Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections

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Abstract

Projections of climate for the 2080s from an ensemble of global climate models (GCMs) run under a medium-high (A2) emissions scenario are used to simulate changes in groundwater resources of a Chalk aquifer in central-southern England. Few studies that have investigated the impacts of climate change on groundwater resources have addressed uncertainty. In this paper the uncertainty associated with use of a suite of GCM outputs in catchment scale impact studies is quantified. A range of predictions is obtained by applying precipitation and temperature change factors, derived from thirteen GCMs, to a distributed recharge model and a groundwater flow model of the Chalk aquifer of the Marlborough and Berkshire Downs and South-West Chilterns in the UK. The ensemble average suggests there will be a 4.9% reduction in annual potential groundwater recharge across the study area, although this is not statistically significant at the 95% confidence level. The spread of results for simulated changes in annual potential groundwater recharge range from a 26% decrease to a 31% increase by the 2080s, with ten predicting a decrease and three an increase. Whilst annual recharge is not found to change significantly, the multi-model results suggest that the seasonal variation in the groundwater resource will be greater, with higher recharge rates during a reduced period of time in winter. The spread of predictions for changes in river baseflow, at the bottom of the largest river sub-catchment, is from -16 to +33% in March and from -68 to -56% in October. The effects of climate change are shown to depend significantly on the type of land-use. It is concluded that further research is required to quantify the effect of different vegetation types on chalk covered by different thicknesses of soil and their response to a changing climate.

Keywords
Groundwater resources; Chalk; Climate change; Global climate model

1. Introduction

Evidence that the global climate is warming is now unequivocal (IPCC, 2007) with 11 of the 12 years between 1995 and 2006 ranking among the 12 warmest years in the instrumental record of global near-surface air temperature over land and sea surface temperature since 1850. The warming trend of 0.13 ± 0.03°C during the last fifty years is twice that of the last one hundred years (IPCC, 2007) and it is very likely that most of the observed increase in global mean temperature is due to anthropogenic greenhouse gas emissions (IPCC, 2007).

Similarly to the global climate, the climate of the United Kingdom (UK) has changed and average temperatures have risen. The instrumental record of temperature for Central England (Parker et al., 1992; Parker and Horton, 2005) provides evidence of this, showing that 11 of the 20 warmest years between 1659 and 2009 have occurred since 1990. 2006 was the warmest year on record in the UK. Whilst a series of droughts during the 1990s and in 2003 (Beniston, 2004), and the extreme flooding in the UK during 2007 has led to a perception of climate change, trends in hydro-meteorological variables are not obvious (Marsh and Hannaford, 2007). However, there is some evidence for increasing runoff in catchments in Scotland and in maritime western areas of England and Wales (Hannaford and Marsh, 2006). The analyses of Maraun et al. (2008) and Osborn et al. (2000) have shown a long-term increase in the intensity of winter precipitation within the UK, which are consistent with future projections from the UK Meteorological Office's Hadley Centre of hotter and drier summers, and warmer and wetter winters (Hulme et al., 2002). Warming in the UK, relative the 1961-1990 average, could range from 2 to 3.5°C by the 2080s according to the four UK Climate Impacts Programme 2002 (UKCIP02) scenarios (Hulme et al., 2002), but there is uncertainty in the magnitude of the warming, with greater ranges also suggested (e.g. of up to nearly 6°C; Rowell, 2006). In terms of precipitation totals, the sign of the change can be either positive or negative depending on which climate model is considered, particularly in spring, summer and autumn (Rowell, 2006).

2. Background

In recent years a significant amount of research has been undertaken to examine the range of possible impacts of climate change on surface water resources, however, research examining the effects on groundwater remains limited and even inadequate (Bates et al., 2008). Groundwater resources may be relatively robust in response to changes in the driving climate variables under climate change compared with surface water, due to the buffering effect of groundwater storage. Thus, the role of groundwater in the management of water resources is likely to become more important because it can be used to support public water supply and ecosystem services during longer drought periods projected under climate change scenarios for southern UK (Murphy et al., 2009).

Bates et al. (2008) and Dragoni and Sukhija (2008) present reviews of the potential effects of climate change on groundwater and summarise the findings from a number of studies using climate change scenarios to quantify catchment scale impacts. Most of these impact studies have used a physically-based model to simulate the response of the groundwater system to a change in climate, however, some have developed empirical models based on historical data (Krüger et al., 2001; Bloomfield et al., 2003). Whichever approach is adopted, it is necessary to quantify the change in the driving variables of the catchment model, e.g. precipitation and temperature, under future conditions. This can be done by constructing plausible scenarios that are informed by the results of global climate models (GCMs) (e.g. Eckhardt and Ulbrich, 2003; Woldeamlak et al., 2007), which for example, incorporate different percentage changes in annual or seasonal precipitation (e.g. Malcolm and Soulsby, 2000) or by transferring GCM output to the catchment scale more directly (e.g. Herrera-Pantoja and Hiscock , 2008).

Whichever method is used to define the change in the climate at the catchment scale, the results of an impact study should be presented within the context of the uncertainty that is inherent in the modelling process. There are a number of sources of uncertainty that should be considered, relating to the simulation of the catchment or groundwater system, to the definition of the future climate and to future socio-economic change at the local or catchment scale (Holman, 2006). With respect to groundwater modelling, there is uncertainty associated with the conceptual model of the system (Bredehoeft, 2005; Poeter and Anderson, 2005), the numerical model structure and its parameters (Refsgaard et al., 2005; Wilby, 2005) and the data on which it is based. Furthermore, process response under climate change is uncertain. For example, it is possible that the functional relationship between temperature, precipitation and recharge cannot be assumed to remain constant under a changing climate (Younger et al., 2002). With regard to the projections of climate change, there are also a number of sources of uncertainty: (i) the formulation and accuracy of GCMs, (ii) the magnitude of anthropogenic emissions, (iii) the temporal and spatial effect of natural variations internal to the climate system and (iv) the method of downscaling global climate information to the regional or catchment scale (Rowell, 2006).

Wilby and Harris (2006) address the quantification of uncertainty when linking GCMs to hydrological models and apply a probabilistic framework to present the uncertainty associated with (i) hydrological model parameters, (ii) the ability of different GCMs to reproduce present day climate variables used in impact assessment, (iii) downscaling GCM output to define regional climate change scenarios and, (iv) CO_2 emissions scenarios. Uncertainty is quantified using a Monte Carlo analysis based on the CATCHMOD hydrological model of the Thames basin in the UK. Uncertainties in river flow predictions due to emissions and hydrological model uncertainty are shown to be comparable but the current differences between GCMs introduce the most significant degree of uncertainty. Rowell (2006) found the dominant source of uncertainty in precipitation and temperature changes to be the climate model formulation (global and regional) considering the outputs from the EU PRUDENCE project (Christensen, 2002). Prudhomme and Davies (2008) find, when assessing climate change impacts on the hydrology of four UK catchments by the 2080s, that GCM uncertainty is the largest of these sources of uncertainty.

3. Rationale

Few studies of the effects of climate change on groundwater have used ensembles of scenarios, either taken from a range of climate models or by the application of different downscaling methods. One of these is the study of Eckhardt and Ullbrich (2003) in which low and high emissions scenarios are developed for precipitation and temperature based on simulations of five GCMs reported as part of the ACACIA project (Parry, 2000). Woldeamlak et al. (2007) also use an ensemble of five scenarios, developed by the Royal Netherlands Meteorological Institute, that are stated to represent realistic representations of the range of climate change projections from GCMs. Other groundwater studies include those of Rosenberg et al. (1999), Croley and Luukkonen (2003), Brouyere et al. (2004) and Hanson and Dettinger (2005), which apply GCM projections of change to catchments but none of these use more than three different GCMs in their assessment. Goderniaux et al. (2009) use six regional climate models to assess the impacts of climate change on groundwater reserves in the Geer basin, Belgium. A notable exception, however, is the investigation of Serrat-Capdevila et al. (2007) in which 17 GCMs and four emissions scenarios are applied to assess the effects of climate change on the San Pedro Basin, USA, using a transient groundwater-surface water model.

Within the UK there are relatively few studies that have examined the effects of climate change on groundwater resources. Examples include that of Yusoff et al. (2002), in which the UK Hadley Centre's HADCM2 GCM was applied to estimate changes in the groundwater resources of a Chalk aquifer in Eastern England and that of Younger et al. (2002) in which GCM output is applied to a physically-based groundwater flow model to assess the effects of climate change in the Yorkshire Chalk aquifer. Holman (2006) and Holman et al. (2005a; 2005b) develop tools for the integrated assessment of the impacts of both climate and socio-economic change and adaptation options across the four interacting sectors of agriculture, biodiversity, coastal zones and water resources and apply these to a region of eastern England. Another more recent study of UK groundwater resources has been undertaken by Herrera-Pantoja and Hiscock (2007), which estimates changes in potential groundwater recharge and the severity, persistence and frequency of extreme periods at three locations using a stochastic weather generator. Similarly to many of the studies in the UK, a Hadley Centre model is used (HADRM3H), in this case to perturb historic climate data based on four emissions scenarios for the 2020s, 2050s and 2080s.

Considering the limited number of groundwater related studies, particularly within the UK, and the fact that few of these have assessed the range of predictions that can be obtained if a suite of GCMs is applied, this paper addresses the issue of GCM uncertainty in an assessment of the impact of climate change on groundwater resources. Changes in soil drainage, henceforth referred to as potential recharge, river baseflows and groundwater levels are examined. The study uses outputs from 13 GCMs (Table 1) to provide an indication of the level of confidence to be attached to the results of the impact assessment. The simulated climate variables from these 13 GCMs are available from the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre. In this study

GCM outputs for the 2080s under the A2 emission scenario (IPCC, 2000) are used to calculate monthly percentage changes in climate variables from the generally accepted baseline period from 1961 to 1990. These change factors (CF) are used to generate future sequences of precipitation and potential evapotranspiration (PET) by perturbing historic sequences of these variables. However, as discussed later, because of catchment hydrological data limitations, the catchment models can only simulate the historic period between 1971 and 2003. The change factors are linearly scaled to reflect the use of a baseline period different from 1961-1990, similarly to the linear scaling used to generate the UKCIP02 scenarios for a range of time horizons (Hulme et al., 2002).

4. Study area

The study area is located 70 km west of London and covers an area of approximately 2600 km^2 (Figure 1 and Figure 2). It encloses the Marlborough and Berkshire Downs and the south-western part of the Chilterns, which are areas of gently undulating Chalk downland. The River Thames flows onto the area, and the Chalk, near Wallingford and off the study area near Windsor. The elevation of the ground surface ranges from approximately 20 m at Windsor to 250 m towards the northern edge of the region. The main urban centres are the towns of Newbury, Reading and High Wycombe towards the south-east. The Downs and Chilterns are predominantly rural comprising mostly arable and horticultural land and grassland though there are significant areas of deciduous woodland covering the Chilterns and the lower reaches of the Kennet and Pang valleys (Figure 3). The Goring Gap is a deeply incised valley in the Chalk hills in the centre of the area, which contains and was formed by the River Thames that runs south-south-east through a breach in the Chalk (Sumbler, 1996). The River Kennet, Lambourn and Pang drain the Chalk of the Marlborough and Berkshire Downs and are ecologically important rivers, while the River Wye drains the Chilterns. The upper reach of the River Kennet is designated as a Site of Special Scientific Interest under UK legislation because of its richness of fauna and flora and the River Lambourn is a Special Area of Conservation under the European Union’s Habitats Directive.

The region lies at the north-western edge of the synclinal geological structure forming the London Basin, principally on the soft white limestone of the Cretaceous Chalk (Sumbler, 1996) (Figure 2). The siltstones and sandstones of the underlying Upper Greensand crop out in the north and are underlain by the mudrocks of the Gault Clay. In the south, the

Chalk is overlain by deposits of Palaeogene age, consisting of the sands and gravels of the Lambeth Group, the London Clay Formation and younger sand formations. The Downs and the Chilterns consist of a series of north-facing escarpments with a corresponding dip slope of up to two degrees descending southwards and to the south-east.

The Chalk is the major aquifer of the UK (Allen et al., 1996) and supplies approximately 70% of the water used for public supply in South-East England. Due to the permeable nature of the rock, the density of surface water courses is low and chalk rivers typically have baseflow components of more than 90% of the total flow. Chalk is fine grained and because its pores are generally less than 1 µm in size water within the matrix is relatively immobile in the saturated zone, where fractures contribute virtually all of the specific yield and transmissivity. These tend to be higher near to rivers, where the fractures have been enlarged by dissolution. This results in relatively gently sloping water tables and thick unsaturated zones of up to approximatey 120 m beneath the hills of the Downs and Chilterns. The physical properties of the chalk result in atypical groundwater behaviour. For example, rapid rises in the water table are a feature of chalk aquifers, with 10 to 20 m rises in a less than three months being common across interfluve areas at the beginning of the winter recharge season (Allen et al., 1997). Such large fluctuations in groundwater level cause the headwaters of chalk rivers to move significant distances up and down the catchment during the year. The position of the source of the River Lambourn (Figure 1) can vary by up to 10 km between wet and dry periods and such extremes have been experienced in the relatively recent past (Marsh and Dale, 2002; Finch et al., 2004; Pinault et al., 2005).

The groundwater system consists of the Chalk and the minor aquifers of the Lambeth Group underlying, and sand formations overlying, the London Clay. The London Clay has a very low permeability and promotes significant runoff to rivers where it crops out. Overlying both the Chalk and Palaeogene deposits are river terrace deposits, which can be up to 20 m thick. These sands and gravels can play an important role in river-aquifer interaction.

Groundwater head contours in the Chalk, based on mean observed groundwater levels, are presented in Figure 4. These illustrate that the rivers are the main outflows in the system and control the direction of groundwater flow, with groundwater flowing east from the Berkshire Downs and west from the South-West Chilterns to the Thames. The River

Kennet also influences groundwater flow, especially in the Marlborough Downs in the west of the study area. The mean flows in the River Kennet at Theale, Lambourn at Shaw and Pang at Pangourne are approximately 8.35×10^5, 1.48×10^5 and 0.55×10^5 m^3day^{-1}, respectively. In addition to river flows, groundwater discharges from the Chalk aquifer via springs on its scarp slope along the northern and western boundary of the area. Groundwater also flows to the south-east into the London Basin.

