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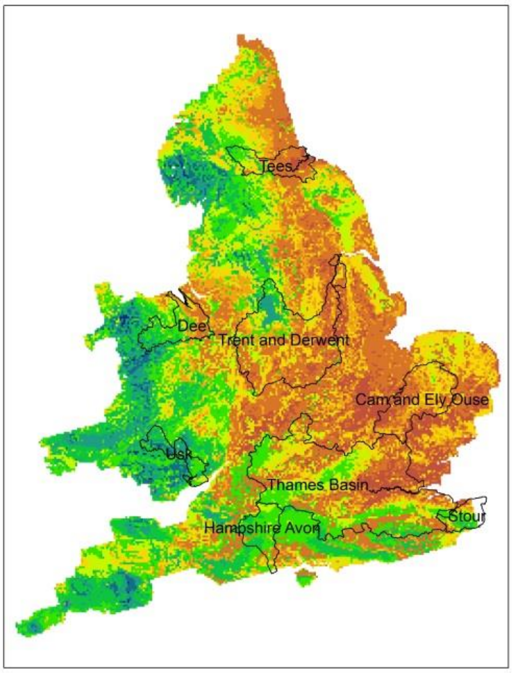
Land Use, Climate Change and Water Availability: Preliminary modelling of impacts of climate change and land use change on groundwater recharge for England and Wales

Groundwater Programme

External Report OR/14/018



BRITISH GEOLOGICAL SURVEY

GROUNDWATER PROGRAMME

EXTERNAL REPORT OR/14/018

Land Use, Climate Change and Water Availability: Preliminary modelling of impacts of climate change and land use change on groundwater recharge for England and Wales

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Summary

To investigate how land use and climate change can affect potential recharge, rainfall and temperature data from 11 Regional Climate Models (RCMs) from the Future Flow and Groundwater Level (FFGWL) project have been fed into the recharge model ZOODRM. This has produced potential recharge for the whole of England and Wales for three time slices (2020s, 2050s and 2080s). Allied to this, the historic rainfall and potential evaporation time series have been run for both historic and "extreme assumed" land use change. The recharge model was run using different land cover mapping (LCM) datasets (LCM2000 and LCM2007) as well as three scenarios: all arable, all grass and all forested. A more subtle change in land use was investigated by swapping 50% of one land use for another, e.g. arable to forested.

This work has been undertaken as part of the Abstraction Reform (AR) process, a Defra led process which aims to produce a revised abstraction licencing regime. To provide consistency with the AR process the catchments used in the AR pilot study have been used (Dee, Ely-Ouse, Hampshire Avon, Stour, Tees, Trent and Derwent). In addition, the Thames Basin has been added and the results summarised for England and Wales. The results for the Thames Basin produced anomalous values which were thought to be related to the size, shape and orientation of the catchment. To investigate the impact of orientation, then two east-west and two north-south strips were also examined. The results have been presented as both difference maps of long-term average recharge and box and whisker plots for both the absolute values of recharge and the differences between the modified run and its basecase (historical simulation).

The catchments chosen have a range of sizes and are located in different climate conditions around the country. The response to climate change reflects this with recharge decreasing or increasing depending on the RCM used for the input data and time slice. The following generalisations by catchment can be made:

- Dee – lower recharge in general with increasing recharge through the time slices
- Ely-Ouse – very slight increase in recharge which increases through the time slices
- Hampshire Avon –variation depending on the RCM; no significant change across the time slices
- Stour – reduction in recharge
- Tees – reduction in recharge which decreases through time slices
- Thames – variation depending on the RCM; significant outliers with increased recharge in the 2080s
- Trent – variation depending on the RCM; increased recharge through the time slices
- Usk – increased recharge; consistent over time slices

In terms of the effect of land use change then variation due to subtle 'real changes' in historic land use (between LCM 2000 and LCM 2007) is small, although locally significant. Extremes of land use change are predicted to result in significant change but these scenarios are very unlikely to be realised. For the Dee, Hampshire Avon, Tees and the Usk the change in recharge due to land use change and due to climate change is comparable, for the Ely-Ouse and Trent the change in recharge less due to land use change than for climate change and for the Stour and England and Wales as a whole the change is greater. This was investigated further by swapping out different land use types, i.e. arable to forested. This showed much less variation, and was less significant in comparison with climate change.

The original question that the modelling work was to address relates to the relative changes in recharge with respect to climate change as opposed to land use change. Taking England and Wales as a whole then the order of change in recharge due to land use variation is: socio-economic land use (LCM2000 w.r.t. LCM2007) is less than spatial replacement is less than wholesale replacement (i.e. all one land use type for England and Wales). Comparing the

magnitude of these changes with those resulting from climate change show that variation of recharge related to climate change falls within the range of that resulting from land use change. However, the variation of recharge due to the use of different RCMs is comparable with the overall variation of land use change.

Further work is recommended as follows:

- Understand the climate models used to feed into the FFGWL RCMs alongside an improved representation of droughts resulting from “blocking highs” – slow moving pressure systems in the Atlantic.
- Use of National Ecosystem Assessment land use scenarios in the model to compare with the quantification of climate change runs.
- Combine the potential recharge produced with other recharge models (e.g. those produced for the Environment Agency by consultants or in the published literature) and/or produce water balances to help validate the recharge quantified.
- Undertake further analysis of the results, such as monthly summaries of potential recharge and analyse how this changes for each time slice and across catchments.
- Quantify the uncertainty in the results.

1 Background

1.1 INTRODUCTION

This report forms part of the Defra "Land-use climate change and water availability project Phase 2a" which has been funded by Defra, with co-funding provided by NERC via CEH and BGS. The project is a follow on project from the Environment Services to Sicen Partnership (ESSP) "Can land use and land management make a difference to water availability under conditions of climate change: A potential way forward?". The work was undertaken by Cranfield University, CEH and BGS. It was split into three work packages:

- Task A - Conduct a systematic review of the evidence for the interactions of land use climate change and water availability [undertaken by CEH]
- Task B - Develop a range of plausible future land use, land management and growing season changes [undertaken by Cranfield]
- Task C- Undertake initial quantification, including establishing the baseline [undertaken by Cranfield and BGS]

Each work package has reported separately, this is the report for the BGS component of Task C: Initial quantification. The work describes in this report compliments that undertaken by Cranfield University for Task C. Their work used a point model, WaSim to simulate runoff and baseflow for a variety of soil types and climate scenarios (Holman and Hess, 2014). The results of the work have been collated into a single, summary document.

1.2 WORK UNDERTAKEN

1.2.1 Introduction

The work undertaken was split into two parts:

- the impact of climate change on recharge at a catchment and national scale; and
- the impact of land use change on recharge at a national scale.

The recharge and runoff modelling work was undertaken for the whole of England and Wales (Figure 1) and results have also been extracted for the catchments which have been the subject of other Abstraction Reform work: the Usk, Trent and Derwent, Hampshire Avon, Ely-Ouse, Dee, Stour and Tees, as well as the Thames Basin (Figure 2). The land use change assessment was undertaken using land cover mapping (LCM) data. The recharge model ZOODRM was used for all the simulations.

1.2.2 Future Flow and Groundwater Level dataset

This project has relied on the datasets produced by the Future Flow and Groundwater Level (FFGWL) project which was funded by Environment Agency, UKWIR and Defra and was undertaken by CEH, BGS and Wallingford Hydro Solutions Ltd. As part of this project, datasets were developed based on 11 Regional Climate Model (RCM) results: Had-RM3 using A1B "medium" scenarios. However, the results from this model are produced at 25 km squares and are not spatially coherent. The FFGWL project has downscaled and bias corrected to produce daily 1 km^2 gridded datasets for Temperature, Precipitation and Potential Evaporation (Prudhomme et al., 2013). This produced eleven (a-k) model runs covering the period from 1950 to 2098 and whilst they don't include particular historically recorded events (e.g. the 1975/6 drought), they are representative of the climate during that period, and subsequent simulated climate evolution. Further information can be found at http://www.ceh.ac.uk/sci_programmes/water/futureflowsandgroundwaterlevels.html.

