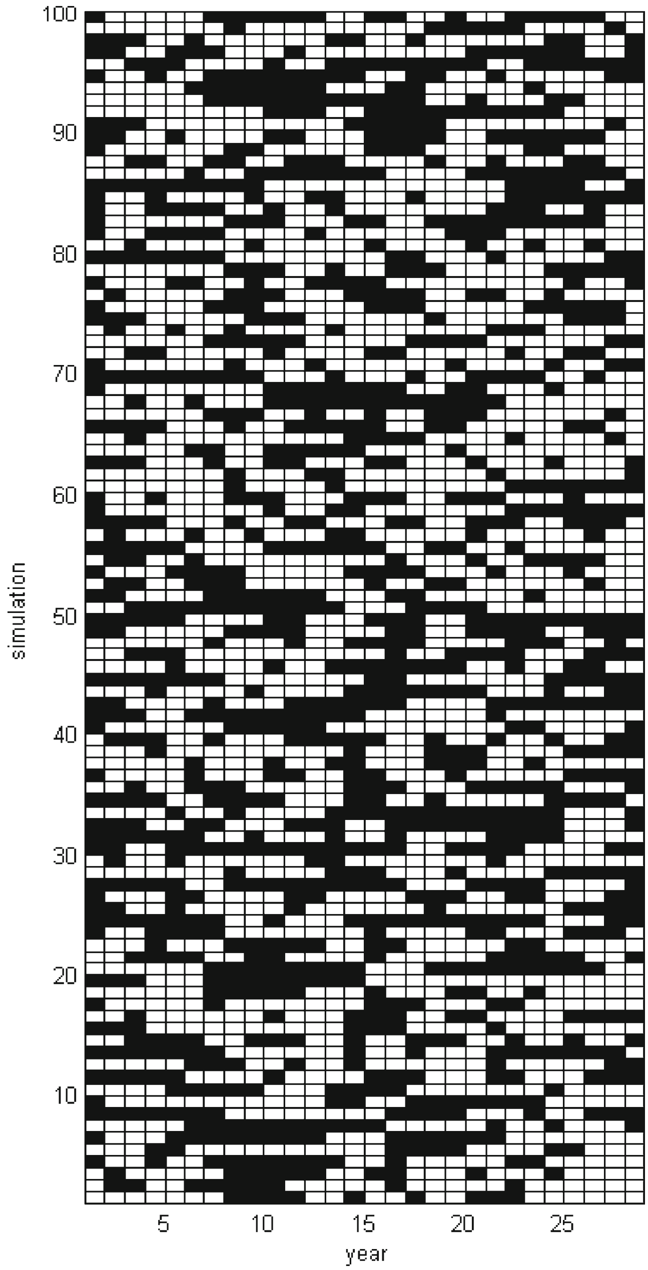

Fig. 8 Persistence of dry/very dry years within 100 simulations of potential recharge for a loam soil in a 2050s High climate (*white* = dry or very dry potential recharge years)

than the differences between the time slices in the probability distribution from all emissions scenario/time slice simulations (e.g. 2020s Low vs. 2050s High in Fig. 5). Whilst no individual time series shown in Fig. 6 will be identical to that which eventually occurs, each of the time series are statistically as probable as each other, and, as importantly, as probable as the single time series derived from the change factor method. The uncertainty also differs between soil types, with the differences in potential recharge between soil types being greater than the differences within soil types, consistent with Schibek and Allen (2006). In particular, there is less difference between scenarios for the sandy soil compared to the loamy soil, as the increased potential evapotranspiration is not realised in many years because of the absolute soil moisture deficit limit imposed by the lower water holding capacity of the sandy soil.

Presenting the changing impacts of climate change with time based on the results of a single set of deterministic potential recharge estimations is failing to capture the inherent natural variability in weather. As such, the false impression of certainty might lead to inappropriate designs of water resource management systems. Although Dessai and Hulme (2007) found that the local water resources plans in the east of England were robust to climate change uncertainties, this partly arose because the design of large-scale adaptation options (e.g. extension of water treatment works) was based on the outputs from the HadCM3 climate model, used in the generation of the UKCIP02 scenarios, which is drier than most other GCMs. Although water-resource planners may perturb historical extreme droughts—the worst that's been known—by the climate scenarios, it is important to assess whether such an approach is capturing the possible range of future droughts. It is apparent from Figs. 7 and 8 that extreme droughts might occur within climate scenarios that do not represent extreme changes in period means. For example, annual and winter (December–February) precipitation changes by around –2 and +7%, respectively, in the 2020s High scenario, but individual simulations contain up to 22 out of 29 years (76%) in which annual potential recharge is within the lowest 40% of baseline values. The high levels of uncertainty in both potential recharge variability and the magnitude and persistence of recharge droughts demonstrated in this study suggests that adaptive infrastructure and management systems (Pahl-Wost et al. 2007) informed by risk-based frameworks (Willows and Connell 2003), incorporating the twin-track approaches of supply and demand management (Kirshen 2002), are needed which can cope with the future uncertainty and range of possible outcomes.