Long-term average rainfall varies between 580 mm $year^{-1}$ in the lower areas of the region and 810 mm $year^{-1}$ over the higher ground and is approximately uniformly distributed throughout the year. Annual PET is around 600 mm $year^{-1}$ but is seasonal due to variations in monthly temperature. For example, mean annual temperature at Wallingford is 9.5℃ but varies between 3.7℃ on average in Jan uary and 16.3℃ in July. Rates of groundwater abstraction for agricultural, industrial and public water supply have increased from approximately 3.3×10^5 m^3day^{-1} in 1970 to 4.7×10^5 m^3day^{-1} in 2003 (Jackson et al., 2006a).

5. Methodology

5.1 Recharge Modelling

Variations in potential recharge across the study area are calculated using a distributed ZOODRM model (Mansour and Hughes, 2004). Similarly to Herrera and Pantoja (2008), we use the term *potential recharge* to mean drainage from the base of the soil. The ZOODRM recharge model (Figure 5) is slightly larger than the groundwater model because it simulates indirect recharge that originates from surface runoff across the impermeable London Clay in the south-east. ZOODRM has been extensively tested and applied to a wide variety of settings from the semi-arid zone of the West Bank, Palestine (Hughes et al., 2008) to urban regions (Campbell et al., 2010). In this study evapotranspiration and recharge from the base of the soil zone are simulated using a Penman-Grindley soil moisture balance approach (Penman 1948; Grindley, 1967) applying the concepts of a soil moisture field capacity and plant root constants and wilting points. The balance between rainfall, evapotranspiration, surface runoff and potential recharge across the area is simulated on a daily time step, using information on the spatial variation in land surface elevation, land-use, geology, rainfall and PET. A digital terrain model is used to route runoff across the land surface, which can subsequently infiltrate to form indirect recharge. The proportion of rainfall forming runoff is related to the topography, soil type and geology. Land-use is assumed to be constant over time but root constant and wilting point values are defined for each vegetation type for each month of the year following their seasonal growth rates.

The baseline period (1971-2003) is simulated using a network of 57 raingauges with daily time series. PET rates are taken from the UK Meteorological Office Rainfall and Evaporation Calculation System (MORECS) (version 2.0, Hough and Jones, 1997), which is based on the Penman-Monteith equation (Penman, 1948; Monteith, 1965). The ZOODRM model is calibrated by adjusting runoff coefficients to match the surface runoff components of river flow measured at sixteen gauging stations along the rivers and by comparison against detailed total and groundwater balances for each river catchment in the region. Over the dip slope of the uncovered Chalk potential recharge varies from approximately 0.4 mm day^{-1} in the lower lying areas to 1 mm day^{-1} over the high ground of the Marlborough Downs and Chilterns (Figure 4). There is no recharge where the very low hydraulic conductivity London Clay covers the Chalk and on the steeper scarp slope of the Chalk recharge rates are low. Simulated mean monthly potential recharge for the baseline period, averaged across the whole of the groundwater model area, varies from 0.02 mm day^{-1} in July to 1.53 mm day^{-1} in January.

A one-month delay in the timing of the arrival of the recharge leaving the soil zone and reaching the water table is implemented. This assumption is reasonable considering previous modelling (Jackson et al., 2006b) and recent intensive monitoring of the chalk unsaturated zone (Ireson et al., 2006), which identified a 23.8 day lag between the peak in cumulative effective rainfall and water table response at a site within the study area. However, it is also based on an additional preliminary simulation. Prior to the use of the groundwater model to simulate the impacts of climate change, a historic (1971-2003) simulation is run using a daily time step. In this simulation recharge is transferred instantaneously from the base of the recharge model soil zone to the water table in the groundwater model. The differences between the timing of simulated groundwater maxima and the later observed maxima are then calculated. For the 23 observation boreholes within the study area with sufficiently dense groundwater level time-series to enable this calculation to be made, the lag varies between 0 and 49 days. A comparison of the lag with unsaturated zone thickness reveals no statistically significant correlation. In fact, the longest lag corresponds to a location with only a 12 m thick unsaturated zone. At some of the other sites where the unsaturated zone is thicker than 50 m the lag is less than 14 days. It is likely that this lag is controlled by a number of factors including the nature and thickness of the soil and superficial deposits, the degree of surface weathering of the chalk, the Chalk formation present at outcrop, the intensity and duration of rainfall events and antecedent conditions. Fulton (2009) has used principal component analysis to classify and group the observed groundwater hydrographs within the same study area. This analysis independently identified a group consisting of the four observation boreholes with the longest lag, which are all located within a similar hydrogeological setting of the bottom of a dry chalk valley.

It is recognised that because of the complexities cited above a simplified representation of the unsaturated zone has had to be adopted. A more complex representation of the dual permeability nature of the chalk unsaturated zone is required in some modelling studies but this depends on the time-scale and temporal resolution of the simulation and, the purpose of the modelling. For example, to simulate groundwater flooding in chalk catchments a more detailed representation of the movement of water through both fractures and the matrix of the unsaturated zone is necessary to simulate the possible rapid response of the water table under extreme rainfall. However, for thirty-year simulations of Chalk groundwater resources, as in this study, this is not necessary nor generally tractable because of the prohibitive computational costs of simulating unsaturated flow in areally extensive models. This statement is supported by the large amount of regional Chalk aquifer groundwater modelling that has been undertaken within the UK in which the micro-scale processes occurring in the chalk unsaturated zone have been neglected and good simulations produced (Rushton et al., 1989; Salmon et al., 1996; Power and Soley, 2004). Such an approach has also been applied in other climate impact studies in which the Chalk has been modelled (Herrera-Pantoja and Hiscock, 2008; Younger et al., 2002; Yusoff et al., 2002).

5.2 Groundwater Modelling

Groundwater flow in the Chalk aquifer system is simulated using the ZOOMQ3D finite difference code (Jackson and Spink, 2004). The transient groundwater model simulates fluctuations in groundwater level, river baseflow and spring discharge along the Chalk scarp slope using a weekly time-step. Rivers are simulated using an interconnected set of river reaches that exchange water with the aquifer according to a Darcian type flux equation. The vertical variations in the hydraulic properties of the chalk and river valley gravels are represented using a three-layer model, with the geological and hydrogeological structure being based on geological models of the lithostratigraphy within the wider London Basin. A detailed GSI3D (Kessler et al., 2008) geological model of the Chalk and valley gravels constrains the ZOOMQ3D model in an 8 km square region around Goring (Jackson et al., 2006a).

The groundwater model has been calibrated through comparison with groundwater levels at 207 observation boreholes and river baseflow at 20 gauging stations. To illustrate that the groundwater model adequately reproduces the observed groundwater response, simulated and observed groundwater levels are plotted for a typical hydrograph in Figure 6. Whilst the modelled hydrograph is not perfect it is good in comparison with other regional Chalk modelling examples (Power and Soley, 2004;) and reproduces the multi-year autocorrelation in groundwater levels. In the following it is assumed that groundwater abstraction does not change between the baseline period (1971-2003) and the 2080s.

5.3 Climate change scenarios

The most widely deployed methodological framework for assessing the impact of climate change on a catchment uses a limited number of global or regional climate model outputs, and is as follows. First, scenarios describing the future climate of the catchment are derived using climate model outputs, either by applying them directly to the catchment, or by downscaling them using empirical methods (Wilby and Wigley, 1997). The use of empirical methods can simply involve the perturbation of historic time series using projected monthly changes in climate or the application of more sophisticated techniques enabling variance modification, such as statistical downscaling. Second, these scenarios are run through a physically-based model to derive future time series of catchment state variables. Changes are calculated by comparing the indicators derived from these future series with the same indicators derived from modelled historic or baseline series.

The simplest method for modifying time series of catchment model input using GCM output is the delta change or change factor (CF) method (Wilby and Harris, 2006). For a given variable, the difference between the simulation by a GCM of a reference climate (e.g. 1961-1990) and a future climate are used to adjust sequences of catchment model driving variables. Whilst the CF approach offers a robust method to compare average outcomes from different climate models, it cannot provide any information on changes in hydrological extremes (Graham et al., 2007) because it assumes that the variability of the climate remains unchanged in the future. Changes in both average conditions and extremes can be investigated using downscaling techniques either in the form of *dynamical downscaling*, in which output from a regional climate model (RCM) is used, or *statistical downscaling*, in which relationships are sought between GCM simulated large-scale atmospheric state variables (predictors) and observed local or regional climate variables (predictands).

For analysis of climate change impact on non-extreme variables the CF method remains one of the most widely used and is used here. Change factors are used to perturb historic sequences of daily rainfall and monthly PET. These adjusted sequences are applied to the ZOODRM distributed recharge model, which calculates potential recharge for the transient ZOOMQ3D groundwater flow model of the Chalk aquifer.

Change factors have been calculated using outputs from 13 GCMs reported in the Fourth Assessment Report of the IPCC (IPCC, 2007) which have been obtained from the IPCC Data Distribution Centre (http://www.ipcc-data.org/ar4/gcm_data.html). The factors used in this study represent projected changes for the 2080s time horizon under the A2 emissions scenario (IPCC, 2000). They are derived by calculating the difference between the GCM simulated baseline (1961-1990) and future (2071-2090) climate variables. The 2080s time horizon is selected as it has the strongest ratio between signal of change and natural variability. The A2 scenario is one of the most commonly considered scenarios and is equivalent to the medium-high of the UK Climate Impacts Programme’s 2002 (UKCIP02) scenarios (Hulme et al., 2002).

6. Results

This section presents the suite of simulated *changes* in groundwater state variables. For clarity, calculated values of decreases in a variable are prefixed with a minus sign and increases with a plus sign.

6.1 Changes in climate variables

6.1.1 Precipitation

Ensemble average changes, expressed as spatial averages of all 13 GCM CFs across the study area, suggest a decrease in precipitation between May and October and an increase from November to April (Figure 7). This seasonal pattern of change is the same for most GCMs with the magnitude of changes varying between GCMs. No more than two GCMs indicate a decrease in winter (November to February) or increase in summer (June to September). The maximum increase is predicted to occur in December, for which the ensemble average change is +0.62 mm day^{-1}. For December and January all but one of the GCMs simulates an increase with a maximum of +1.61 mm day^{-1}. Only the CSMK3 (see Table 1) model simulates a reduction in rainfall in January of -0.01 mm day^{-1}. Decreases are greatest in August with an ensemble average change of -0.64 mm day^{-1}. The ensemble spread is also largest in August with predicted changes ranging from -2.43 mm day^{-1} (GFCM20) to +0.32 mm day^{-1} (MIMR). October is the month for which the agreement between GCMs is greatest with predictions of change ranging from -0.4 to +0.11 mm day^{-1}.

6.1.2 Temperature

All 13 GCMs indicate a warming of at least 1.4°C for any individual month (Figure 7). Between November and June the average of the ensemble is in the range +2.33 to +2.65°C. However, between July and October the ensemble average is in the range +2.92 to +3.83°C. As with precipitation the spread of the change in temperature is greatest during summer. For August the GIER and NCPCM models simulate an increase in temperature of +2.0°C, whereas the GFCM20 and the CNCM3 models simulate an increase of +5.8 and +5.9°C, respectively.

6.1.3 Potential Evapotranspiration

In the absence of GCM outputs for some of the climate variables needed to calculate the Penman-Montieth equations, changes in PET rates are estimated using the Thornthwaite equation (Thornthwaite, 1948), which only requires temperature as input. Percentage changes have been calculated at Wallingford, where historic temperature series are available, and then applied to MORECS-PET data to produce future PET series following the CF method. Kay and Davies (2008) discuss in detail the application of the Thornthwaite equation for calculating percentage changes in PET from GCMs.

The percentage changes in PET are smallest in early summer and largest in winter with ensemble averages ranging from +19.5% in June to +70.8% in February (Figure 7). In contrast to precipitation and temperature the spread of the monthly ensembles of change in PET are relatively uniform. Notable anomalously high percentage changes in PET of +99% and +115% are calculated by the GFCM20 run for January and February, respectively, however these are applied to relatively low rates of PET during winter. For reference, mean monthly PET between 1961 and 1990 varies between approximately 13 mm $month^{-1}$ in December and 95 mm $month^{-1}$ in July.

6.2 Groundwater state variables

The effects of climate change on potential groundwater recharge, river baseflow and groundwater levels in the Chalk aquifer are assessed for the 2080s time horizon and compared to the baseline period (1971-2003). Annual changes are presented first before describing the seasonal response of the system.

6.2.1 Annual changes

Catchment potential groundwater recharge

Simulated changes in mean annual potential recharge range from +31% (Lambourn, INCM3) to -26% (Chilterns, NCCCSM) (Figure 8). Reductions in potential recharge are calculated using the outputs from 10 of the 13 GCMs for all catchments and only under the CNCM3, GIER and INCM3 projections is an increase in potential recharge to the aquifer simulated. Across the whole of the study area the ensemble average represents a 4.9% reduction in annual potential recharge. The agreement about the sign of the change in the predictions would suggest a reduction of potential recharge in the study area, however bootstrapped 95% confidence intervals on the ensemble mean are -11.9% and 2.3%. Only at a confidence level of 84% are the bounds on the confidence interval of the mean both negative. The ensemble averages represent decreases of -2.8, -3.2, -2.7, -5.7, -9.1 and -6.8% for the Upper Kennet, Lower Kennet, Lambourn, Pang, Chilterns and Wye catchments, respectively, which are equivalent to changes of between -0.01 mm day^{-1} (Lower Kennet) and -0.07 mm day^{-1} (Chilterns). However, the bootstrapped confidence intervals on these means again indicate uncertainty about the sign of the change; only for the Chilterns and Wye catchments are the lower and upper 95% confidence intervals on the ensemble mean both negative.

The decrease in potential recharge is greater than 10% for the majority of GCMs across east of the study area (Lower Pang, Chilterns and Wye) whereas in the central and western region, generally less than one-third of the GCMs predict a decrease greater than 10% (Figure 9). Only two GCMs suggest an increase in potential recharge greater than 10% across the majority of the area to the west of the Pang. None of the simulations result in an increase in potential recharge of more than 10% across the Chilterns and Wye catchments. A comparison of the land-use map (Figure 3) with Figure 9 indicates that the largest reductions in potential recharge are associated with areas of deciduous woodland. This is linked to the greater rooting depth of these predominantly beech (*Fagus sylvatica*) covered areas compared to grassland and arable crops. The simulated differences in potential recharge between woodland and grassland and associated implications for climate change impact assessment are considered in more detail in the discussion section.