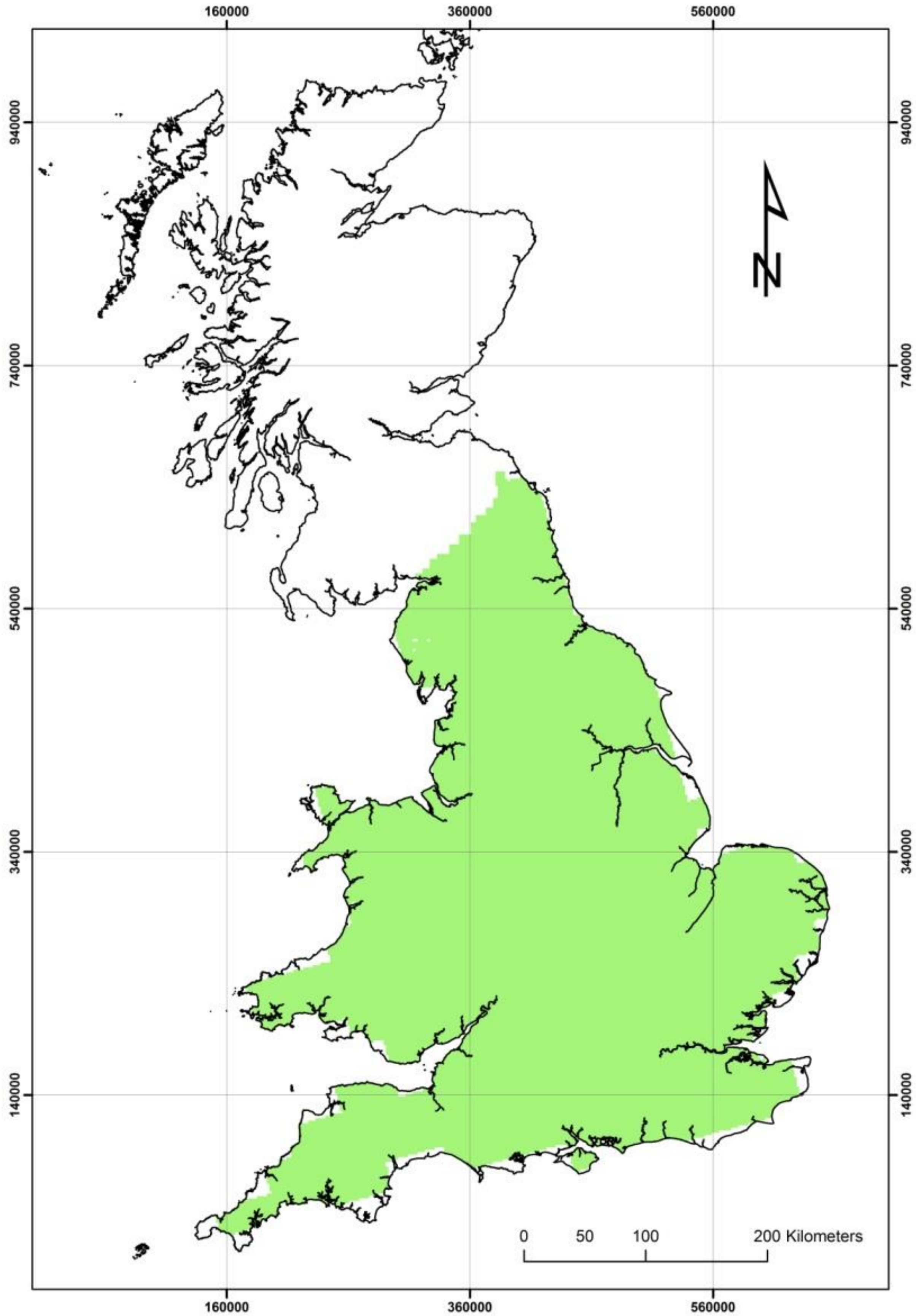


Figure 1. Extent of the area representing England and Wales

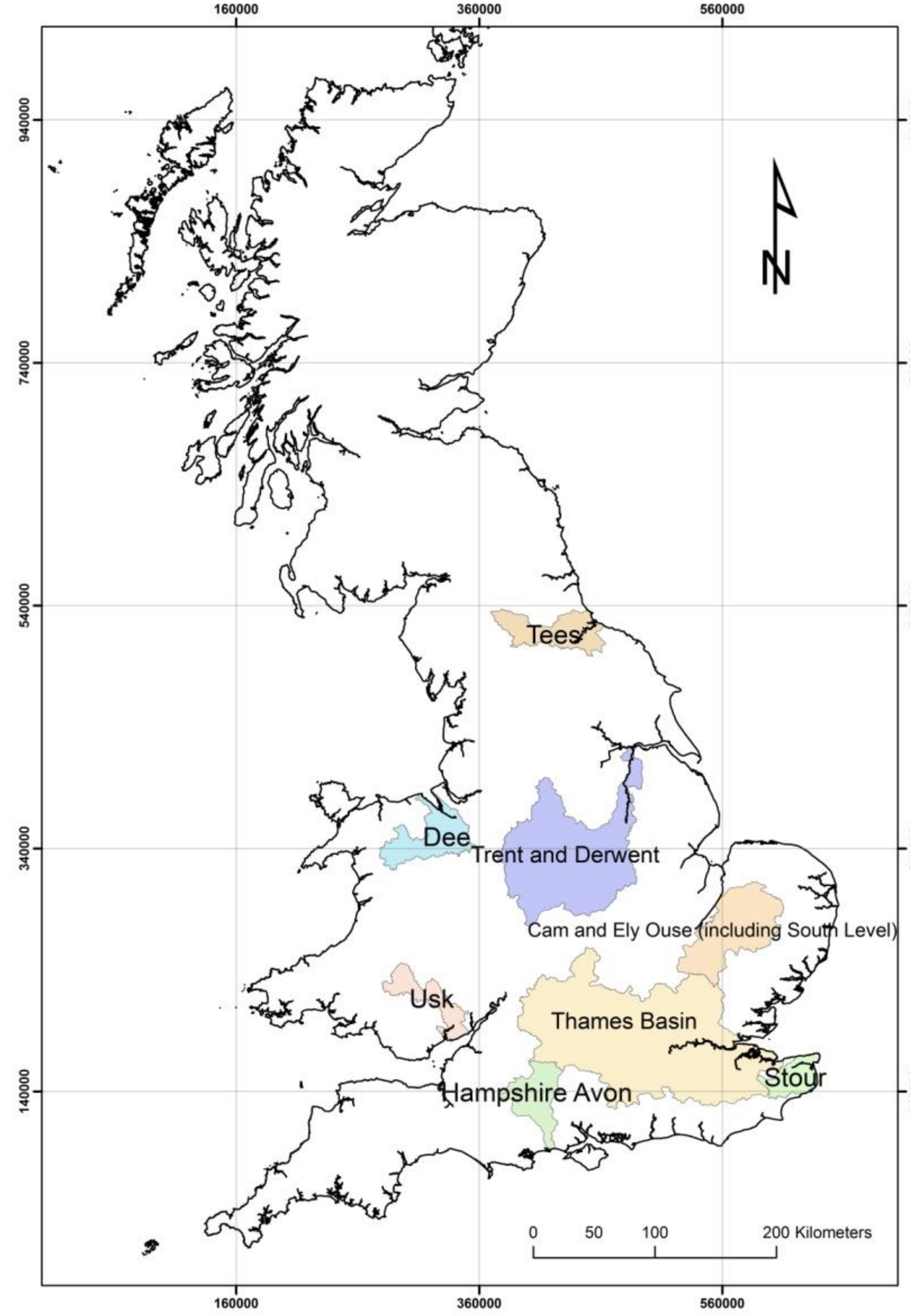


Figure 2. Locations of the eight catchment areas included in the study

2 Modelling approach adopted

2.1 INTRODUCTION

The distributed recharge model ZOODRM (Mansour et al., 2011) is used to calculate the soil moisture deficit and soil storage. ZOODRM belongs to the suite of object oriented models ZOOM (Jackson and Spink, 2004) developed at BGS. ZOODRM calculates distributed potential recharge values using rainfall and potential evaporation data, crop root constant, and soil characteristics such as the moisture content at field capacity and, moisture content at wilting. The recharge algorithm applied in this work is the simplified FAO method (Griffiths et al., 2006).

Whilst ZOODRM has been developed as a recharge model, for this project it has been used to calculate Hydrologically Effective Rainfall (HER). HER being defined as the component of rainfall left after actual evaporation has been taken off. The FAO56 method has been used to produce a surplus from the soil store, this is split into runoff and recharge using a runoff coefficient to define the ratio between the two.

Three sets of runs have been undertaken for this project: historical simulation, Climate Change using the FFGWL hydrology and land use change.

Table 1. Summary of data used for each set of runs.

Variable	Historical simulation	FFGWL	Land use change
Rainfall	Daily $1km^2$ gridded rainfall for January 1961 to December 2010	Daily $1km^2$ gridded rainfall appropriate climate runs from a-k for three time slices: 2020s, 2050s and 2080s	Same as for Hist. Sim.
Potential Evaporation	MORECS 40 x 40 km^2 monthly PE from January 1961 to December 2012	PE for appropriate climate runs from a-k for three time slices: 2020s, 2050s and 2080s	Same as for Hist. Sim.
Digital Elevation Model (DEM)	CEH DTM 50 m Resolution	Same as for Hist. Sim.	Same as for Hist. Sim.
Land Cover Map	LCM 2000 1 km Resolution	Same as for Hist. Sim.	Modified for each run.
Soil data	HOST soil data 1 km Resolution	Same as for Hist. Sim.	Same as for Hist. Sim.
Runoff coefficients	Calibrated, but distributed by geological outcrop	Same as for Hist. Sim.	Same as for Hist. Sim.
Crop coefficients	See Table for RAW/TAW	Same as for Hist. Sim.	Same as for Hist. Sim.

Further explanation of the data is provided in the section below.

2.2 DATA USED

2.2.1 Rainfall

Figure 3 shows the LTA rainfall distribution (1961-2008) across England and Wales. The UK has a Maritime Climate characterised by a predominantly westerly wind direction. This leads to a "conveyer" of frontal systems off the Atlantic which brings moisture preferentially to Wales and the West of England. Orographic effects (higher ground enhancing rainfall) means there is rainfall gradient from higher ground in the west to lower lying areas in the east. The highest rainfall totals occurring in Wales, Cornwall, North Devon and further north in Lancashire and the Lake District (Cumbria).

2.2.2 Potential Evaporation

Figure 4 illustrates the MORECs (Hough and Jones, 1997) results for 1961 to 2008. Potential Evaporation is controlled by temperature, windspeed and direction combined with sunshine hours. The spatial distribution of long-term average PE is the inverse of rainfall, decreasing from west to east. The minimum PE occurs in Wales and the Lake District whilst the highest PE is observed to the east of the country.

2.2.3 Land-use

The majority land use for England and Wales is presented in Figure 5. There is a roughly east-west split in terms of land-use across England, with the land cover mapped in north-western and south-western England being improved and semi-natural grassland. With the exception of urban areas, central and eastern England is predominantly arable. Parts of southern, central and north-western England are heavily urbanised, containing the London, Birmingham and Liverpool/Manchester conurbations respectively. Wales has a similar land cover for north-western and south-western England that is predominantly improved and semi-natural grassland.

2.2.4 Soils

The HOST soil map (Boorman et al., 1995), as presented in Figure 6, reflects the underlying geology with the soil types in the south and east of England dominated by Cretaceous Chalk and Jurassic Limestones. The western part of England along with Wales is predominantly derived from shales, siltstones and clays or hard rocks.

2.2.5 Implications for recharge calculation

Rainfall, PE, land use (and subsequent crop growth) along with soil type all act in combination to control potential recharge. The rainfall decreases from west to east, whilst the PE increases. Mitigated by land use and the distribution of soils, this means that recharge generally decreases eastwards. Distribution of long-term average potential recharge maps for England and Wales are presented and discussed in Section 3.2, see for example, Figure 8.