Although it does not detract from the overall conclusions of this paper, it must be acknowledged that this study has not included a complete representation of the uncertainties arising from the use of RCM or GCM data. In particular the UKCIP02 scenarios represent the outputs from a single GCM/RCM, albeit it a 'dry' model which represents a worst case for this region (Dessai and Hulme 2007). There are many sources of uncertainties in climate impact studies in addition to those of the downscaling uncertainty and emissions. These include uncertainties in GCM initial conditions, model structure (GCM, RCM structure and impact model) and impact model parameters (Kay et al. 2009). Many authors have identified the important uncertainties arising from the climate models themselves (e.g. Wilby and Harris 2006; Markoff and Cullen 2008; Vidal and Wade 2008). However, Kay et al. (2009), Prudhomme and Davies (2008) and Wilby and Harris (2006) all found downscaling uncertainty to be significant, albeit less important than GCM uncertainty but more important than uncertainty in emissions scenario and impact model parameters.

 DOI 10.1007/s10040-009-0457-8

It is apparent that valuable insights into the uncertainty of future potential recharge estimation can be gained from stochastic, as opposed to change factor, methods. However, to both parameterise and validate weather generators and to use the resultant stochastic weather or potential recharge simulations within a groundwater modelling study is a much more resource-intensive exercise than using the simpler change factor method. Holman (2006) suggests that the significance of future changes in hydrologically effective precipitation should be assessed within the context of exploitable groundwater resources, and the impacts of any change for the aquatic environment or for future groundwater quality. Diaz-Nieto and Wilby (2005) further suggest that change factor methods are most appropriate for broad-brush high-level assessments rather than for detailed assessments. It is therefore suggested that stochastic potential recharge estimates need only be routinely incorporated into impact studies in aquifers or areas which may be sensitive to changes in the temporal magnitude, sequencing and persistence of recharge droughts, e.g.:

- Aquifers with low residence times and limited resilience to recharge droughts
- Aquifers or groundwater management units where available groundwater resources are almost fully exploited under current climatic conditions
- Areas where groundwater is the predominant water resource for economically important human uses, e.g. domestic/industrial water demand, high value irrigated crops etc.
- Aquifers in which elements of the hydrogeological system are vulnerable to changes in groundwater levels, e.g. groundwater dependent terrestrial ecosystems (wetlands), chalk streams, or coastal aquifers

Where simpler potential recharge models, which can easily be run stochastically, are combined with more computationally intensive groundwater models, it may not be feasible to run the groundwater model with the full range of stochastic recharge data. In these cases, the multiple recharge time series should be sampled according to the distribution of contextually important time series variables, e.g. recharge drought severity and persistence (water resource management); high recharge years (groundwater flooding) etc. However, fundamentally it is recommended that the effects of different sequencing and persistence within scenarios derived from multiple climate models are examined on the hydrogeological output variables in groundwater modelling studies, rather than only carrying out a sensitivity analysis of changes to the magnitude of events within the baseline sequencing.

Conclusions

Potential groundwater recharge has been estimated for a site in East Anglia, UK, using daily time-series weather derived by the stochastic Climatic Research Unit weather generator and the deterministic change factor method using UKCIP02 climate change scenarios of period means. Whilst small changes in median annual potential recharge are calculated between the 2020s High and 2050s High scenarios, there is significant uncertainty given the spread of median annual potential recharge across individual stochastic simulations.

Analysis of the 100 29 hydrological-year simulations shows that the numbers of very dry to very wet recharge years varies significantly between simulations, given the same climate change scenario. For the 2050s High scenario, the number of very dry years (defined as having an annual potential recharge below the 20th percentile of the baseline simulation) ranges from 4 to 16 out of 29 years, whilst very wet years (annual potential recharge greater than the 80th percentile of the baseline simulation) range from 1 to 12. There is similar uncertainty in the multi-year persistence of such recharge droughts.

This study has shown that using stochastic weather generators to provide daily time-series input for recharge calculation provides a better estimation of the uncertainty in potential recharge, compared to deterministic perturbation (e.g. change factor) methods, which should be captured within impact studies in aquifers or areas which may be sensitive to changes in the temporal sequencing and persistence of recharge droughts. The high levels of uncertainty in both potential recharge and the magnitude and persistence of recharge droughts suggests that adaptive infrastructure and management systems informed by risk-based frameworks, incorporating the twin-track approaches of supply and demand management, are needed which can cope with the future uncertainty and range of possible outcomes.

Acknowledgements The Engineering and Physical Sciences Research Council-funded BETWIXT (Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes) project and Clare Goodess (BETWIXT co-ordinator) are gratefully acknowledged for the provision of the daily time-series data. The United Kingdom Climate Impacts Programme (UKCIP) is acknowledged for use of the UKCIP02 climate change scenarios, and Dr Juan Rodríguez Díaz and Dr Jerry Knox (Cranfield University) for the change factors. We thank the reviewers for their constructive comments.

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