Baseflow

Percentage changes in mean river baseflow are plotted in Figure 10. The largest spread of results is calculated for the Wye at Hedsor for which the range of change is between -74% (NCCCSM) and +88% (INCM3). This is partly because it is the smallest catchment but also because it is covered by a greater proportion of deciduous woodland compared to other areas. The influence that the vegetation cover has on the results is considered in the discussion section. The spread of results is smaller for the Kennet at Theale at which changes are between -17% (NCCCSM) and +24% (INCM3). The ensemble averages represent changes in annual baseflow of -2.3 % (Theale), -3.6 % (Shaw), -8.0 % (Pangbourne), and -22.1% (Hedsor), which are equivalent to -18×10^3, -4×10^3, -4×10^3 and -8×10^3 $m^3 day^{-1}$, respectively. A reduction in baseflow is predicted by 10 of the 13 GCMs at all four gauges and only the CNCM3, GIER and INCM3 simulations produce an increase in baseflow. These results suggest that baseflow is likely to decrease by the 2080s in the study area. However bootstrapped 95% confidence intervals on the ensemble mean of the percentage changes in flow are: -7.6 and 3.7% for Theale; -12.7 and 7.3% for Shaw; -16.8 and 2.5% for Pangbourne; -42.6 and 2.4% for Hedsor. Therefore, as with potential recharge the sign of the change is uncertain. The magnitude of the reduction varies across the region with decreases in baseflow being larger in smaller catchments when expressed as a percentage change. This is because smaller catchments are generally located at higher elevations where reductions in groundwater level mean that proportionally more groundwater flows beneath the gauge on a river than in the channel.

Groundwater levels

Changes in groundwater level are plotted in Figure 11 for 16 observation boreholes located throughout the study area (Figure 5 and Table 2). In contrast to catchment potential recharge and river baseflow, which are both spatial integrals of recharge, the magnitude of the change in groundwater level depends on both the change in the recharge and the position of the borehole. Over the interfluves, groundwater levels are relatively high and adjust by a larger amount in response to a change in recharge compared to the groundwater level near to a river, where the water table is more closely tied to the elevation of the ground surface.

For all of the selected boreholes, there is generally a good agreement in the direction of the changes. Reductions are calculated for all of the observation boreholes under all but three GCMs (CNCM3, GIER and INCM3), except at the Old Hat borehole in the Lower Kennet, where the groundwater level is also simulated to rise slightly under the HADCM3 scenario. The spread of change is greatest at Stonor Park (from a +4.1 m change under INCM3 scenario to -7.1 m under NCCCSM). The ensemble averages (squares in Figure 11) vary between a maximum decline in groundwater level of -2.7 m at Stonor Park to no change in level at Great Park Farm. The effect on the groundwater level at the Great Park Farm is small because this is located in the confined part of the aquifer, where groundwater flow is limited. Results for this borehole are therefore not discussed further.

In the Kennet, Lambourn and Pang catchments, the spread of predictions is lowest at Manton House Farm (-0.8 m to +0.9 m), near to the upper reaches of the River Kennet, and largest at Prebendal Farm (-3.1 m to +3.84 m) at the top of the Lambourn catchment. The reduction in annual groundwater levels, as described by the ensemble averages, is larger across the Chilterns than to the west of the River Thames: -2.7 m to -0.6 m in Chilterns, -0.6 m to -0.1 m in the Upper Kennet, -0.5 m to -0.1 m in the unconfined Lower Kennet, -0.4 m for both boreholes in the Lambourn catchment, and -0.8 m to -0.4 m in the Pang catchment.

6.2.2 Seasonal changes

Perhaps more important than changes in average water balance components are changes in the seasonal response of the aquifer when considering, for example, pressures on river ecology during periods of low flow or the sustainability of public water supply boreholes during summer. Because of this, changes in the monthly mean values of catchment potential recharge, river baseflow and groundwater level have also been calculated for those catchments and locations described previously. Changes in monthly means are calculated for each of these three state variables under each GCM scenario.

POTENTIAL GROUNDWATER RECHARGE

Figure 12 shows monthly changes in potential recharge for the Kennet, Lambourn, Pang and Chilterns catchments. Despite relatively uniform rainfall throughout the year, potential recharge is seasonal, with most replenishment of the groundwater system occurring between October and April and little potential recharge from May to September. On average simulated historical potential recharge rates for these four catchments are less than 0.26 mm day^{-1} between May and September and 1.6 and 1.9 mm day^{-1} in December and January, respectively.

The spread of the ensemble of simulated future potential recharge is also seasonal, with less variability in summer due to potential recharge rates being close to zero, despite the greater spread of projected summer rainfall (Figure 7). During winter, the field capacity of the soil is reached more frequently and for longer periods of time and therefore changes in precipitation are transferred into changes in potential recharge more directly. For the Chilterns catchment, the largest spread is in December, with increases between +1.3 mm day^{-1} (CSMK3) and +2.9 mm day^{-1} (INCM3). In July, the largest monthly mean potential recharge of 0.02 mm day^{-1} is simulated under the INCM3 model.

The ensemble averages indicate an increase in potential recharge between November and February in the Kennet, Lambourn and Pang catchments and between December and

February across the Chilterns. Potential recharge rates decline during the rest of the year, and future ensemble averages are significantly lower than historic values in April and October (Figure 12). Specifically all of the models in the ensemble simulate lower than historic recharge rates for the months of September and October. This suggests, with a high degree of confidence, a shortening of the potential recharge season, with soil moisture deficits developing earlier in the year and persisting for longer into autumn. For the Kennet, Lambourn, Pang and Chilterns catchments potential recharge rates during April are suggested to decrease from 0.40, 0.45, 0.39 and 0.52 mm day^{-1} to 0.25, 0.28, 0.23 and 0.31 mm day^{-1}, respectively. During October potential recharge rates are suggested to decrease from 0.62, 0.71, 0.58 and 0.79 mm day^{-1} to 0.29, 0.33, 0.30 and 0.41 mm day^{-1}, for the same catchments, respectively.

BASEFLOW

The effect of changes in the magnitude and timing of potential recharge on river baseflow is presented in Figure 13. Similarly to potential recharge, the ensemble average shows an increase in baseflow in winter at Theale, Shaw and Pangbourne, with higher baseflows from January to April at Theale and Shaw, and in February and March at Pangbourne. The peak in baseflow is later than that of potential recharge due to the fixed one-month delay in the drainage of water from the soil through the unsaturated zone in the model. Increases in ensemble average baseflows are smaller at Pangbourne because of the greater proportion of broad-leaved woodland within the catchment, reducing potential recharge rates. In March, changes in the ensemble average at Theale, Shaw, Pangbourne and Hedsor are equivalent to +5.0, +6.6, +2.5 and -7.4% of the simulated historic averages, respectively. During November decreases in the ensemble average at Theale, Shaw, Pangbourne and Hedsor are equivalent to -16.9, -29.9, -32.2 and -64.3% of the simulated historic averages, respectively.

The uncertainty associated with simulated changes in river baseflow as defined by the spread of the predictions is greatest during February. At Theale, for example, future February baseflow is 1078×10^3 m^{3}day^{-1} (ECHOG) and 1799×10^3 m^{3}day^{-1} (INCM3), compared with a simulated historic mean of 1190×10^3 m^{3}day^{-1}. However, INCM3 predictions are significantly outside the range of the others, and ignoring this GCM would significantly reduce this spread. In November, reductions in mean baseflow are suggested by all GCMs at all four gauges. At Pangbourne, for example, modelled future baseflows are in the range 15×10^3 m^3day^{-1} (GFCM20) to 29×10^3 m^3day^{-1} (GIER), which is lower than the simulated historic value of 32×10^3 m^3day^{-1}.

Figure 14 compares the monthly ensemble average changes in potential recharge and baseflow. Significant reductions in potential recharge are simulated during April and October, with potential recharge rates decreasing by between 0.14 and 0.22 mm day^{-1} in April and by between 0.29 and 0.44 mm day^{-1} in October. For reference, the mean potential recharge during the baseline period (1971-2003) is 0.67 mm day^{-1} across all of the selected catchments.

GROUNDWATER LEVELS

Figure 15 shows future mean monthly groundwater levels at four of the observation boreholes. At the Manton House and Old Hat boreholes ensemble average groundwater levels are higher than the historic means between February and April, however at Banterwick Barn and Stonor Park, ensemble average levels are lower than the historic values for all months of the year. This reflects the lower rates of potential recharge simulated under future conditions towards the east of the model domain, where there is a greater percentage of deciduous woodland cover.

Bootstrapped 95% confidence intervals on the ensemble mean are presented in Table 3 for the months of March and October. For March the 95% confidence levels on the ensemble mean do not bracket the historic mean at Manton House, Old Hat and Stonor Park; at Manton House and Old Hat they are higher and at Stonor Park lower. However, at Banterwick Barn they do bracket the historic mean and therefore the changes suggested by the ensemble mean at this site are not significant at this confidence level. In March, the ensemble averages are 0.4 m and 0.61 m higher than the historic monthly means of 132.87 and 95.99 m above sea level (m aSL) at Manton House and Old Hat, respectively, with the predictions varying between 132.32 and 135.01 m aSL at Manton House and between 95.22 and 99.42 m aSL at Old Hat.

For October the 95% confidence levels on the ensemble mean again do not bracket, and are lower than, the historic mean at Manton House, Old Hat and Stonor Park. However, they do bracket the historic mean at Banterwick Barn and therefore the difference between the ensemble mean and historic mean at this site is not significant at this confidence level.

7. Discussion

In general, the results of this modelling study indicate that uncertainty about the change in the climate by the 2080s, as described by the outputs of 13 GCM simulations based on the A2 emissions scenario, translates into significant uncertainty about changes in mean groundwater resources. The recharge and groundwater flow models developed here do not all agree about the sign of the change: ten simulate a decrease in *mean* potential recharge and three an increase. This might suggest that the amount of groundwater available for the environment will diminish but the wide spread of the results means that the sign of the change has not been found to be significant at the 95% confidence level. Of more significance are seasonal changes. Specifically, all of the models in the ensemble simulate lower than historic recharge rates during September and October, and 11 predict decreases in April. This is offset by increases in recharge in the winter. Nine of the simulations predict more recharge in December and January but there remains a high degree of confidence associated with the prediction of a shorter recharge season. However, these findings do not take into account other human induced effects such as changes in water use, groundwater abstraction and land-use.

Of the climate change studies that have investigated UK groundwater resources and been reported in the peer-reviewed literature, none has examined the influence of GCM uncertainty on the results. The most recent comparable UK-based study is that of Herrera-Pantoja and Hiscock (2007), which considered impacts on two other catchments in south-east England. Whilst only a single GCM is applied in this study, the sensitivity of the results to arbitrary changes in winter precipitation of ±20% and increases in summer rainfall of up to 40% is examined. Their results suggest reductions in potential recharge of 20% and 40% for sites in East Anglia and Sussex, respectively. These values were obtained by applying catchment scale models and climate projections from the HADCM3 GCM under the A1F1 SRES emission scenarios (IPCC, 2000). By comparison, annual potential recharge, expressed by the average of the ensemble of 13 runs undertaken in this work, is calculated to decrease by between 2.7 and 9.1% across the Marlborough and Berkshire Downs and South-West Chilterns by the 2080s. The spread of the simulations ranges from a 26% decrease for the Chilterns catchment under the NCCCSM scenario to a 31% increase within the Lambourn catchment under the INCM3 scenario. However, the 95% confidence intervals on the mean of the ensemble of simulated changes in average recharge for the whole study area are -11.9 and 2.3%. Consequently, the sign of the change in potential recharge is uncertain at this confidence level.

The reason for the differences between the results of Herrera-Pantoja (2007) and this work is likely to be due to the choice of emissions scenario. Annual precipitation change factors for the A2 scenario applied here range from -19.2% to +16% and the ensemble average is equivalent to a 2% decrease. For annual potential evaporation increases of between 22 and 37% are derived from the GCMs. In contrast at the two sites modelled by Herrera-Pantoja and Hiscock (2007) rainfall is projected to decrease by 3 and 12% and potential evapotranspiration increase by up to approximately 70%.

Whilst catchment model uncertainty can be significant, it is considered unlikely that the differences between the results of Herrera-Pantoja and Hiscock (2007) and this work are due to differences in the catchment scale models applied because both studies use similar soil-moisture balance models based on a Penman-Grindley technique (Rushton, 2003). Indeed most of the models used to calculate potential recharge to aquifers within the UK have been based on similar representations of the soil water store (Finch, 2001; Heathcote et al., 2004).

The results of this impact assessment have highlighted the effect of variations in land-use and associated vegetation type on potential groundwater recharge. In particular one of the most noticeable features of the results is the difference in drainage from deciduous woodland and grass covered soils, with larger reductions being simulated beneath woodland. This can be identified by comparing the land-use distribution (Figure 3) with the spatial patterns of simulated potential recharge (Figure 9). Decreases in potential recharge of more than 10% are predicted by 10 of the 13 models across the wooded parts of the study area. In sub-regions of the study area, across which precipitation and potential evapotranspiration rates are similar and within which wooded areas and non-wooded areas abut, this is apparent.

Differences in potential recharge beneath woodland and grassland have been observed and simulated in the Pang catchment previously by Finch (2000; 2001). Finch (2000) uses a simple daily water balance model to simulate measured soil water content on a sandy loam soil at two sites within the Pang catchment: one under grass and one in an adjacent deciduous wood. Mean annual runoff and potential recharge within the wood are simulated to be less than half of that under grass, which is attributed to greater interception losses from the trees and their greater rooting depth. Whilst evapotranspiration rates of trees and grass are significantly different on sandy soils, this has been shown to not be the case on chalk soils. Roberts and Rosier (2005) provide evidence that potential groundwater recharge on shallow chalk soils is similar under grass and woodland because of the properties of the chalk. On thin soils the matrix of fine pores in the underlying chalk can provide an upward supply of water that allows grass to evapotranspire at the potential rate during all but the driest of summers. Consequently, the concept of a field capacity is not realistic.

Using a spatially distributed recharge model, Finch (2001) also shows the importance of soil characteristics on potential groundwater recharge, again within the Pang catchment. In this study, higher potential recharge rates are found to be associated with soils developed on the Clay-with-Flints, which cover a significant proportion of the Chalk; compared to chalk soils, less rainfall is required to replenish the soil water store of Clay-with-Flints soils and therefore the recharge season begins earlier in the year.