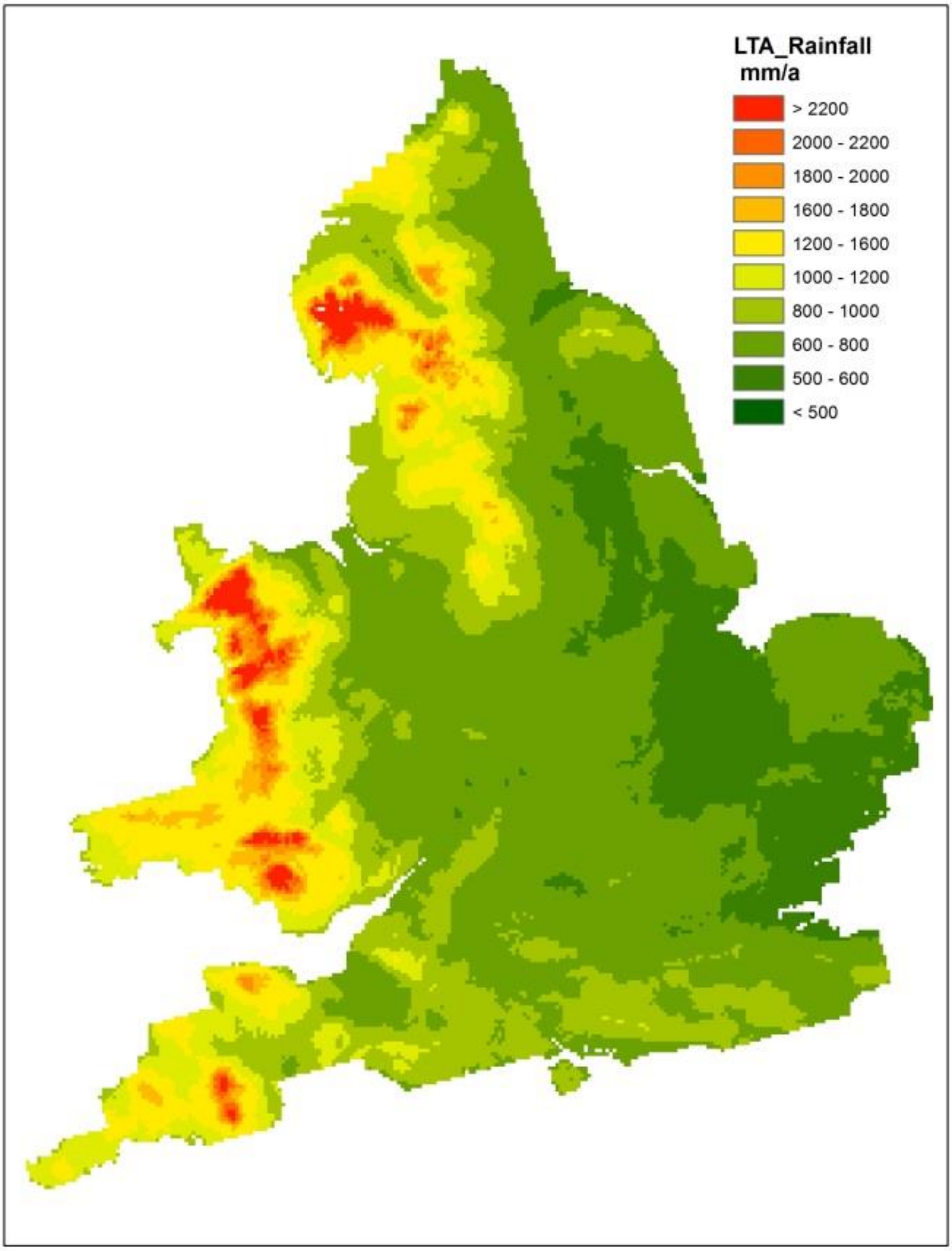


Figure 3. Long-term average rainfall

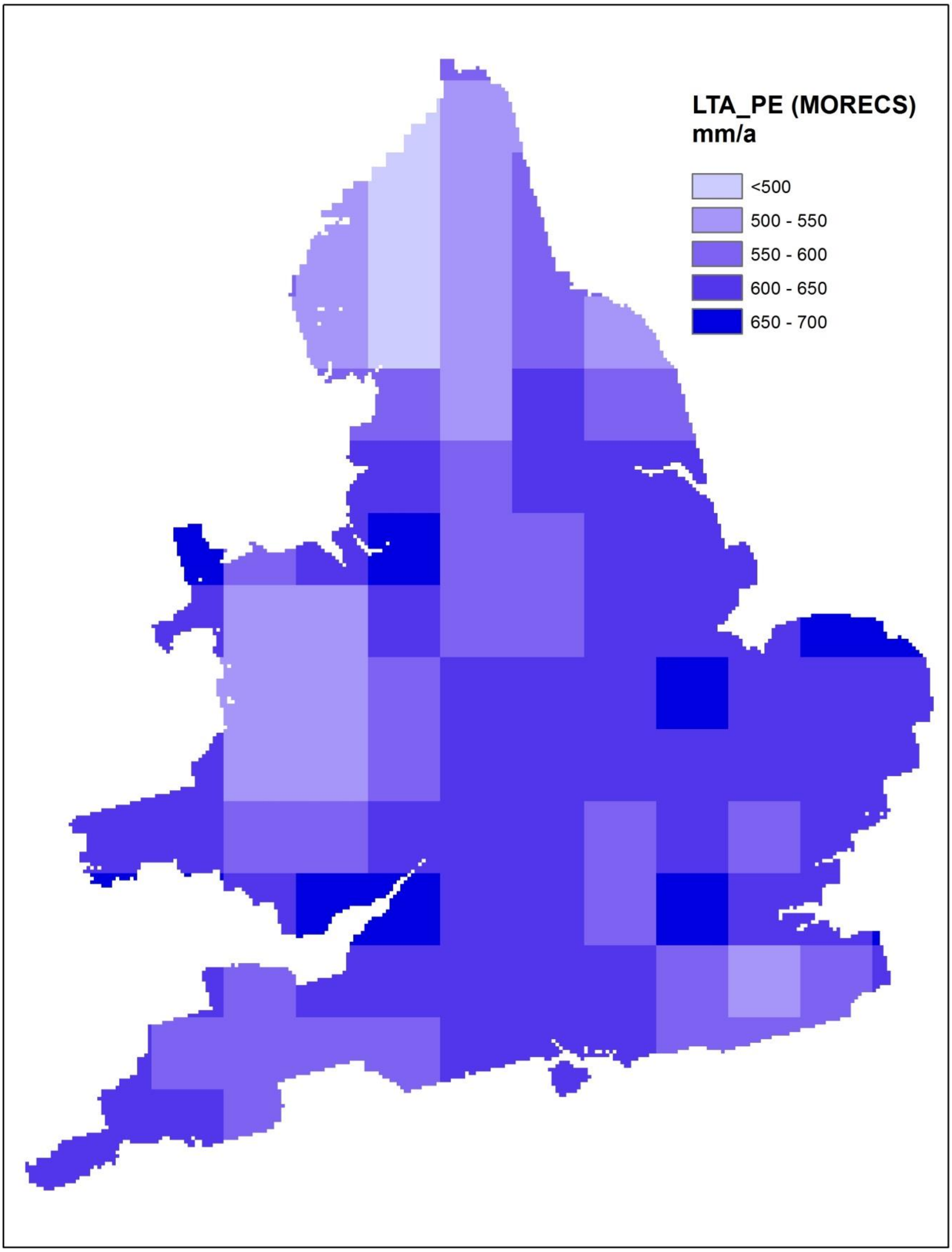


Figure 4. Long-term average potential evaporation calculated from MORECs

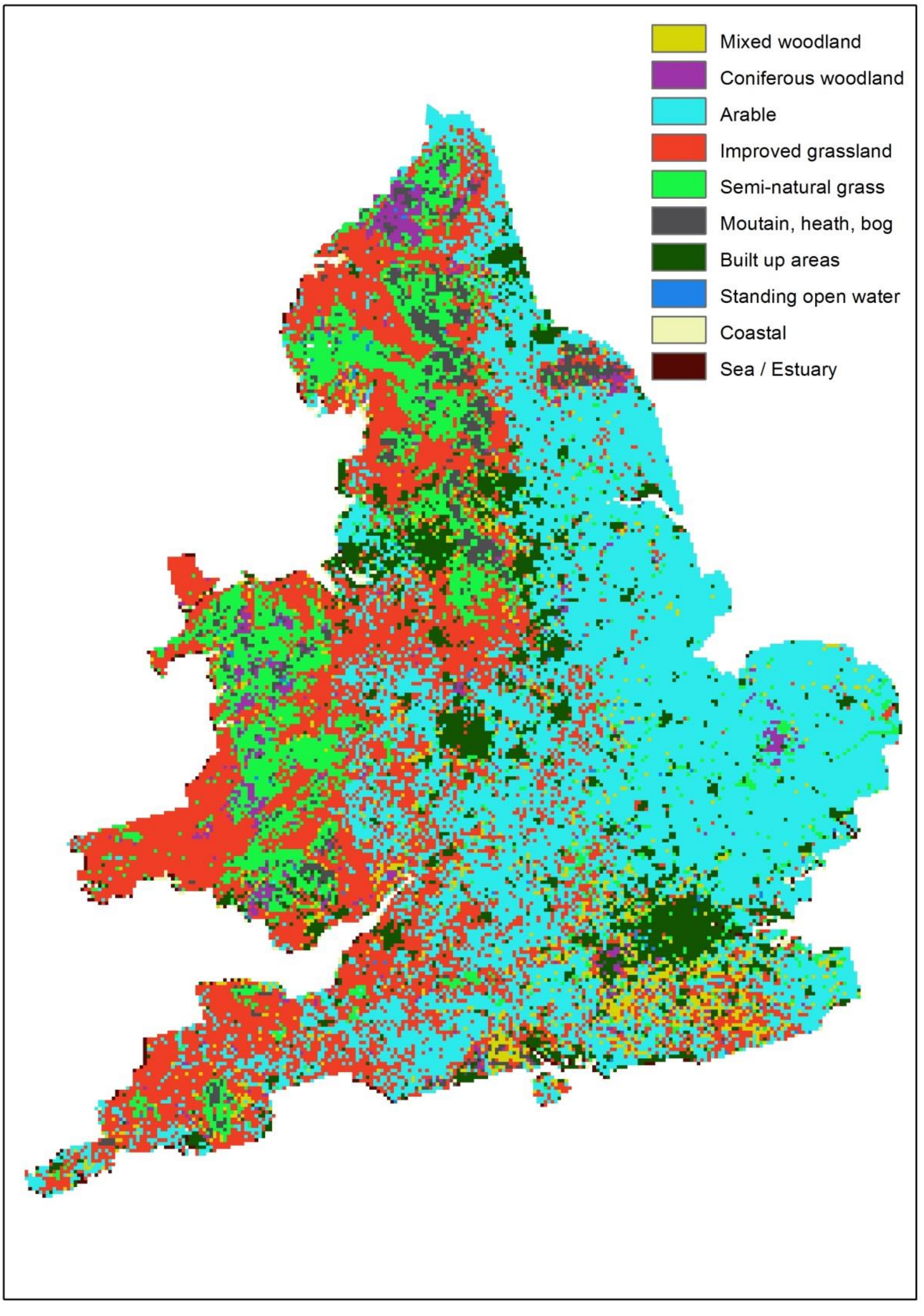


Figure 5. Majority land use (LCM2000)