These studies highlight that variations in potential groundwater recharge across the Marlborough and Berkshire Downs and South-West Chilterns are controlled by both the type of vegetation and the nature of the soil. On thicker, freer draining soils, for example associated with the Clay-with-Flints, Lambeth Group or River Thames terrace deposits, spatial variations in potential recharge are likely to be more sensitive to land-use patterns. In contrast, on shallow chalk soils the effect of climate change may be less sensitive to vegetation type because the chalk enables plants with different rooting depths to evapotranspire at the potential rate during dry periods. Wellings and Bell (1980) did however, observe that during the dry summer of 1976 actual evaporation fell below the potential rate on a chalk grassland site, near Winchester, UK. Conditions that are drier than 1976 are likely to be the norm by the end of the century. Average central England summer (May to October) temperature was 1.4°C hotter during 1976 than the 1961-1990 mean (Parker et al., 1992), whereas the projections of summer temperature for the 2080s by the 13 GCMs used here represent increases between 1.9 and 4.3°C. It is likely therefore that the capacity of the chalk to sustain plant growth during dry periods will diminish.

As with most UK regional groundwater assessments, the recharge model applied in this study uses the concept of a soil field capacity. Much of the Chalk in the study area is covered by superficial deposits and the application of Penman-Grindley techniques is reasonable, however, it is recognised that the representation of potential recharge from thin chalk soils could be improved within the code. Additional observational data are required to quantify the components of the soil-water balance, to improve the understanding of the role of superficial deposits and soil thickness in controlling recharge under various types of vegetation and to condition numerical catchment scale recharge models prior to climate change impact assessment. Some such data were collected as part of the UK Natural Environment Research Council funded Lowland Catchment Research (LOCAR) programme (Wheater et al., 2007) at well-instrumented sites on different soils within Chalk catchments but much of these have not yet been analysed. Such an analysis would lead to improvements in the representation of recharge through spatially variable soils and superficial geological formations.

8. Conclusions

Groundwater is the major source of water for public supply in the densely poulated south-east of England. It is necessary to assess the possible effects of climate change on groundwater resources so that timely adaptation strategies can be formulated and strategic water resource management plans developed. In order to do this satisfactorily an understanding of the sources of uncertainty associated with an impact assessment is required. This paper has addressed the most significant of these sources of uncertainty, that derived from projections of future climate from global climate models. An ensemble of catchment scale simulations has been perfomed applying precipitation and temperature change factors for the 2080s calculated using output from 13 GCMs run under the A2 emissions scenario (IPCC, 2000).

The ensemble of groundwater recharge and flow simulations, performed using a model of the Chalk aquifer of central-southern England, has shown that the impact of GCM uncertainty is significant. The catchment scale predictions do not all agree about the sign of the change in potential groundwater recharge, however, 10 of the 13 simulations suggest that it will decrease by the end of the twenty-first century and therefore, that groundwater levels and river flows will also be lower. The spread of simulated changes in mean potential groundwater recharge range from -26% to +31%. Simulations based on the

CNCM3, GIER and INCM3 GCMs generate increases in groundwater resources. The simulation based on the HADCM3 GCM is very similar to the average of the ensemble, which represents a change in potential recharge from -2.7% in the Lambourn catchment to -9.1% in the Wye catchment. Bootstrapped 95% confidence intervals on the ensemble mean of the percentage change in baseflow in the River Kennet at Theale are -7.6 and 3.7%. Therefore, the sign of the change is uncertain at this confidence level.

The range of predictions of change in river baseflow is related to catchment size. For the River Wye, which has the smallest catchment, the change in baseflow ranges from -74% to +88%. For the Kennet, the largest catchment, this range is from -17% to +24%. Changes in mean groundwater level depend on the location of the borehole in addition to changes in recharge. Groundwater level changes will be larger across the interfluves. The ensemble average suggests that mean groundwater levels will decline at all of the boreholes considered in this study, however, the simulated changes are not statistically significant at the 95% confidence level at all of the boreholes considered.

On average the multi-model results suggest that the seasonal variation in the groundwater resource will be enhanced with more potential recharge occuring during the winter but for a shorter period of time. Significant changes are likely to occur during April and October. The ensemble average suggests that potential recharge across the Kennet catchment will decrease from 0.4 to 0.28 mm day^{-1} during April and from 0.62 to 0.29 mm day^{-1} during October. However, under the GIER model, for example, potential recharge in the Kennet catchment increases by 0.14 mm day^{-1} in April and decreases by 0.11 mm day^{-1} in October. Reductions in river baseflow are most significant during November, with simulated changes ranging from -5 to -27% on the River Kennet at Theale. During February baseflows are predicted to change by between -9 and +51% at Theale, with the ensemble average suggesting a 5% increase in flow.

Whilst this work has addressed one aspect of the uncertainty inherent in climate change impact assessments, a number of assumptions have been made. An investigation of the full range of uncertainty would require the consideration of differences between GCMs, downscaling errors, internal climate variability and the accuracy of catchment models. At the catchment scale, process descriptions are inherently simplistic and furthermore inadequately understood, particulary when considering the heterogeneous nature of the land surface. This work has highlighted the limited amount of research that has been undertaken to describe the water requirements of different types of vegetation on different soils and geological formations. Additional research is required to assess how the chalk unsaturated zone supplies the water demand of different plants under drought conditions. Linked to this is the impact of land-use change on groundwater resources, which in this study has been neglected. Here it has been assumed the land-use will not change over the coming century but this will certainly not be the case. As Holman (2006) points out, impact assessments will need to consider socio-economic and land-use change scenarios in addition of changes in climate. Whilist this is yet another source of uncertainty, its inclusion in impact studies will improve our ability to develop good adaptation measures.

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Model	IPCC-DDC Acronym	Modelling Group	Country	Spatial Resolution	
				Mesh (Long x Lat)	~ km over UK
CCSM3	NCCCSM	National Centre for Atmospheric Research	USA	Gaussian 256 x 128	140 x 140
CNRM-CM3	CNCM3	Météo-France / Centre National de Recherches Météorologiques	France	Gaussian 128 x 64	280 x 280
CSIRO-Mk3.0	CSMK3	CSIRO Atmospheric Research	Australia	Gaussian 192 x 96	190 x 220
ECHAM5/ MPI-OM	MPEH5	Max Planck Institute for Meteorology	Germany	Gaussian 192 x 96	190 x 220
ECHO-G	ECHOG	Meteorological Institute of the University of Bonn, KMA meteorological inst., and M & D group	Germany / Korea	Gaussian 96 x 48	375 x 375
GFDL-CM2.0	GFCM20	Geophysical Fluid Dynamics Laboratory	USA	Regular 144 x 90	250 x 200
GFDL-CM2.1	GFCM21	Geophysical Fluid Dynamics Laboratory	USA	Regular 144 x 90	250 x 200
GISS-ER	GIER	NASA / Goddard Institute for Space Studies	USA	Regular 72 x 46	500 x 390
INM-CM3.0	INCM3	Institute for Numerical Mathematics	Russia	Regular 72 x 45	500 x 400
IPSL-CM4	IPCM4	Institut Pierre Simon Laplace	France	Regular 96 x 72	375 x 250
MIROC3.2 (medres)	MIMR	National Institute for Environmental Studies, and Frontier Research Centre for Global Change	Japan	Gaussian 128 x 64	280 x 280
PCM	NCPCM	National Centre for Atmospheric Research	USA	Gaussian 128 x 64	280 x 280
UKMO-HADCM3	HADCM3	UK Met. Office	UK	Regular 96 x 73	375 x 250

Table 1 GCMs considered in this study. More details at http://www-pcmdi.llnl.gov. GCM grid-boxes with less than 50% land were excluded and no re-gridding was performed.

Catchment	Area (km^2)	River gauge	Observation boreholes
Upper Kennet	448		Hackpen Cottages, Manton House, Membury House
Lower Kennet	454	Theale	Great Park Farm, Old Hat, Whitehouse
Lambourn	228	Shaw	Faarn Combe, Prebendal Farm
Pang	158	Pangbourne	Banterwick Barn, Everington House, Peasemore
Chilterns	386		Gallowstree Common, Mapledurham, Stonor Park, Well Place, Woodbarn Farm
Wye	152	Hedsor	

Table 2 Catchment summary

		Manton House	Old Hat	Banterwick Barn	Stonor Park
March	Historic mean for month	132.87	95.99	91.22	89.06
	Ensemble average of the simulated monthly means	133.27	96.60	90.78	86.71
	Bootstrapped 95% confidence interval on ensemble average	132.89 - 133.64	96.04 - 97.18	89.91 - 91.86	85.43 - 88.58
October	Historic mean for month	128.97	90.72	87.52	84.74
	Ensemble average of the simulated monthly means	128.70	90.41	86.66	82.07
	Bootstrapped 95% confidence interval on ensemble average	128.61 - 128.83	90.20 - 90.67	85.94 - 87.53	80.91 - 83.65

Table 3 Bootstrapped 95% confidence intervals on the average of the ensemble of simulated monthly mean groundwater levels

Figures

Colour figures for reproduction on web and in print.

Figure 1 Topographic map of the Marlborough and Berkshire Downs and South-West Chilterns showing lower drainage density over the higher ground correlating with the unconfined Chalk

Figure 2 Simplified geological map of study area showing Chalk outcrop in the north and west of the region, which are overlain by unconsolidated Palaeogene deposits as the Chalk dips to the south-east into the London Basin.

Figure 3 Land-use map showing higher percentage of broad-leaved woodland in the Chilterns compared to the Marlborough and Berkshire Downs and the higher density of urban development in the south-east.

Figure 4 Distribution of mean potential recharge for the baseline period (1971-2003) simulated by the ZOODRM model and contours of mean observed groundwater level illustrating the discharge of groundwater to the rivers and Chalk scarp slope springs in the north and west.

Figure 5 Locations of observation boreholes, river flow gauging stations and catchments for recharge assessment

Figure 6 Comparison between simulated and observed groundwater level at Gallowstree Common observation borehole

Figure 7 Projected changes in monthly precipitation, temperature and potential evapotranspiration by GCMs for the Marlborough and Berkshire Downs and South-West Chilterns for the 2080s under the A2 emissions scenario

Figure 8 Percentage change in mean catchment potential recharge for each GCM

Figure 9 Distribution of the number of GCM scenarios in which more than a 10% decrease in potential recharge is simulated

Figure 10 Percentage change in mean river baseflow for each GCM

Figure 11 Change in mean groundwater level at observation boreholes for each GCM

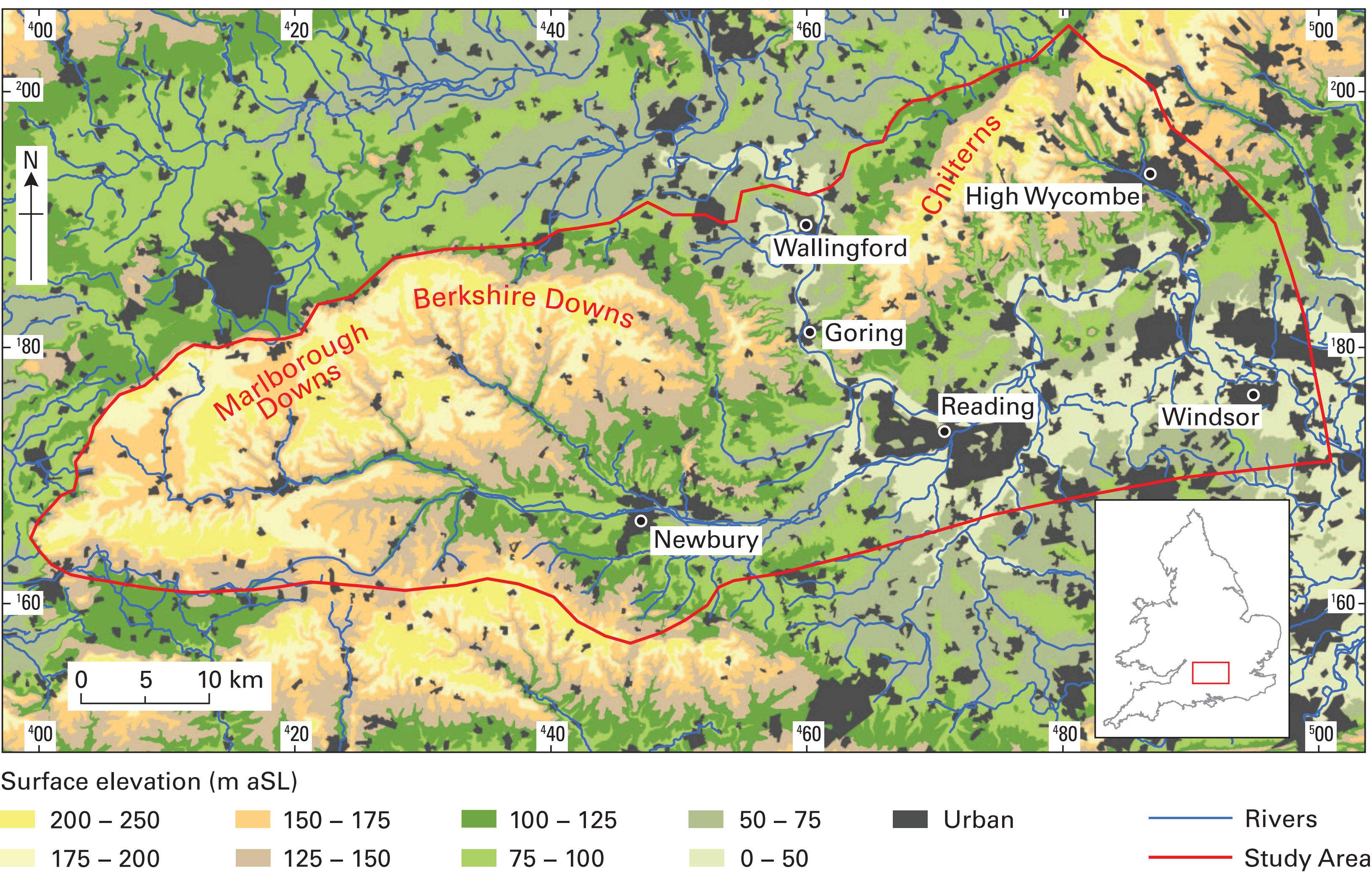
Figure 12 Simulated historic, future and ensemble average monthly mean catchment potential recharge

Figure 13 Simulated historic, future and ensemble average monthly mean river baseflow at gauging stations

Figure 14 Change in monthly mean catchment potential recharge and river baseflow as described by the average of the ensemble of simulations

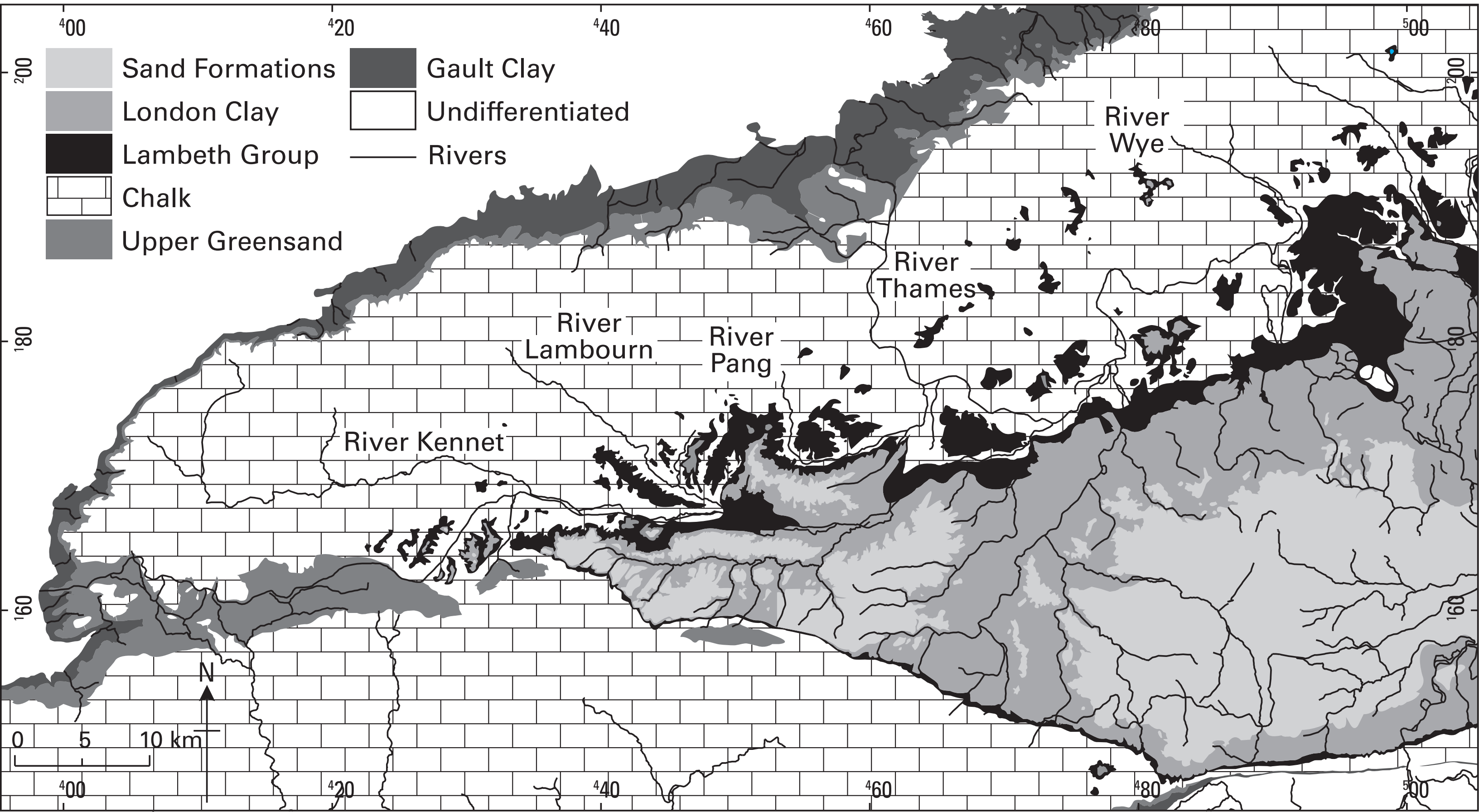
Figure 15 Simulated historic and future monthly mean groundwater levels at selected observation boreholes

Figure 1



400
420
440
460
500
200
180
160
480
N
Marlborough Downs
Berkshire Downs
Chilterns
High Wycombe
Wallingford
Goring
Reading
Windsor
Newbury
0
5
10 km
Surface elevation (m aSL)
200 – 250
175 – 200
150 – 175
125 – 150
100 – 125
75 – 100
50 – 75
0 – 50
Urban
Rivers
Study Area

Figure 2



Sand Formations
London Clay
Lambeth Group
Chalk
Upper Greensand
Gault Clay
Undifferentiated
Rivers
River Wye
River Thames
River Lambourn
River Pang
River Kennet
N
0
5
10 km
400
420
440
460
480
500
200
180
160

Figure 3

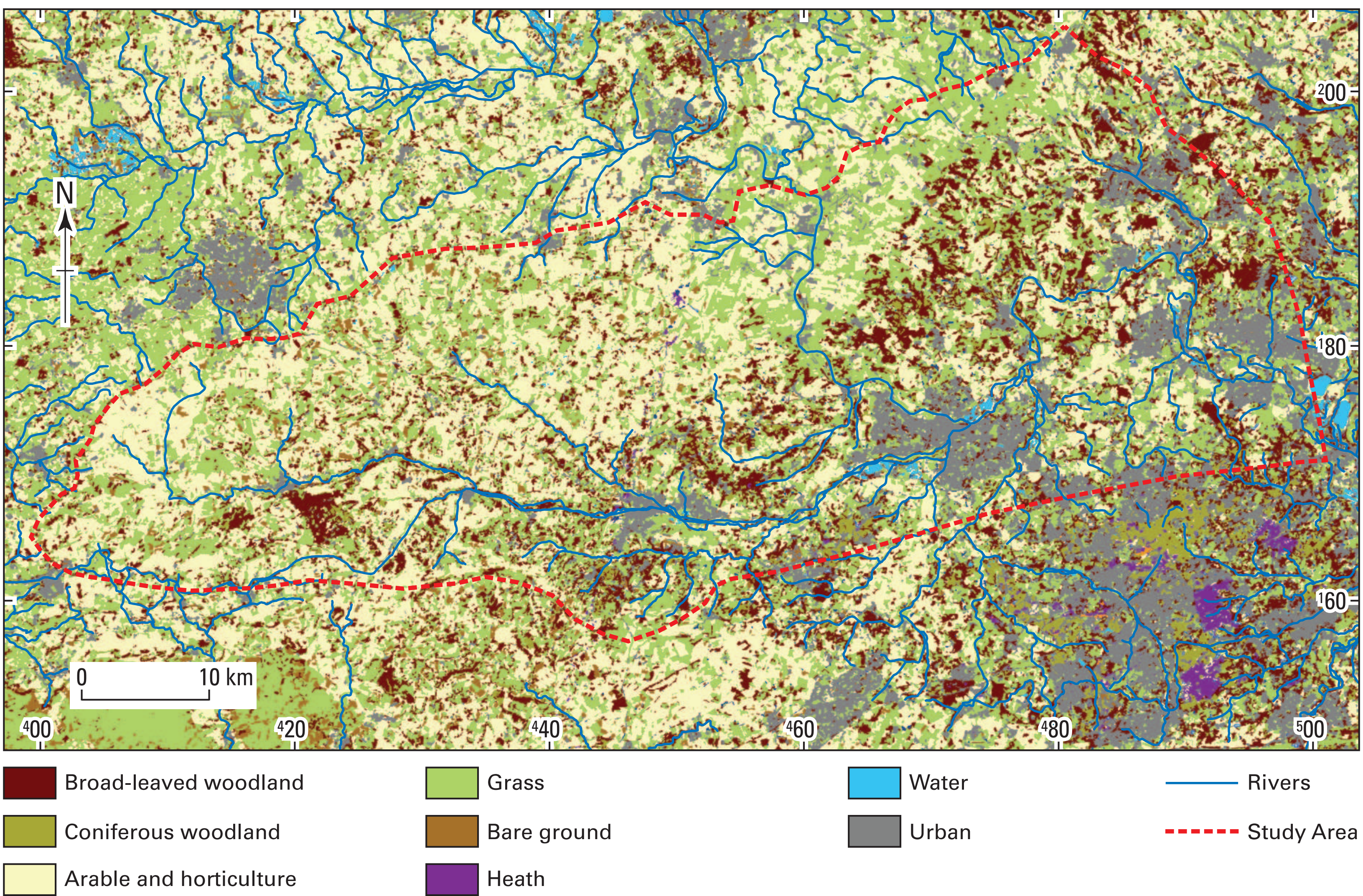

N
0
10 km
400
420
440
460
480
500
200
180
160
Broad-leaved woodland
Coniferous woodland
Arable and horticulture
Grass
Bare ground
Heath
Water
Urban
Rivers
Study Area

Figure 4

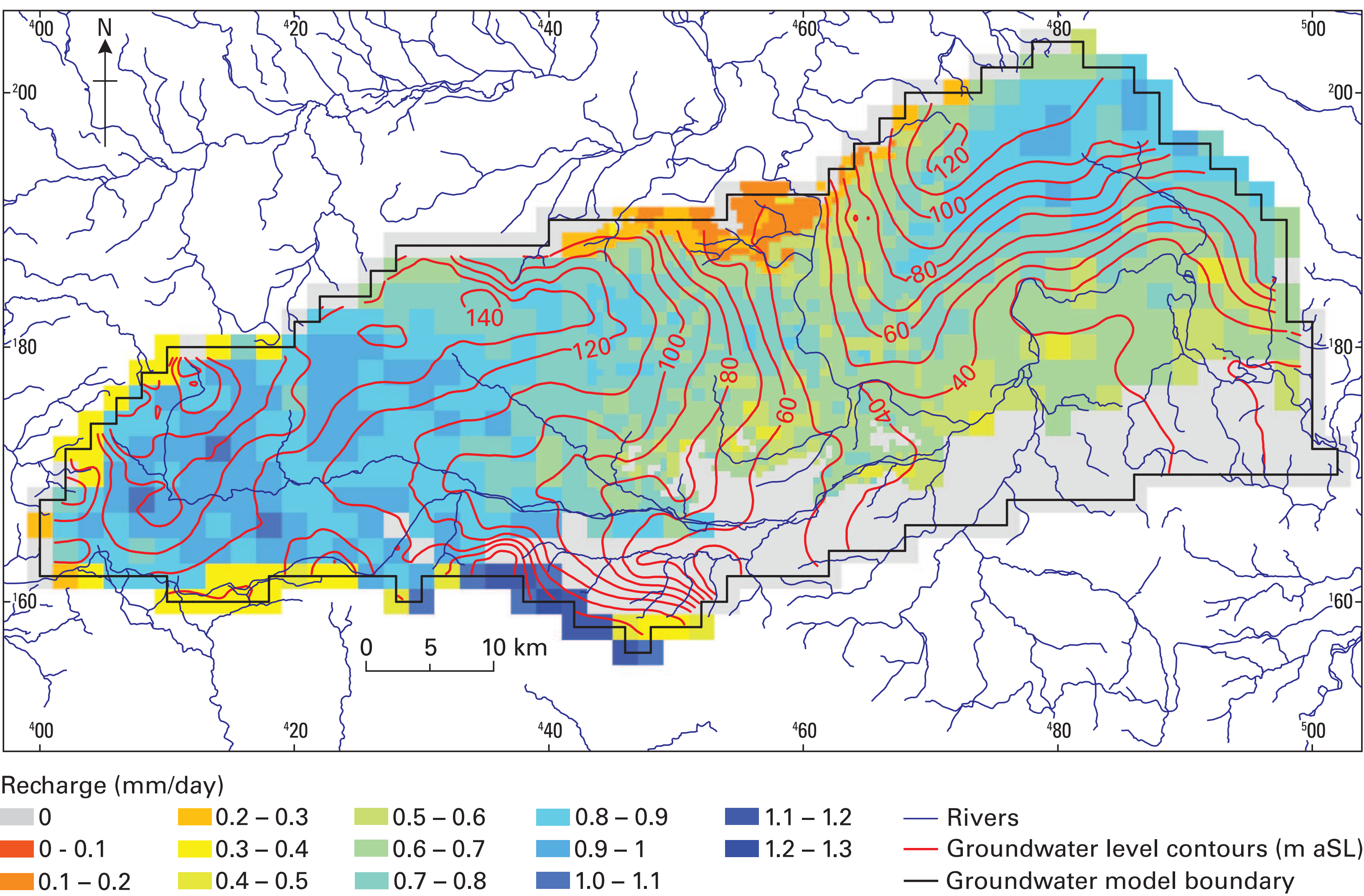
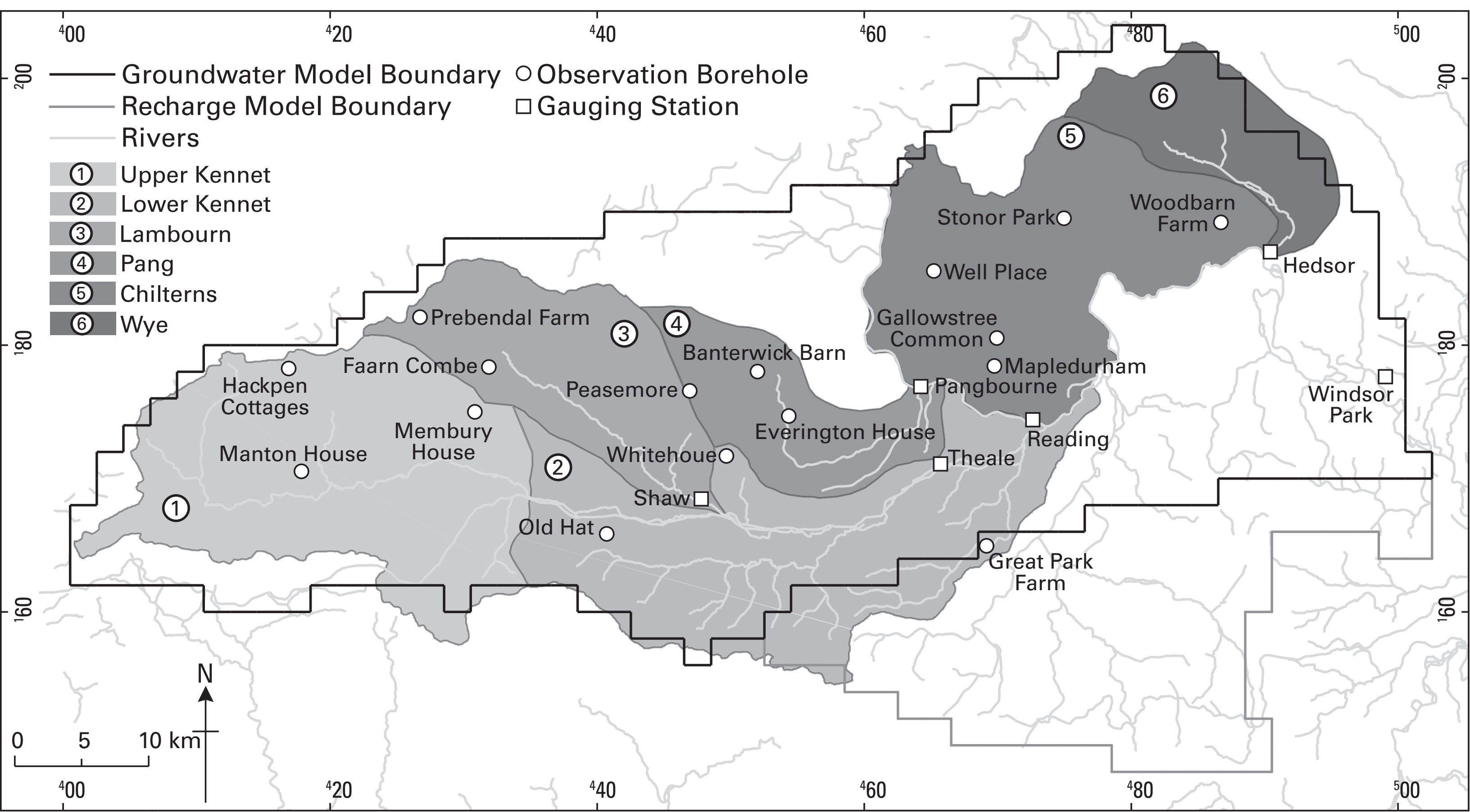
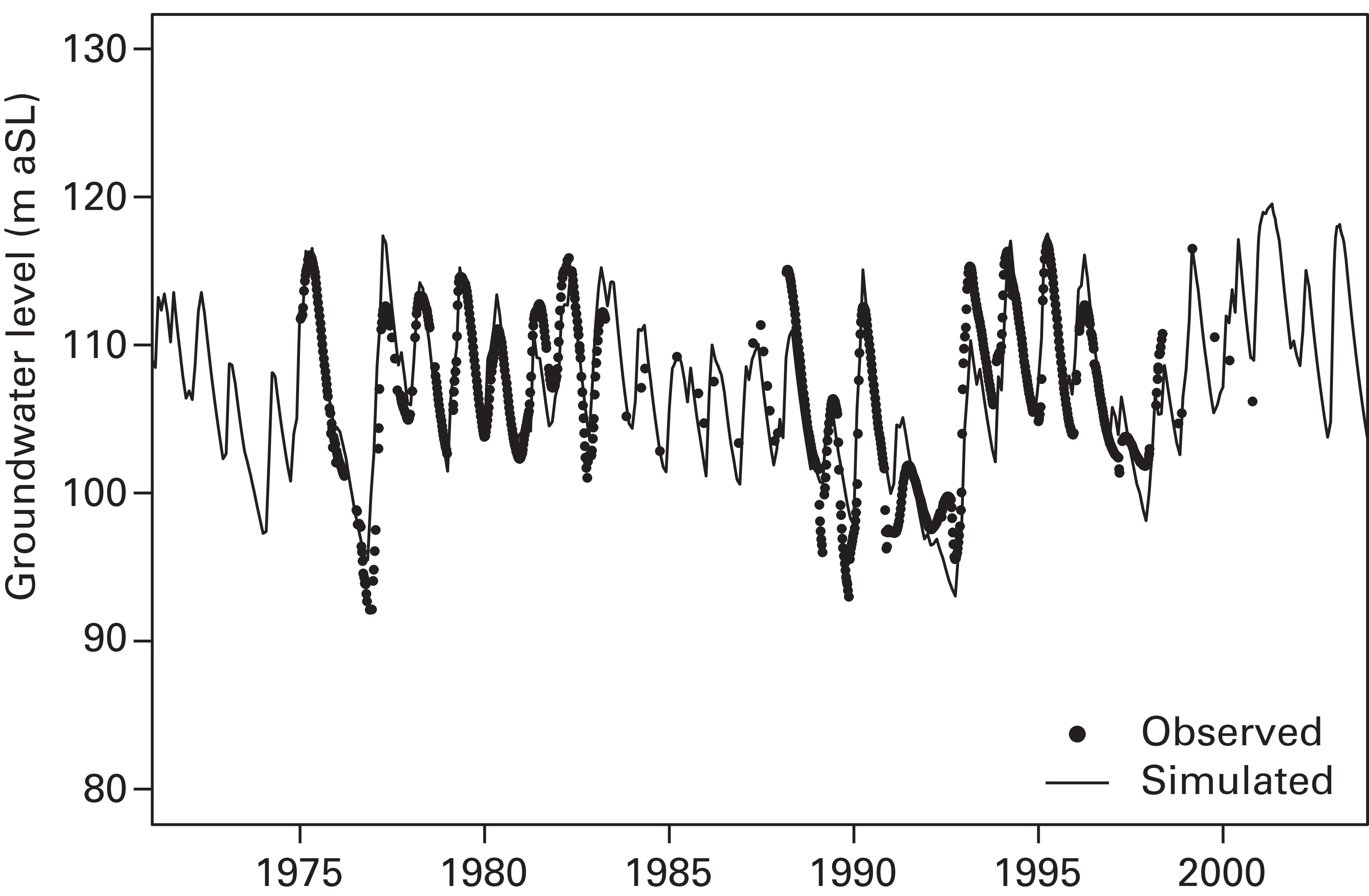