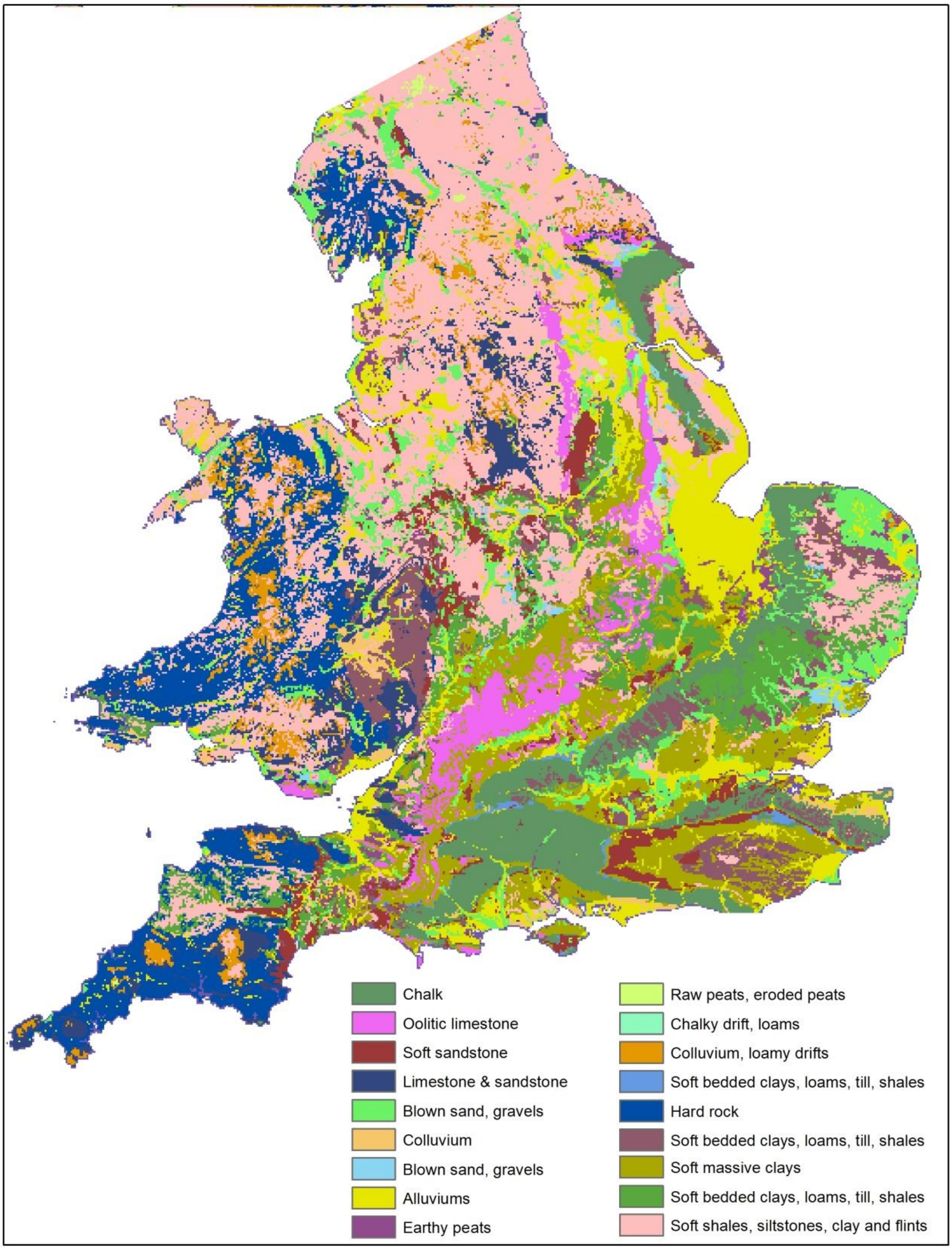


Figure 6. HOST soil map

2.3 DESCRIPTION OF ZOODRM

The grid resolution is 2 km by 2 km and Figure 7 shows the model grid for the whole of England and Wales. Due to the resolution of the figure, the details of the grid can't be seen over England and Wales so details are provide for a northern catchment the Tees and a catchment in the south of England, the River Thames. A soil water balance is calculated at nodes which are located where the grid lines cross. Land use mapping (Figure 5) is used to inform the choice of crop coefficients (Table 2) for the FAO method of calculating a soil balance (Allen et al., 1998). When the soil moisture deficit reduces to zero any additional water is then split between runoff and potential recharge using the runoff coefficient to determine the proportion. Overlaid on this is the river network to which water is routed by the direction of the DEM. Once runoff is generated then it is routed down topographic gradient until it reaches the river where it is routed towards the sea.

For the historical simulation, the model is run from 1st January 1962 to 31st December 1992 using a daily time step.

Table 2. Crop coefficients used for the model simulations

Crop	Maximum Root Depth (mm)	Depletion factor (-)
Deciduous	2000	0.8
Coniferous	1512	0.7
Arable	750	0.8
Grass	450	0.5
Upland	120	0.37
Urban	900	0.5
Open Water	3000	0.999

Further details of the calculation method is provided in Appendix 1.

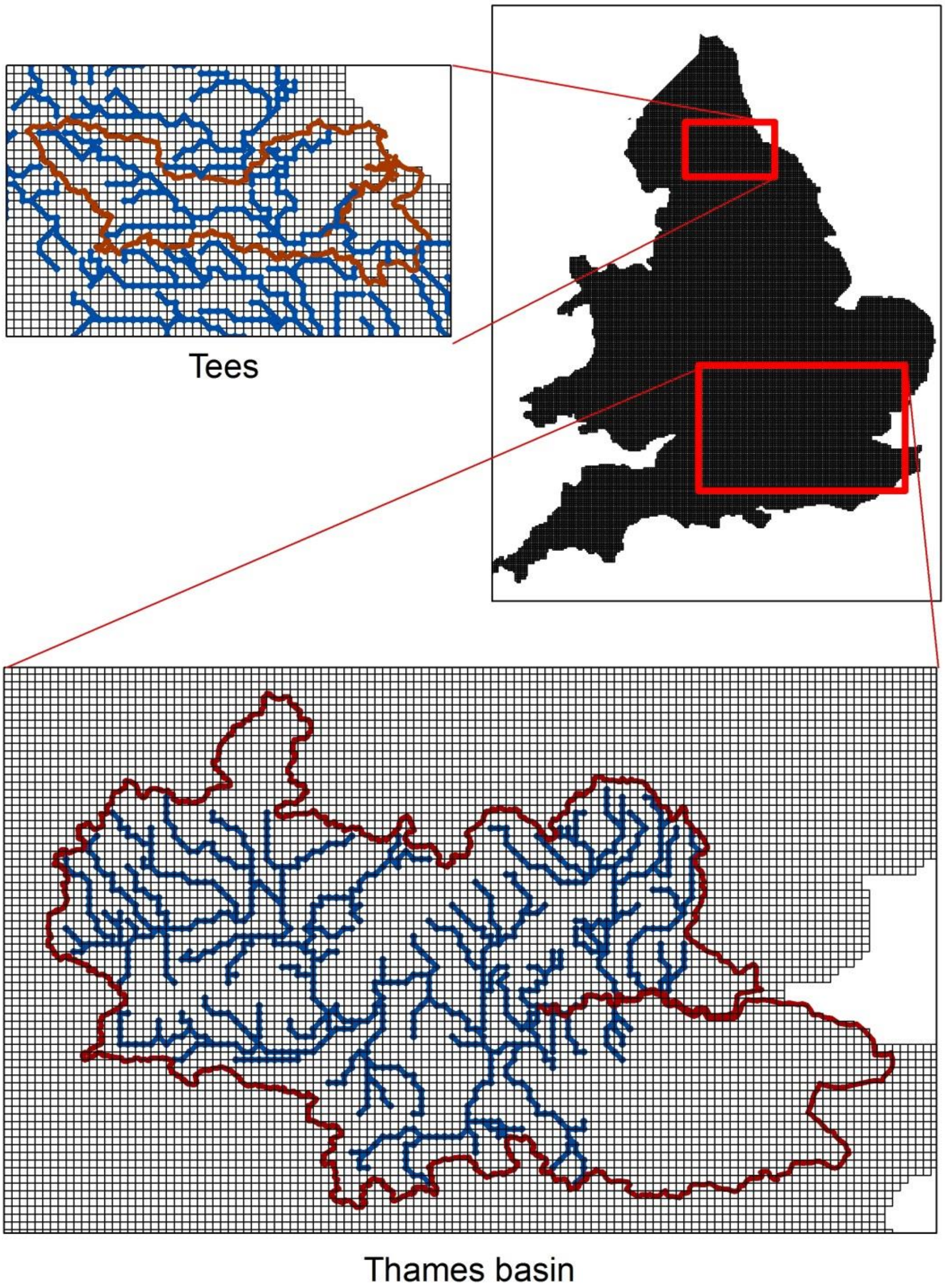


Figure 7. ZOODRM grid

2.4 RUNS UNDERTAKEN

2.4.1 Introduction

As stated above there is a basecase and two sets of runs: climate change based on the FFGWL hydrology dataset and a second to investigate the impacts of land use change. Table 3 details the runs undertaken, the rainfall, PE and land use data sets used as input data.