N
400
420
440
460
480
500
200
180
160
140
120
100
80
60
40
0 5 10 km
Recharge (mm/day)
0
0 - 0.1
0.1 – 0.2
0.2 – 0.3
0.3 – 0.4
0.4 – 0.5
0.5 – 0.6
0.6 – 0.7
0.7 – 0.8
0.8 – 0.9
0.9 – 1
1.0 – 1.1
1.1 – 1.2
1.2 – 1.3
Rivers
Groundwater level contours (m aSL)
Groundwater model boundary

Figure 5



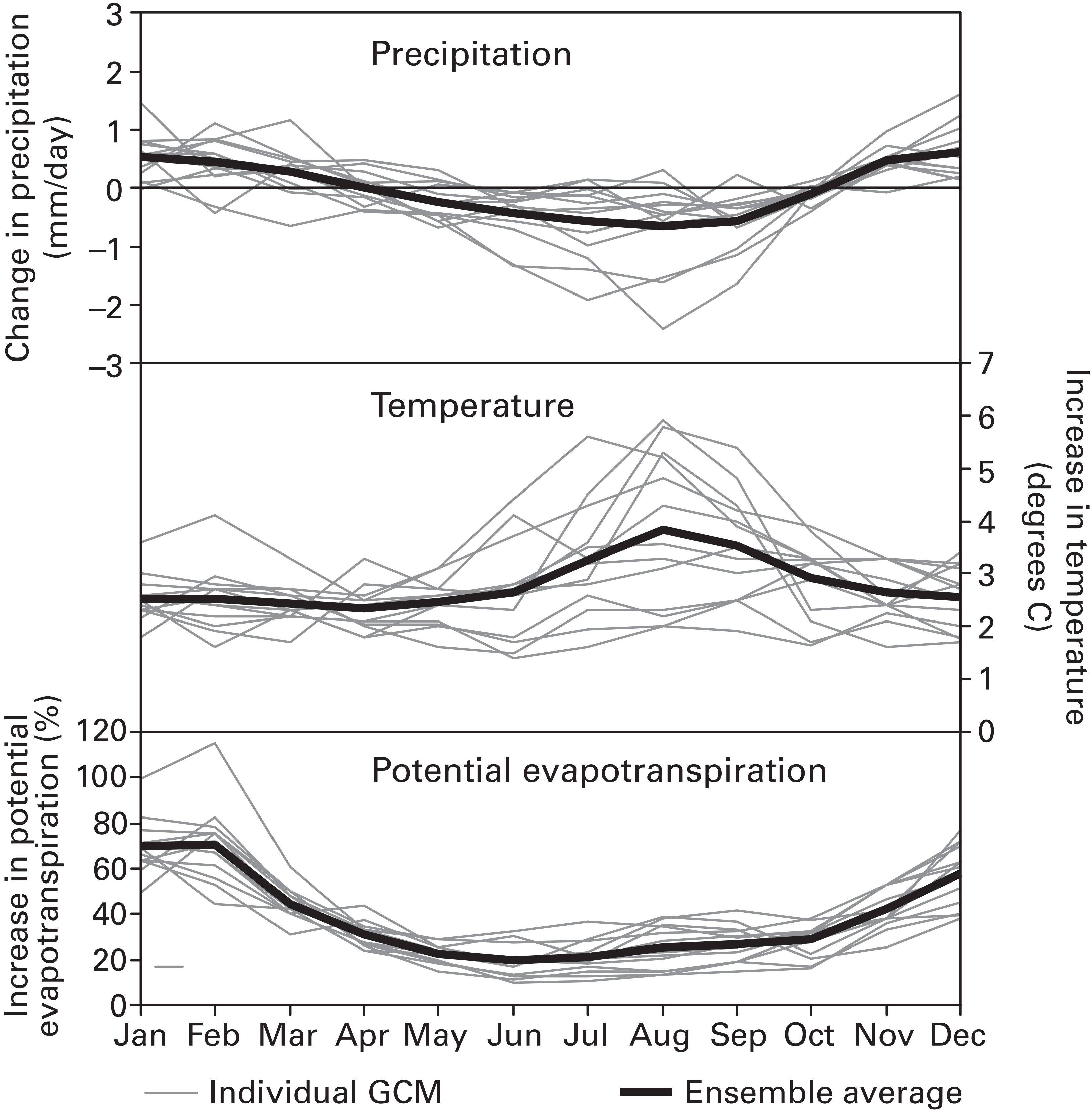
Groundwater Model Boundary
Observation Borehole
Recharge Model Boundary
Gauging Station
Rivers
1 Upper Kennet
2 Lower Kennet
3 Lambourn
4 Pang
5 Chilterns
6 Wye
400
420
440
460
480
500
200
180
160
Hackpen Cottages
Manton House
Faarn Combe
Membury House
Prebendal Farm
Peasemore
Banterwick Barn
Everington House
Whitehoue
Shaw
Old Hat
Stonor Park
Woodbarn Farm
Well Place
Hedsor
Gallowstree Common
Mapledurham
Pangbourne
Theale
Reading
Windsor Park
Great Park Farm
N
0 5 10 km

Figure 6



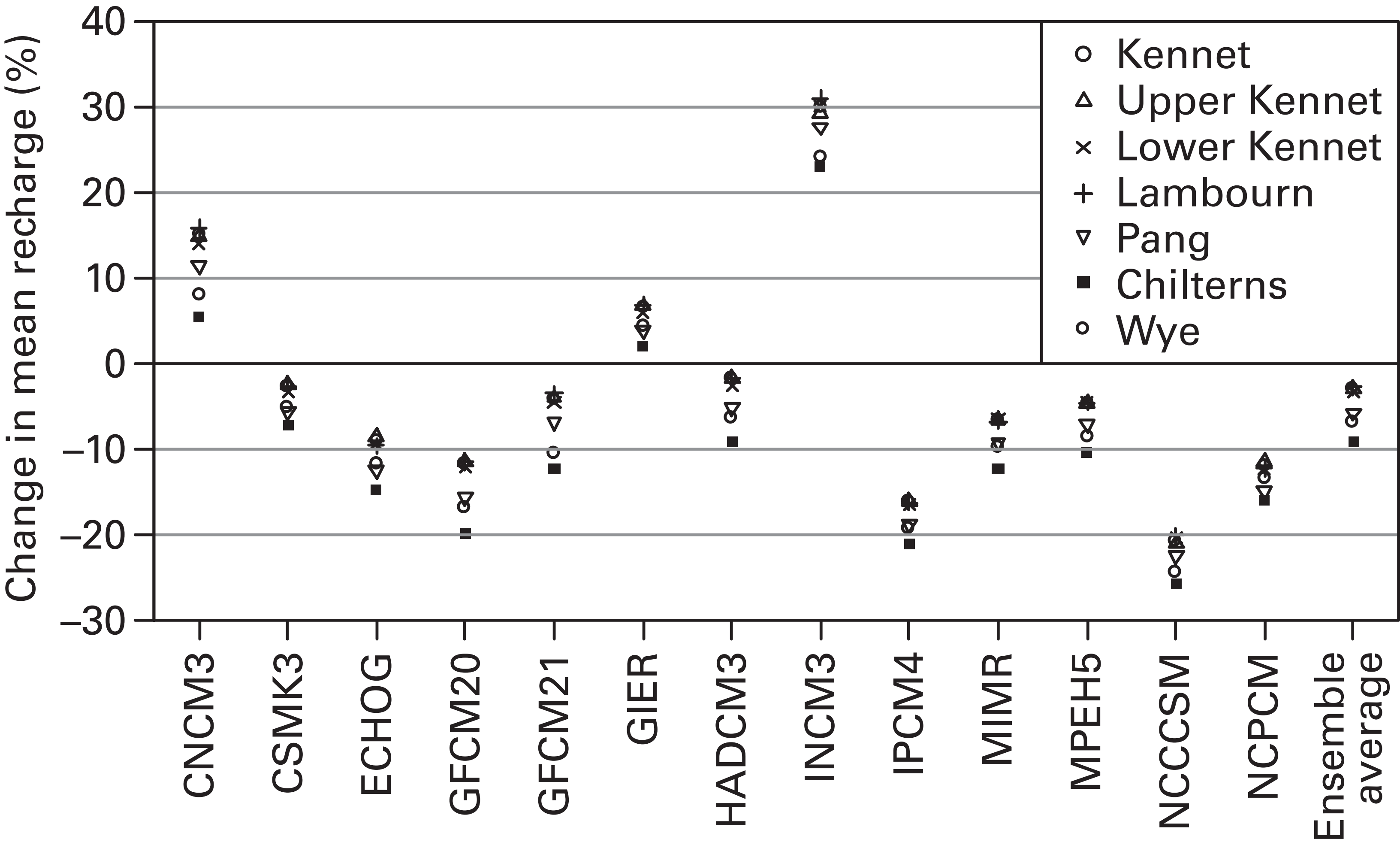
130
120
110
100
90
80
Groundwater level (m aSL)
1975
1980
1985
1990
1995
2000
Observed
Simulated

Figure 7



Precipitation
Change in precipitation (mm/day)
3
2
1
0
–1
–2
–3
Temperature
Increase in temperature (degrees C)
7
6
5
4
3
2
1
0
Potential evapotranspiration
Increase in potential evapotranspiration (%)
120
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Individual GCM
Ensemble average

Figure 8



40
30
20
10
0
−10
−20
−30
Change in mean recharge (%)
Kennet
Upper Kennet
Lower Kennet
Lambourn
Pang
Chilterns
Wye
CNCM3
CSMK3
ECHOG
GFCM20
GFCM21
GIER
HADCM3
INCM3
IPCM4
MIMR
MPEH5
NCCCSM
NCPCM
Ensemble average