Table 3. Summary of runs undertaken

Series	Run	Rainfall	PE	Land use	Notes
Historical Simulation	Basecase	Daily 1km^2 gridded rainfall for January 1961 to December 2011	MORECS 40 x 40 km^2 monthly PE from January 1961 to December 2012	LCM2000	Basecase for all runs; run from 1962-1992
Climate Change	a	FFGWL : Afgcx		LCM2000	Three time slices: 2010-2039, 2030-2069 and 2070-2099
	b	FFGWL : Afixa			
	c	FFGWL : Afixc			
	d	FFGWL : Afixh			
	e	FFGWL : Afixi			
	f	FFGWL : Afixj			
	g	FFGWL : Afixk			
	h	FFGWL : Afixl			
	i	FFGWL : Afixm			
	j	FFGWL : Afixo			
	k	FFGWL : Afixq			
Land use	LCM2007	Daily 1km^2 gridded rainfall for January 1961 to December 2010	MORECS 40 x 40 km^2 monthly PE from January 1961 to December 2012	LCM2007	All land use runs are from 1962-1992
	All woodland			Woodland	Crops coefficients for trees used everywhere
	All grass			Grass	Crops coefficients for grass used everywhere

	All arable			Arable	Crops coefficients for arable used everywhere
	50% woodland to arable			Modifying 50% woodland to arable at the grid node where it occurs	
	50% woodland to grass			Modifying 50% woodland to grass at the grid node where it occurs	
	50% grass to arable			Modifying 50% grass to arable at the grid node where it occurs	
	50% grass to woodland			Modifying 50% grass to woodland at the grid node where it occurs	
	50% arable to woodland			Modifying 50% arable to woodland at the grid node where it occurs	
	50% arable to grass			Modifying 50% arable to grass at the grid node where it occurs	

2.4.2 Historical simulation

The calibration of the recharge model is performed by comparing the simulated overland flows at selected gauging stations to the observed flows. ZOODRM calculates runoff values based on the runoff coefficient values assigned to runoff zones that are derived from hydrogeological and geological maps. 56 gauging stations were selected from The Hydrometric Register and Statistics books published by the Centre of Ecology and Hydrology (NERC, 2003) to calibrate the model. A list of these catchments and their locations are shown in Appendix 2. These are the gauging stations that have the largest catchment areas and are located at the major rivers. In general, the period of record spans over 40 years (1960s-2000s) and consequently the recorded river flows are treated as long term average (LTA) river flows. Because the recharge model ZOODRM does not account for groundwater flows and consequently calculates only the surface water component of the total river flows, the observed LTA surface water components of river flows were used in the model calibrations. These were calculated from the Hydrometric Register book by multiplying average total flows by the residual of 1 minus the baseflow index for each gauging station.

The simulated long term average distributed recharge values provide a baseline to which recharge values calculated using future climate and socio-economic (represented by changes in the land cover map) data can be compared to. However, the distributed recharge model ZOODRM does not account for some processes such as snow melt. These processes are taken into account during the generation of future climate data. The comparison between the results produced using future climate data and historic data produced inconsistent observations mainly at elevated grounds. The LTA historic results are used, therefore, to study the impact of socio-economic changes only

2.4.3 Climate Change

The Future Flows climate data is a set of climate projections, the development of which is described by Prudhomme et al. (2013). They are an 11 member ensemble of transient climate projections based on HadRM3-PEE-UK, which has been used as part of the derivation of the UKCP09 scenarios (Murphy et al., 2007, Prudhomme et al., 2013). 148 years of gridded rainfall and evaporation data for 11 scenarios are available. These are divided into four time horizons. These are: the simulated historic time horizon (1962-1992), the first, second and third time horizons, which are also labelled 30s, 50s, and 70s and covers up to years 2039, 2069, and 2099 respectively.

2.4.4 Land use change

The socio-economic impact on the calculated recharge values are investigated though the use of two different land use cover maps - the LCM2000 (Fuller et al., 2002) and LCM2007 (Morton et al., 2011) in addition to three scenarios where the whole of the country is assumed to be covered by one land use type consisting of either arable, grass, or woodland. It was recognised that changing land use for the whole of England and Wales was unrealistic. Various land use scenarios have been developed including four by the Environment Agency (2009) and six for the National Ecosystem Assessment (NEA, 2011). The latter scenarios show a maximum change of 50% of each land use category related to the baseline.

Whilst it would have been idea to use the NEA scenarios, these were not available in an appropriate form during the project lifetime. Therefore, to assess the impacts of a more realistic set of future land use scenarios, six additional runs have been performed, however, to investigate theoretical, but more likely changes in percentage land use cover. The land use for these six runs is created by replacing 50% of one class where it occurs in the LCM2000 by another class. The classes are replaced in pairs taken from woodland, grass and arable classes.

3 Results

3.1 INTRODUCTION

The following section presents the results produced for the three sets of models runs: historical simulation, climate change using the FFGWL hydrological datasets and land use change. The historical simulation is used as a "basecase" to which the results to the CC and land use simulations are compared. For simplicity long-term average (LTA) potential recharge is used for comparison. The model is run for the full time period (January 1962 to December 1992 for the historical simulation) and then average recharge for this time period produced for each node.

Two ways of presenting the results are used: the first are maps of LTA recharge for the whole of England and Wales and the second are box-whisker plots. The latter is used to summarise differences in behaviour between catchments.

Box and whisker plots are a convenient way of graphically displaying the statistical characteristics of numerical data. A whisker plot is defined mainly by five values:

- The mean of the data which sits in the centre of the box;
- the lower and upper limits of the box which are also called the lower quartile (Q1) and the upper quartile (Q3); and
- the two bars outside the box which are the minimum and maximum values that are not outliers. Outliers below the lower whisker are all the values that are less than $Q1 - IQR$ and those above the upper whisker are all the values that are greater than $Q3 + IQR$ with IQR defined as the inter quartile range, which is the distance between Q1 and Q3. Outliers are rare values but can happen.

3.2 HISTORICAL SIMULATION

Figure 8 shows the LTA potential recharge for the various runs undertaken including the overall historical simulation for England and Wales (top left). The recharge gradient is mainly west to east with potential recharge decreasing from >1200 mm/a in western Wales to <100 mm/a in north Norfolk. The influence of higher rainfall due to orographic effect in Wales and north-west England can be clearly seen. Other influences such as soil type can be observed in the Thames and Wealden basins. The LTA recharge clearly shows the combined influence of spatial distribution of rainfall, PE, land use, soil and geology at outcrop. It is the interaction between these factors and changes to the driving data (FFGWL climate data) and land use which is presented below.