Figure 9

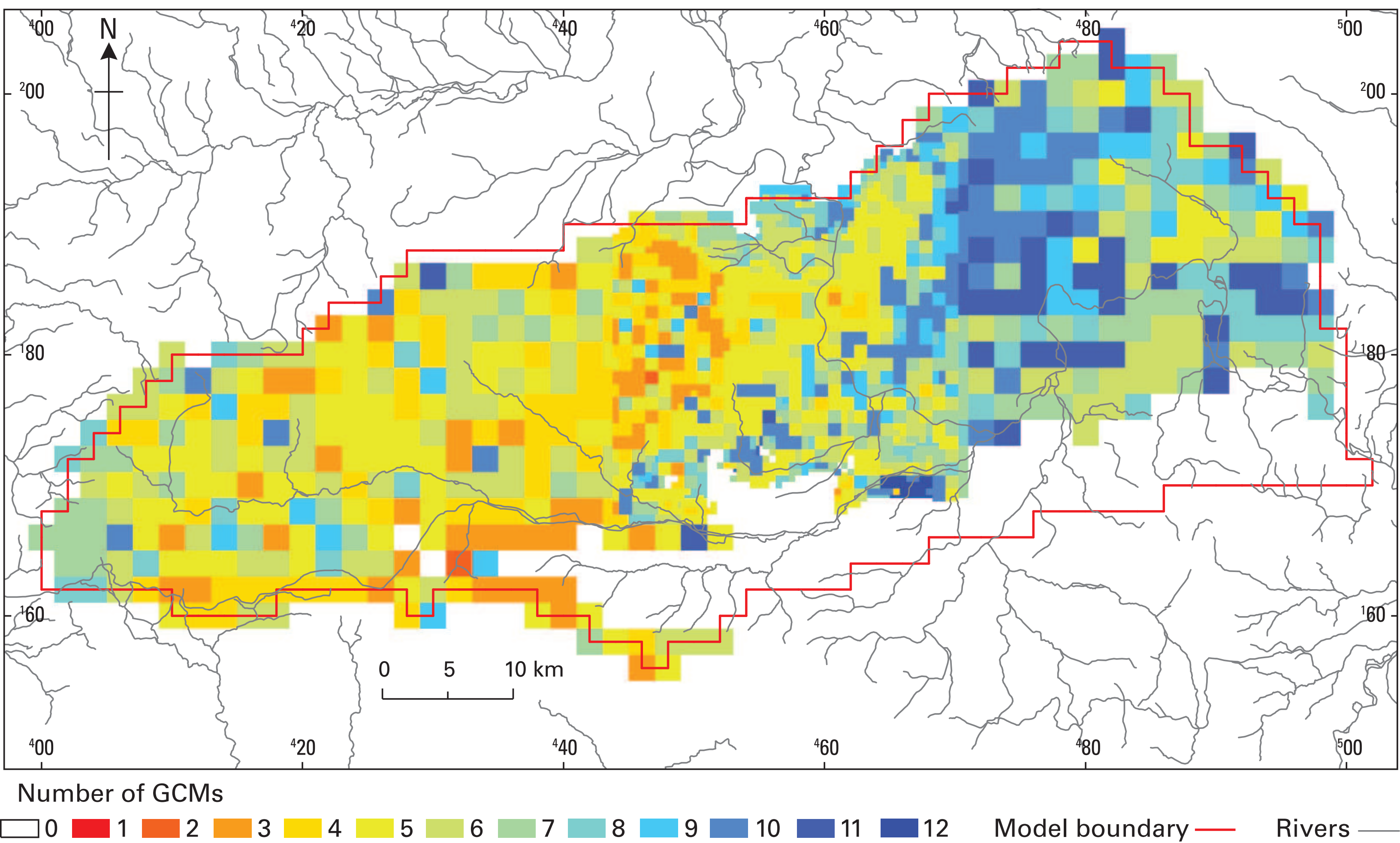

N
400
420
440
460
480
500
200
180
160
0
5
10 km
Number of GCMs
0
1
2
3
4
5
6
7
8
9
10
11
12
Model boundary
Rivers

Figure 10

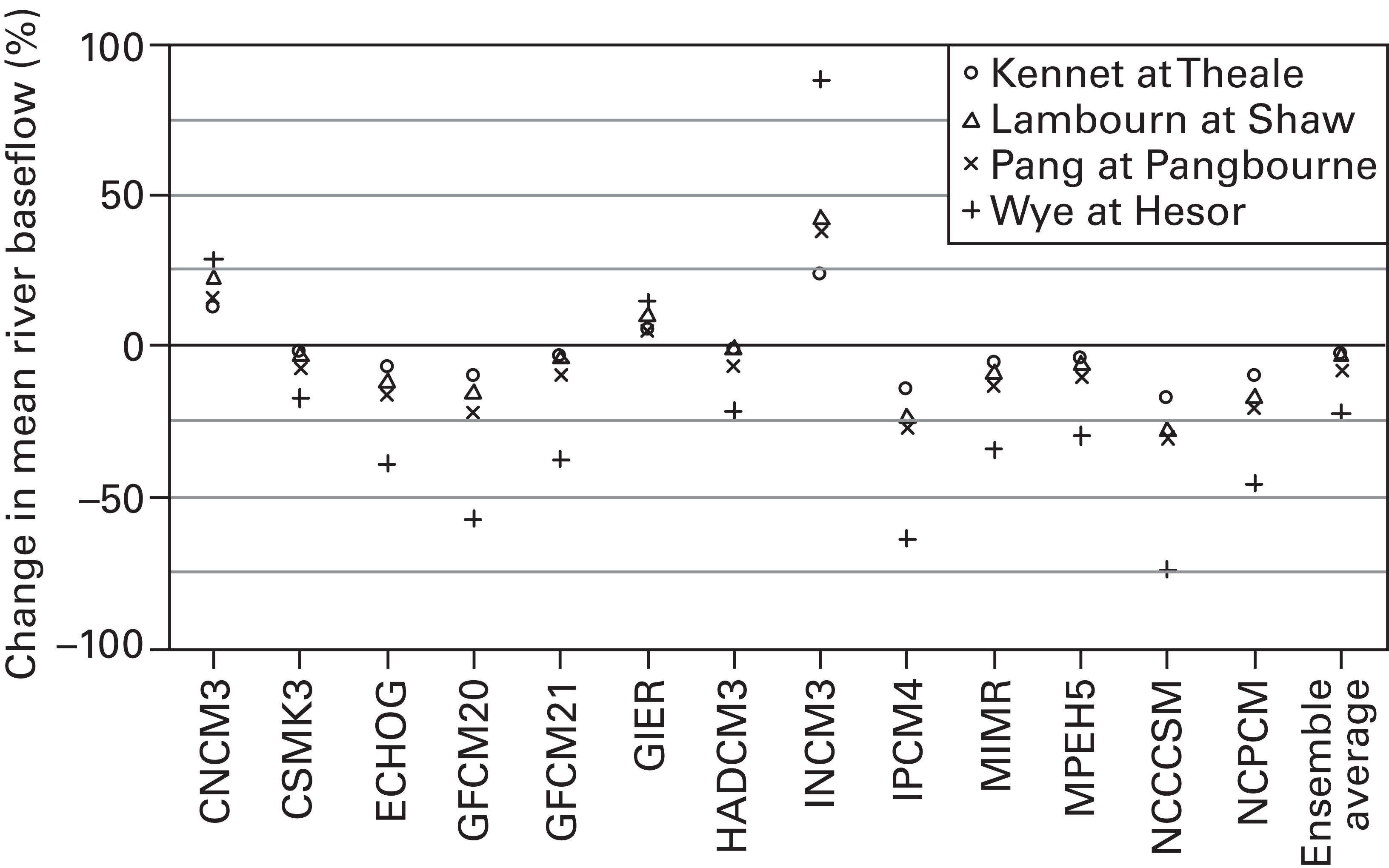

Change in mean river baseflow (%)
100
50
0
−50
−100
Kennet at Theale
Lambourn at Shaw
Pang at Pangbourne
Wye at Hesor
CNCM3
CSMK3
ECHOG
GFCM20
GFCM21
GIER
HADCM3
INCM3
IPCM4
MIMR
MPEH5
NCCCSM
NCPCM
Ensemble average

Figure 11

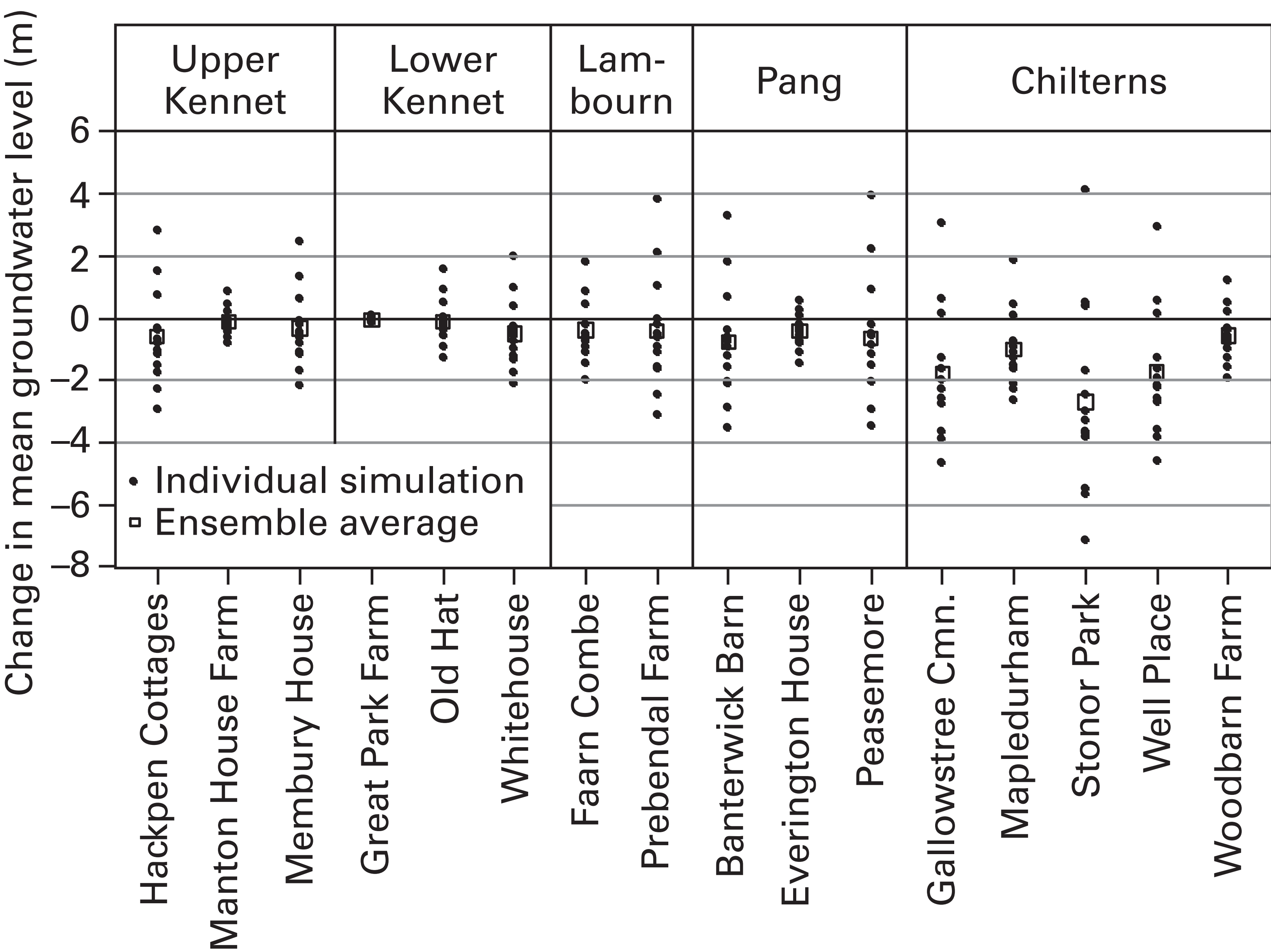
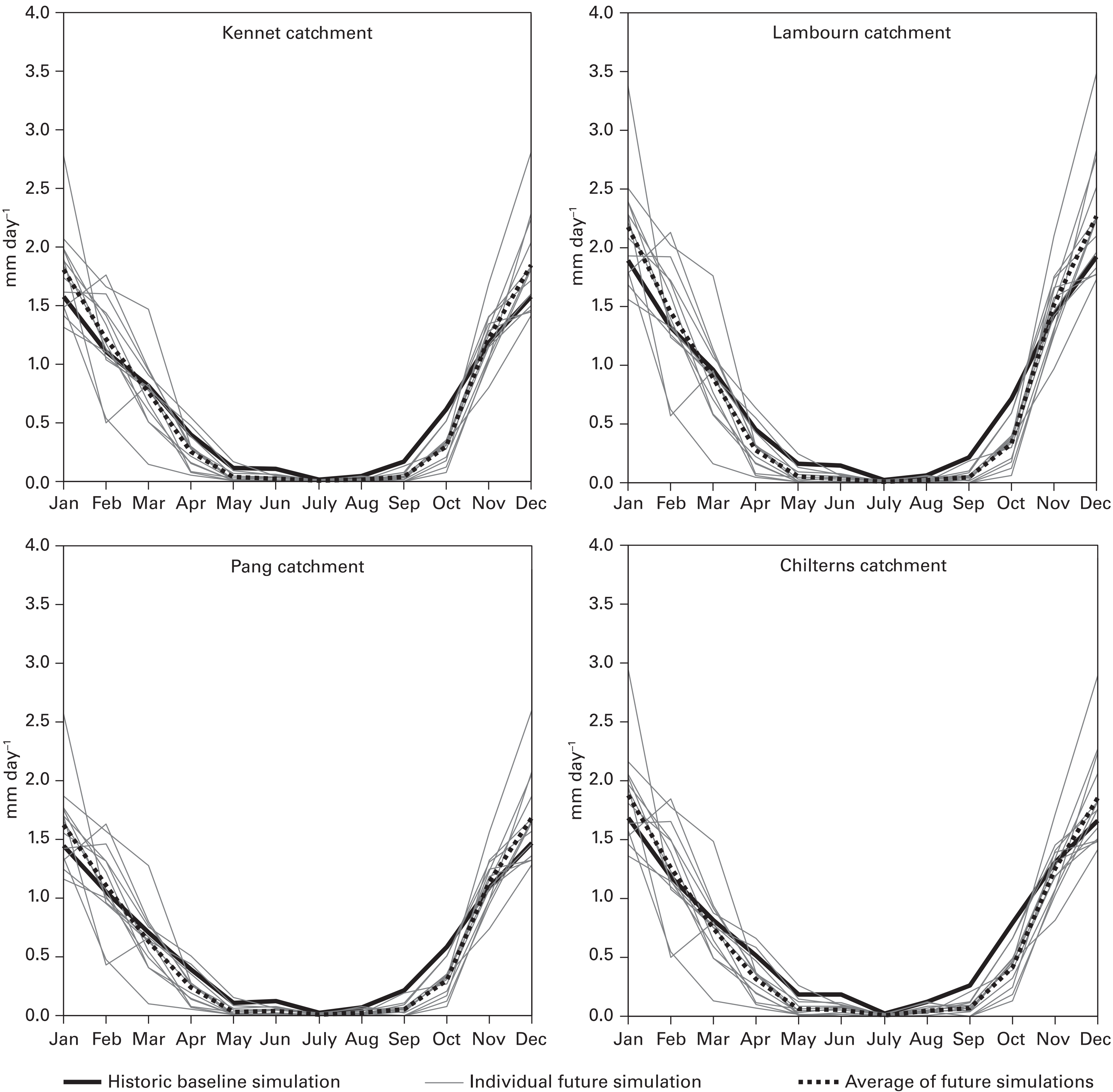