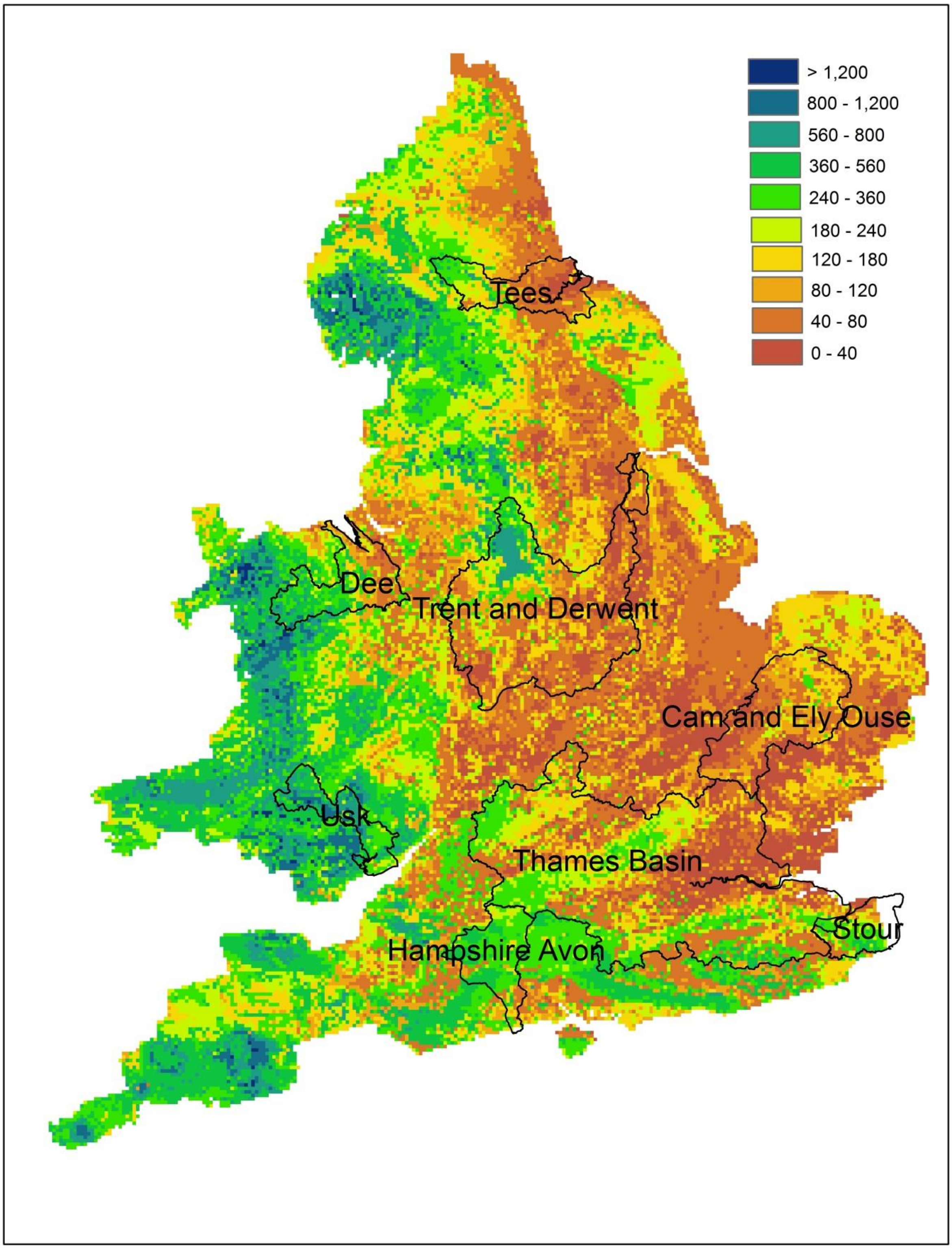
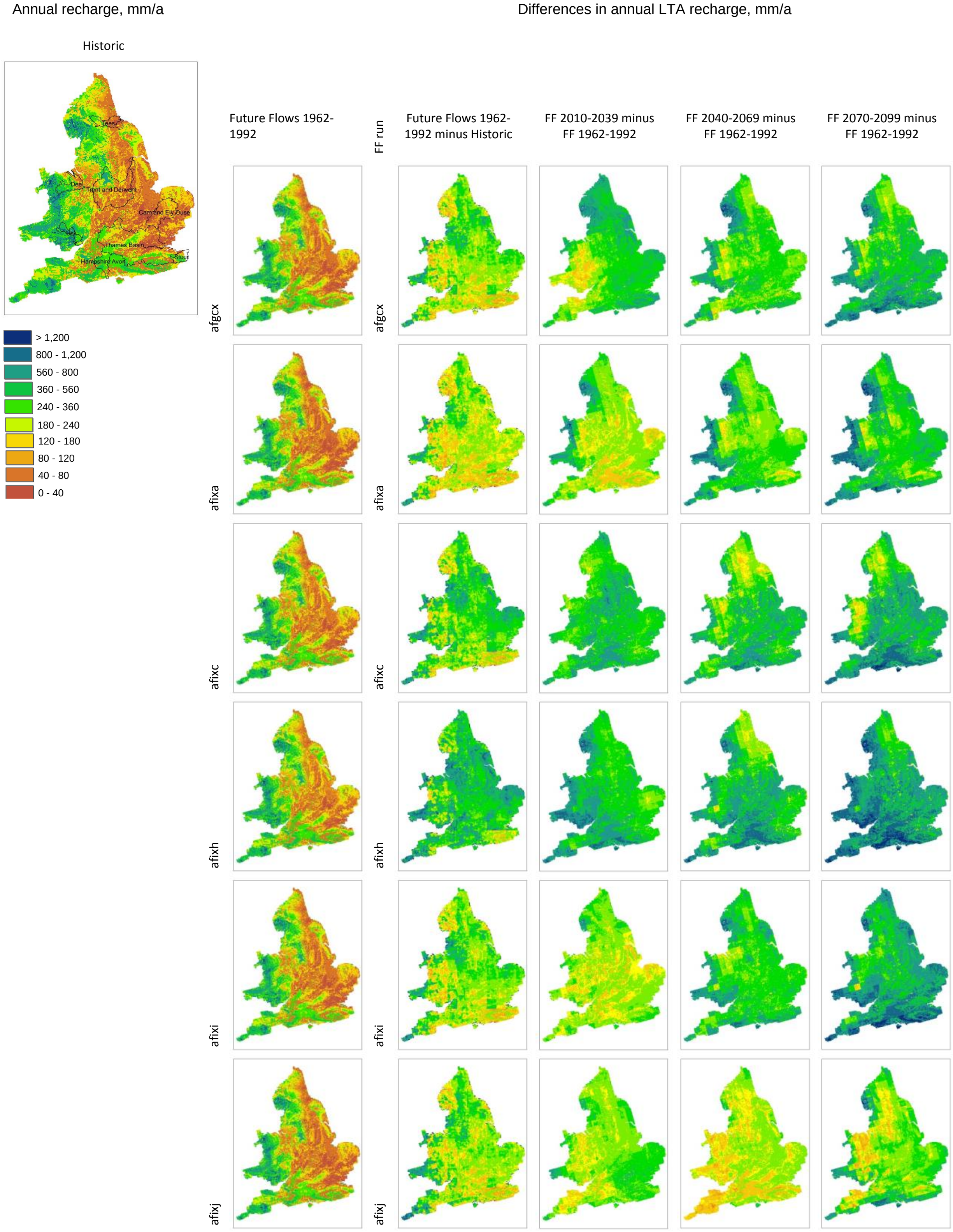
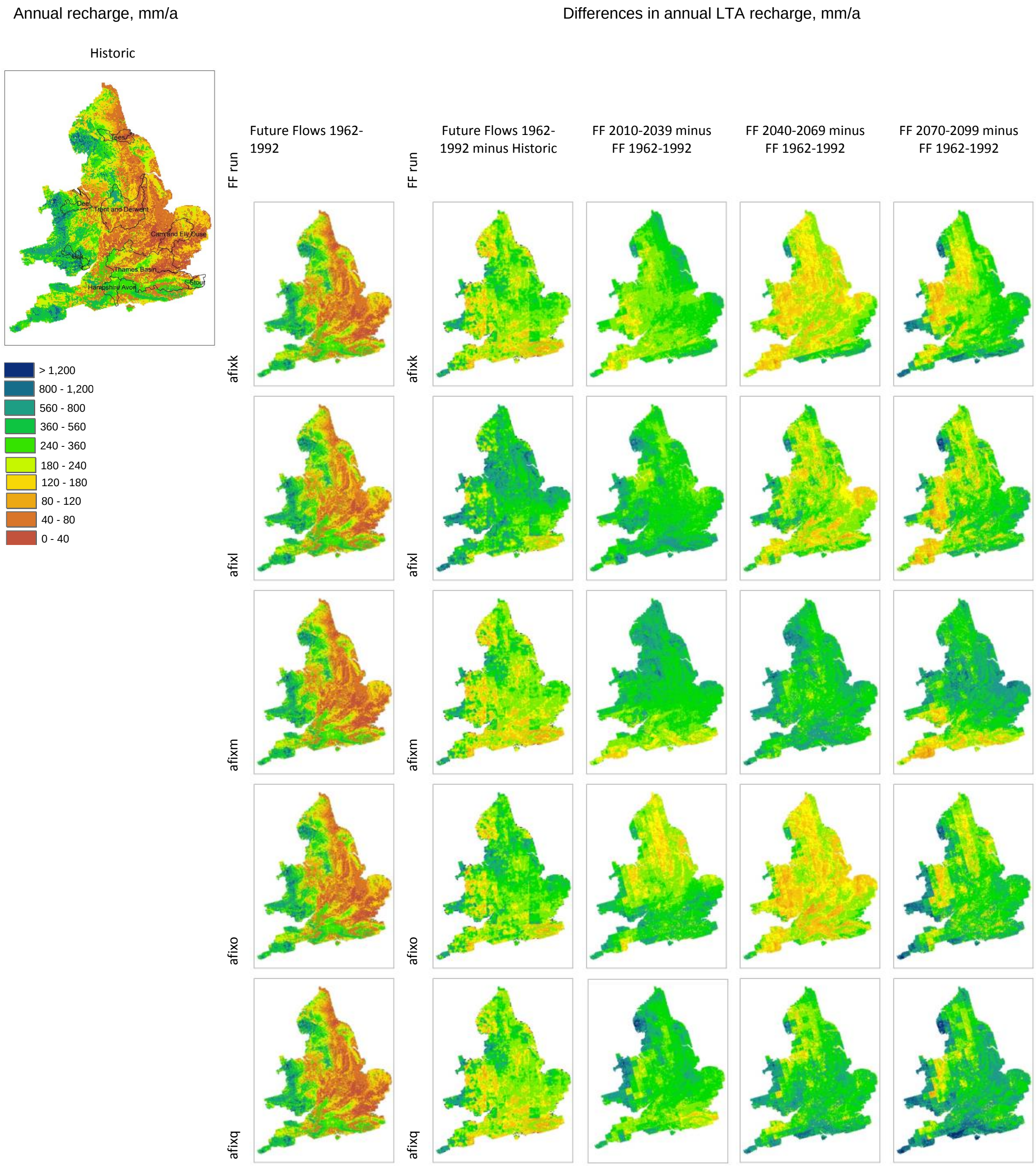


Figure 8. Long-term average recharge for the basecase

Figure 9. LTA recharge for FFGWL climate change runs


Annual recharge, mm/a
Differences in annual LTA recharge, mm/a
Historic
> 1,200
800 - 1,200
560 - 800
360 - 560
240 - 360
180 - 240
120 - 180
80 - 120
40 - 80
0 - 40
Future Flows 1962-1992
FF run
Future Flows 1962-1992 minus Historic
FF 2010-2039 minus FF 1962-1992
FF 2040-2069 minus FF 1962-1992
FF 2070-2099 minus FF 1962-1992
afgcx
afixa
afixc
afixh
afixi
afixj


Annual recharge, mm/a
Differences in annual LTA recharge, mm/a
Historic
Tees
Trent and Derwent
Cam and Ely Ouse
Thames Basin
Hampshire Avon
Stour
> 1,200
800 - 1,200
560 - 800
360 - 560
240 - 360
180 - 240
120 - 180
80 - 120
40 - 80
0 - 40
FF run
Future Flows 1962-1992
Future Flows 1962-1992 minus Historic
FF 2010-2039 minus FF 1962-1992
FF 2040-2069 minus FF 1962-1992
FF 2070-2099 minus FF 1962-1992
afixk
afixl
afixm
afixo
afixq

3.3 CLIMATE CHANGE

3.3.1 Long-term averages for England and Wales

Figure 9 presents the LTA results for the 11 RCMs for each time slice. The first column shows absolute values for the LTA for Future Flows historical simulation, the remaining columns display differences. Column two shows the difference between the FFGWL and the historical simulation, columns three to five show the difference between the FFGWL time slices and the FFGWL historical simulation. The difference between the FFGWL historical simulation and that of the actual historical simulation is necessary as the perturbations in the initial conditions for each FFGWL simulation results in different time series of recharge.