Change in mean groundwater level (m)
Upper Kennet
Lower Kennet
Lam-bourn
Pang
Chilterns
6
4
2
0
−2
−4
−6
−8
• Individual simulation
□ Ensemble average
Hackpen Cottages
Manton House Farm
Membury House
Great Park Farm
Old Hat
Whitehouse
Faarn Combe
Prebendal Farm
Banterwick Barn
Everington House
Peasemore
Gallowstree Cmn.
Mapledurham
Stonor Park
Well Place
Woodbarn Farm

Figure 12



Kennet catchment
Lambourn catchment
Pang catchment
Chilterns catchment
mm day⁻¹
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec
Historic baseline simulation
Individual future simulation
Average of future simulations

Figure 13

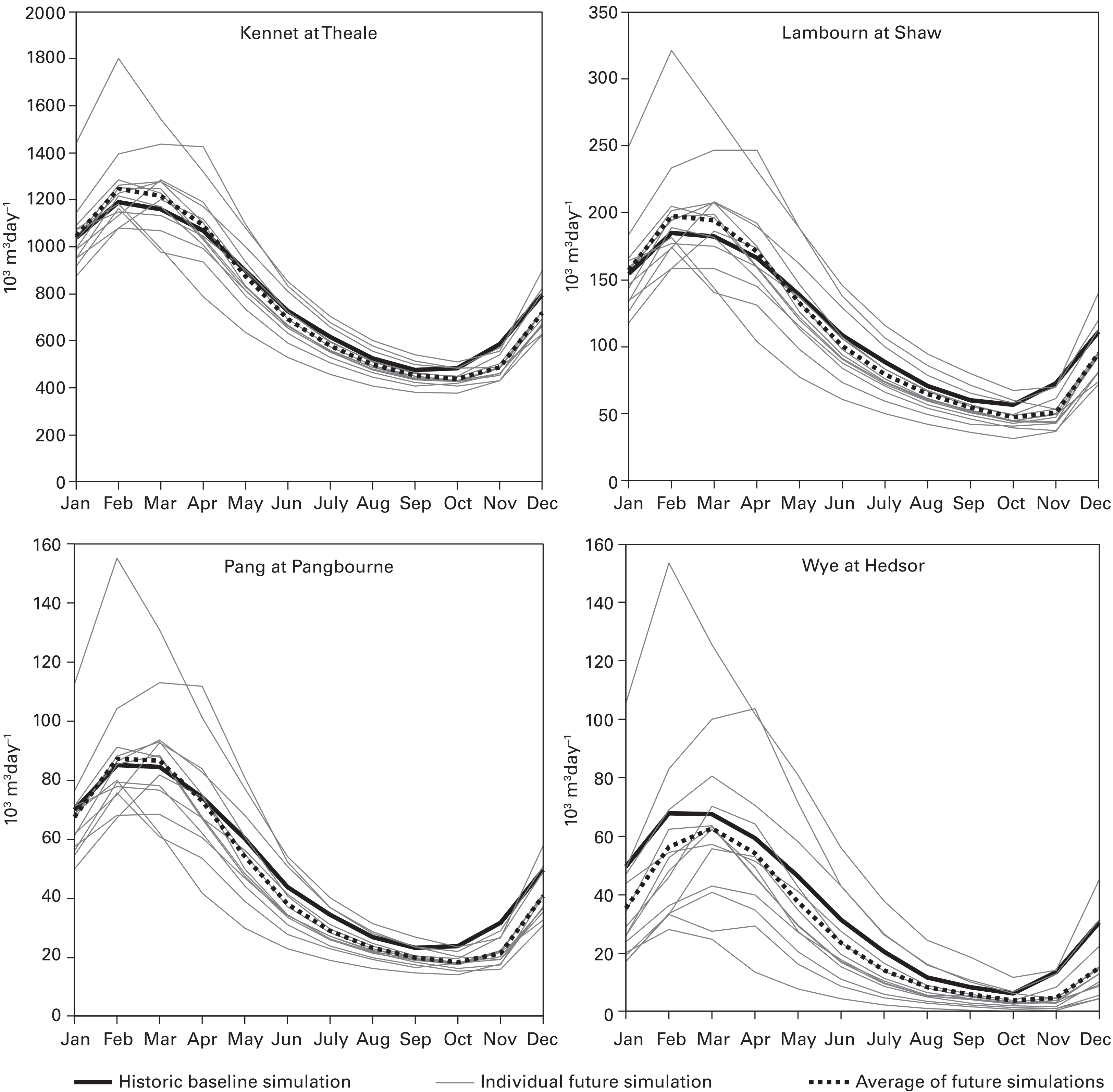
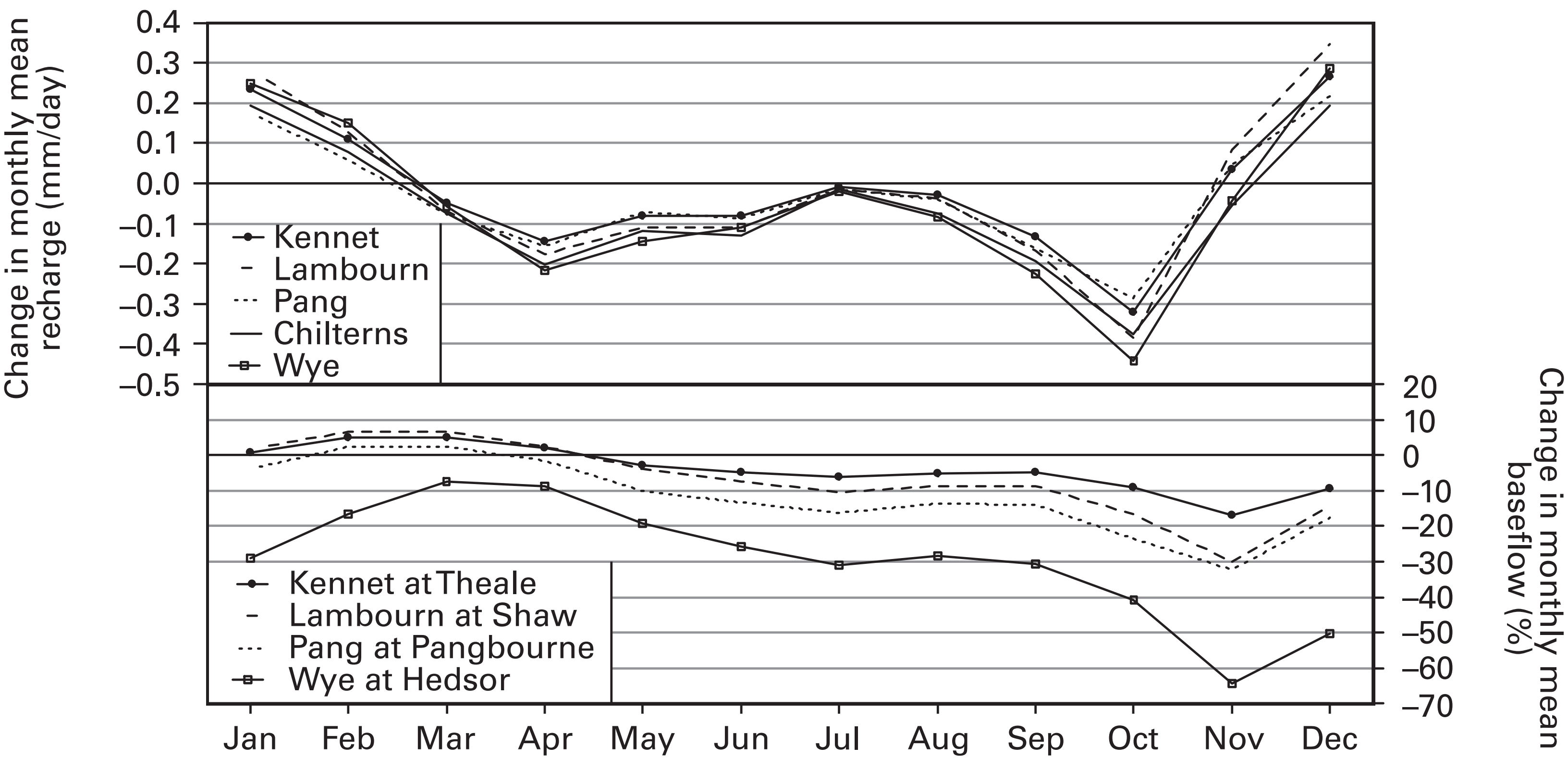
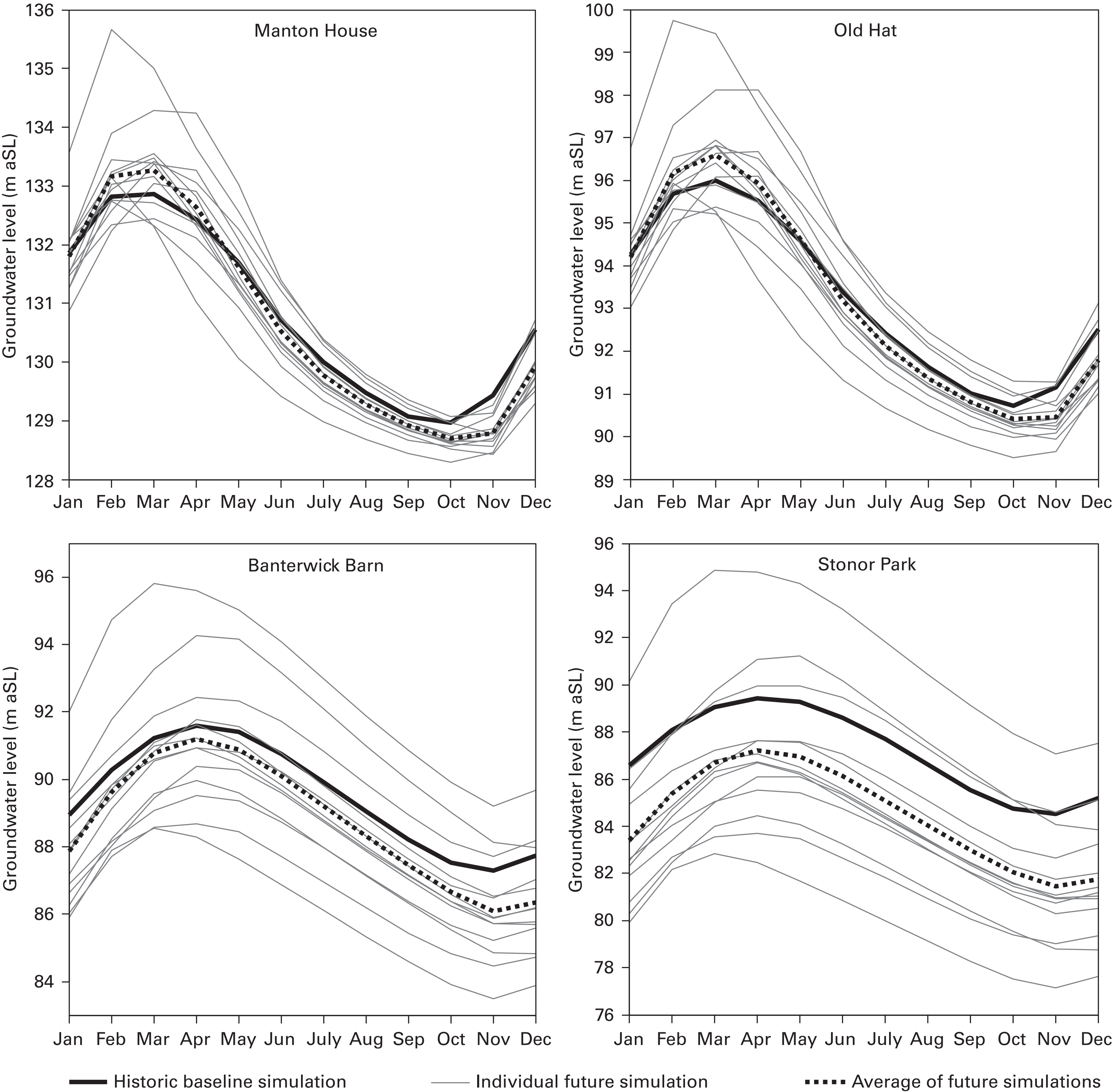

Kennet at Theale
Lambourn at Shaw
Pang at Pangbourne
Wye at Hedsor
10³ m³day⁻¹
2000
1800
1600
1400
1200
1000
800
600
400
200
0
350
300
250
200
150
100
50
160
140
120
100
80
60
40
20
Jan Feb Mar Apr May Jun July Aug Sep Oct Nov Dec
Historic baseline simulation
Individual future simulation
Average of future simulations

Figure 14



Change in monthly mean recharge (mm/day)
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
Kennet
Lambourn
Pang
Chilterns
Wye
20
10
0
−10
−20
−30
−40
−50
−60
−70
Change in monthly mean baseflow (%)
Kennet at Theale
Lambourn at Shaw
Pang at Pangbourne
Wye at Hedsor
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 15


Manton House
Old Hat
Banterwick Barn
Stonor Park
Groundwater level (m aSL)
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec
Historic baseline simulation
Individual future simulation
Average of future simulations