Table 4 shows the summary of the differences for the average recharge for the model simulation. The differences in the average have been summarised by the bars in the right hand column of the table, with blue representing an increase and red a decrease. Bars are produced for the difference between each time slice (2010-39, 2040-2069, 2070-99) and the simulated historic.

Since each RCM has different starting conditions so as to achieve the variability in the future predictions (three timeslices: 2010-39, 2040-2069, 2070-99). These variations between the RCMs also affect the simulation of the historical period which can be compared against recharge calculated for observed data. Therefore, to understand how the different RCMs perform against know conditions the results are compared with those computed from observed data. These are presented in Table 4 in column 2 and presented pictorially in column 6. The latter is shown to illustrate the difference between the simulated historic (resulting from the RCM) and the historical simulation based on gridded observed data.

Examining the difference between the simulated historic and the historic (Table 4; column 2 and 6) shows that the majority of the RCMs are dryer than the observed (afgcx, afixa, afixi, afixj, afixk, afixm and afixq) with the remainder being wetter (afixc, afixh and afixl). Comparing these with the future predictions (Table 4; columns 3 to 5 and 7 for a pictorial representation) allows the examination of whether this pattern is followed in the results for the timeslices. Generally there is greater recharge in the historical simulation than the future predictions. Only simulations afixi and afixk are dryer in both the historical simulation and the future predictions. This suggests that the predictions using the RCMs underestimate recharge for the future predictions.

The following summarises the variation between the future predictions based on the RCMs:

afgcx: the historical simulation results in slightly lower recharge with increasing recharge over the subsequent time slices.

afixa: This historical simulation produces the lowest recharge with recharge increasing over the time slices, but starting from a reduced situation.

afixc: The historical simulation produces slightly increased recharge compared to the historical simulation. Recharge increases over the time slices with the increase in the 2080s being twice that of the 2020s and 2050s.

afixh: This shows the greatest increase in recharge from the historical summation to the simulated historic produced by the RCM. This set of runs produces the greatest increase with the 2080s showing the biggest increase.

afixi: A slight reduction in recharge is observed for the simulated historic. The time slices show an increase in recharge from initially negative value.

afixj: Similarly to afixi, a slight reduction in recharge is observed for the simulated historic. The results for the timeslices are generally lower the 2050s showing the greatest decrease.

afixk: Similarly to afixj, a slight reduction in recharge is observed for the simulated historic. The results for the timeslices are generally lower the 2050s showing the greatest decrease.

afixl: The historical simulation produces significantly increased recharge compared to the historical simulation. The timeslices show an initial increase in recharge but then shows a reduction.

afixm: There is a decrease in recharge compared to the historical simulation, but recharge increases with the greatest increase being for the 2050s.

afio: Recharge is slightly greater for the historical simulation with a reduction for the 2020s and a significant one for the 2050s. There is slightly increased recharge for the 2080s.

afixq: There is a decrease in recharge compared to the historical simulation, but recharge increases with the greatest increase being for the 2080s.

Overall the results show that for the 2050s then recharge is generally lower and further out for the 2080s then recharge is generally higher. The results are mixed for the recent time slice 2020s, with equal numbers of increases and decreases.

Table 4. Summary of differences in average LTA recharge for each RCM timeslice (mm/a)

	SimHis - Hist	30s - SimHist	50s - SimHist	80s - SimHist	SimHis - Hist	Relative average differences for the previous four columns
	Av	Av	Av	Av		
afgcx	-4.26	4.97	5.16	16.28		
afixa	-9.98	-5.12	6.08	14.9		
afixc	4.66	10	8.73	19.78		
afixh	15.4	15.23	16.98	36.46		
afixi	-2.44	-7.79	8.73	28.94		
afixj	-3.19	-3.91	-14.95	-2.26		
afixk	-4.56	-0.47	-14.11	-1.4		
afixl	13.66	8.69	-7.83	-3.47		
afixm	-5.55	6.97	12.57	7.91		
afixo	1.85	-1.61	-19.61	4.65		
afixq	-3.65	7.01	8.34	17.82		

Note: Average differences are shown as coloured squares one for each column of data; blue is a positive difference and red is a negative one.

3.3.2 Catchment summaries using Box-Whisker plots

The following sections describe the variations in recharge values calculated over England and Wales as a whole, and also as sampled for each of the focus CAMS catchments. Recharge values presented in these sections are given in Table 5 and also shown in Figures 10 and 11. The average and maximum LTA recharge values calculated using the historic rainfall and evaporation data are shown in the first and second columns. The third and fourth columns give the maximum and minimum values of the 11 averages of LTA recharge values calculated for the 11 future runs of the first time horizon 2010-2039 (2020s). The fifth and sixth columns contain the second time horizon 2040-2069 (2050s), and the seventh and eighth columns hold the values for the third time horizon 2070-2099 (2070s).

Table 5. Summary of long term average historic and future recharge value characteristics

Catchment	Historic		2010 - 2039		2040 -2069		2070 - 2099	
	Average LTA recharge	Maximum LTA recharge	Highest average LTA recharge of 11 runs	Lowest average LTA recharge of 11 runs	Highest average LTA recharge of 11 runs	Lowest average LTA recharge of 11 runs	Highest average LTA recharge of 11 runs	Lowest average LTA recharge of 11 runs
Dee	0.716	2.911	H: 0.783	J: 0.664	H: 0.768	K: 0.621	H: 0.809	K: 0.613
ElyOuse	0.235	0.682	H: 0.284	A: 0.168	H: 0.31	O: 0.185	H: 0.36	J: 0.216
HampAvon	0.773	1.308	H: 0.907	A: 0.632	H: 0.944	J: 0.653	H: 1.041	M: 0.681
Stour	0.531	1.246	L: 1.31	A: 0.349	H: 0.427	J: 0.337	I: 0.507	M: 0.363
Tees	0.36	2.132	H: 0.412	O: 0.34	H: 0.382	A: 0.346	H: 0.418	K: 0.343
Thames	0.4	1.39	H: 0.46	A: 0.3	H: 0.49	J: 0.34	H: 0.52	J: 0.31
Trent	0.393	2.277	H: 0.453	A: 0.343	H: 0.481	K: 0.339	H: 0.498	J,K: 0.367
Usk	1.374	3.463	H: 1.52	GCX: 1.29	H: 1.474	K: 1.287	H: 1.591	K: 1.315
England and Wales	0.612	7.69	H: 0.695	A: 0.57	H: 0.7	K: 0.56	H: 0.753	K: 0.595

3.3.3 The Dee catchment

The Dee catchment is located to the north of Wales, west of England and Wales (Figure 2). The historic LTA recharge values calculated over the Dee catchment have an average of 0.72 mm/day and a maximum of 2.91 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values vary between -15 and 12 % of the historical LTA average recharge value with highest values calculated as 0.78, 0.77 and 0.81 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.66, 0.62 and 0.61 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10A shows the Whisker plots for the historic and future recharge values calculated over the Dee catchment for the three time horizons. The highest LTA average recharge value calculated as 0.81 mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 0.61 mm/day from projection K for the 2080s. A Whisker plot for the differences between the future and historic recharge values are shown in Figure 11A.

3.3.4 The Ely-Ouse catchment

The Ely-Ouse catchment is located to the east of England (Figure 2). The historic LTA recharge values calculated over this catchment have an average of 0.24 mm/day and a maximum of 0.68 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values vary between -30 and 50 % of the historical LTA average recharge value with highest values calculated as 0.28, 0.31 and 0.36 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.17, 0.19 and 0.22 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10B shows the Whisker plots for the historic and future recharge values calculated over the Ely-Ouse catchment for the three time horizons. The highest LTA average recharge value calculated as 0.36 mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 0.17 mm/day from projection A for the 2020s. The differences between the future and historic recharge values can be clearly seen in this figure as well as in the corresponding Whisker plots shown in Figure 11B.

3.3.5 The Hampshire Avon catchment

The Hampshire Avon catchment is located to the south of England (Figure 2). The historic LTA recharge values calculated over this catchment have an average of 0.77 mm/day and a maximum of 1.31 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values vary between -18 and 35 % of the historical LTA average recharge value with highest values calculated as 0.91, 0.94 and 1.04 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.63, 0.65 and 0.68 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10C shows the Whisker plots for the historic and future recharge values calculated over the Hampshire Avon catchment for the three time horizons. The highest LTA average recharge value calculated as 1.04 mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 0.63 mm/day from projection A for the 2050s. As for the Ely-Ouse catchment, the differences between the future and historic recharge values can be clearly seen in Figure 11C.

3.3.6 The Stour catchment

The Stour catchment is located to the south east of England (Figure 2). The historic LTA recharge values calculated over this catchment have an average of 0.53 mm/day and a maximum of 1.25 mm/day. Calculation of recharge using the 11 rainfall and evaporation future projection values produces LTA average recharge values that are lower than the historical LTA recharge values. The future LTA average recharge values vary between -37 and -4 % of the historical LTA average recharge value with highest values calculated as 0.45, 0.43 and 0.51 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.35, 0.34 and 0.36 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10D shows the Whisker plots for the historic and future recharge values calculated over the Dee catchment for the three time horizons. The highest LTA average recharge value calculated as 0.51 mm/day from projection I for the 2080s. The lowest LTA average recharge value calculated as 0.34 mm/day from projection J for the 2050s. The Whisker plots of the differences between the future and historic recharge values in Figure 11D clearly shows that on average the predicted future values are lower than the historical LTA recharge values.

3.3.7 The Tees catchment

The Tees catchment is located to the north of England (Figure 2). The historic LTA recharge values calculated over this catchment have an average of 0.36 mm/day and a maximum of 2.13 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values vary between -5 and 17 % of the historical LTA average recharge value with highest values calculated as 0.41, 0.38 and 0.42 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.34, 0.35 and 0.34 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10E shows the Whisker plots for the historic and future recharge values calculated over the Tees catchment for the three time horizons. The highest LTA average recharge value calculated as 0.42 mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 0.34 mm/day from projection O for the 2050s. However, there are no significant differences between the future recharge values calculated using the different projections as shown in Figure 11E.

3.3.8 The Thames catchment

The Thames catchment is located to the south east of England (Figure 2). The historic LTA recharge values calculated over this catchment have an average of 0.4 mm/day and a maximum of 1.29 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values vary between -25 and 30 % of the historical LTA average recharge value with highest values calculated as 0.46, 0.49 and 0.52 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.3, 0.34 and 0.31 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10F shows the Whisker plots for the historic and future recharge values calculated over the Thames catchment for the three time horizons. The highest LTA average recharge value calculated as 0.52 mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 0.3 mm/day from projection A for the 2020s. Figure 11F how noticeable differences between the future recharge values calculated using the 11 different projections.

3.3.9 The Trent catchment

The Trent catchment is located in the centre of England (Figure 2). The historic LTA recharge values calculated over this catchment have an average of 0.39 mm/day and a maximum of 2.27 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values vary between -13 and 28 % of the historical LTA average recharge value with highest values calculated as 0.45, 0.48 and 0.5 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.34, 0.34 and 0.37 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10G shows the Whisker plots for the historic and future recharge values calculated over the Trent catchment for the three time horizons. The highest LTA average recharge value calculated as 0.5 mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 0.34 mm/day from projection K for the 2050s. The differences between the future and historic recharge values can be clearly seen the corresponding Whisker plots shown in Figure 11G.

3.3.10 The Usk catchment

The Usk catchment is located south of Wales, west of England and Wales (Figure 2). The historic LTA recharge values calculated over this catchment have an average of 0.1.37 mm/day and a maximum of 3.46 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values vary between -6 and 16 % of the historical LTA average recharge value with highest values calculated as 1.52, 1.74 and 1.59 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 1.29, 1.29 and 1.32 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10H shows the Whisker plots for the historic and future recharge values calculated over the Usk catchment for the three time horizons. The highest LTA average recharge value calculated as 1.59 mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 1.29 mm/day from projection K for the 2050s. The differences between the future and historic recharge values can be clearly seen the corresponding Whisker plots shown in Figure 11H.

3.3.11 England and Wales

The calculated historic long term average (LTA) recharge values vary spatially between near zero to approximately 7.7 mm/day with an average of 0.61 mm/day. The LTA average recharge values calculated from the 11 rainfall and evaporation future projection values did not vary significantly from the historical value with the highest values calculated as 0.69, 0.7 and 0.75 for the three time horizons 2020s, 2050s, and 2080s respectively. The lowest LTA average recharge values are 0.57, 0.56 and 0.6 for the three time horizons 2020s, 2050s, and 2080s respectively.

Figure 10I shows the Whisker plots for the historic and future recharge values calculated over England and Wales for the three time horizons. This figure also reflect the small variations in the calculated recharge values with the highest LTA average recharge value calculated as 0.75

mm/day from projection H for the 2080s. The lowest LTA average recharge value calculated as 0.56 mm/day from projection K for the 2050s.

3.3.12 Additional analysis on recharge values calculated over selected strips across England and Wales.

During the analysis of the recharge model output it was observed that there was greater variability in the Thames Basin in compared to the others. It was postulated that a possible cause of this difference was the size, orientation and position of the catchment. The Thames Basin is elongated in the east-west axis and covers a significant proportion of the distance from the coast to coast. This could mean that it is unduly affected by the west-east nature of the UK's climate. Therefore, a number of runs were undertaken on strips running north-south and east-west. Four strips are selected at the locations and orientations shown in Figure 12. Additional statistical analyses have been performed on these four areas to investigate how the recharge values vary with the location and orientation of the catchment area being investigated.

The Box-Whisker plots of the future LTA recharge values are shown in Figure 13. This figure shows that the differences between the 11 projections LTA recharge calculated over the north south strip across Wales (Figure 13A) are not as clear as the those calculated over the north south strip across England (Figure 13B). It also shows that differences between the 11 projection LTA recharge values calculated over the east west strip at north of England (Figure 13C) are not as clear as those between the recharge values calculated over the east west strip at the south of England (Figure 13D).

3.4 DISCUSSION OF RCM VARIABILITY

The results described above demonstrate that there is a significant variability between LTA recharge produced for each RCM for each timeslice. The RCM which consistently produces the greatest recharge is projection H (afixh). This is wetter for the historic simulation as well as the future predictions suggesting consistency between the historic simulation and future prediction. For the dryer, low recharge case then the results are more mixed, but projection A (afixa) appears to produce the lowest recharge, albeit for the 2020s. For the later timeslices (50s and 80s) then J and K (afixj and afixk) predominate. The latter are dryer for the historic simulation and the future predictions, again suggesting consistency between the historic simulation and future prediction.

Figure 10. Plots of historic and future recharge values

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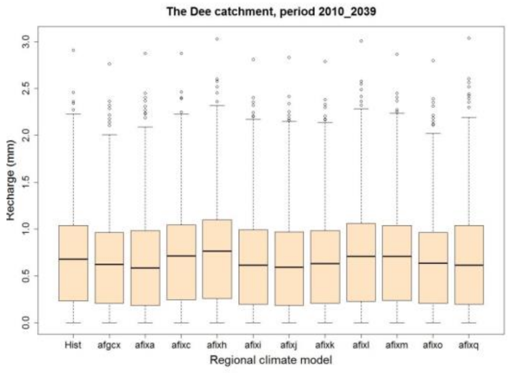
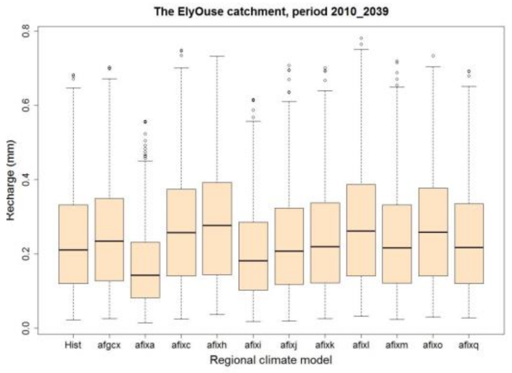
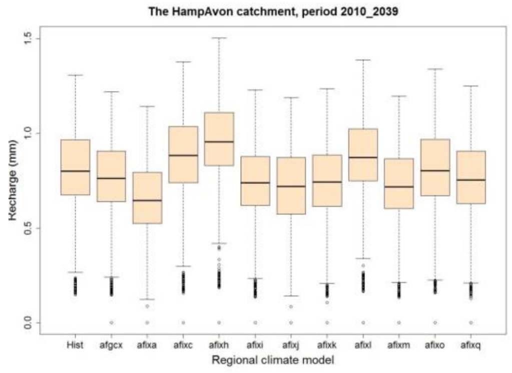
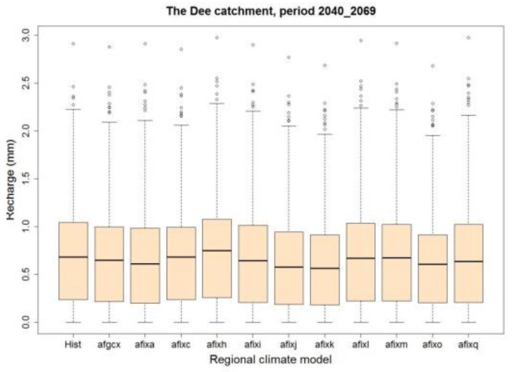
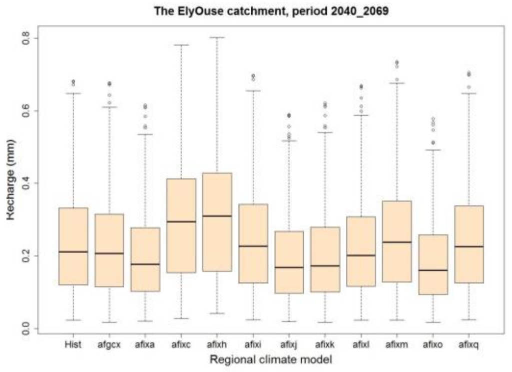
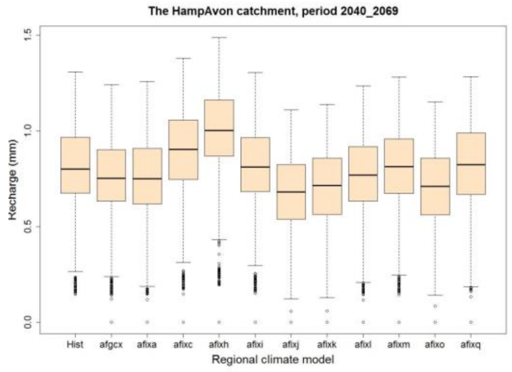
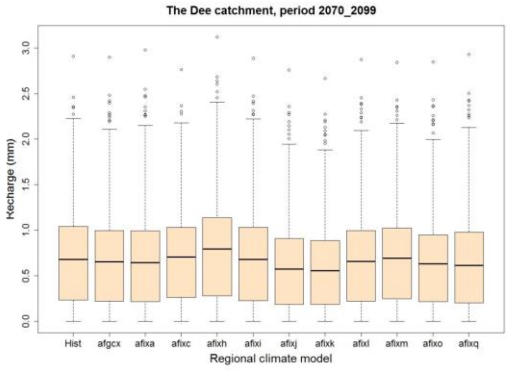
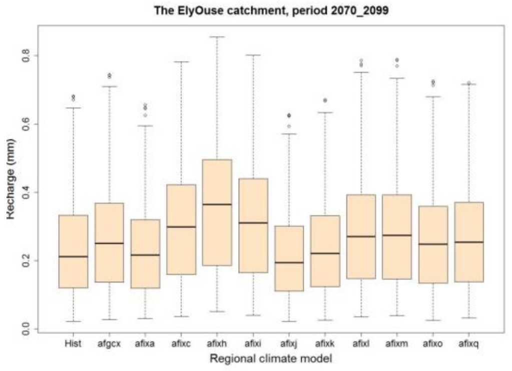
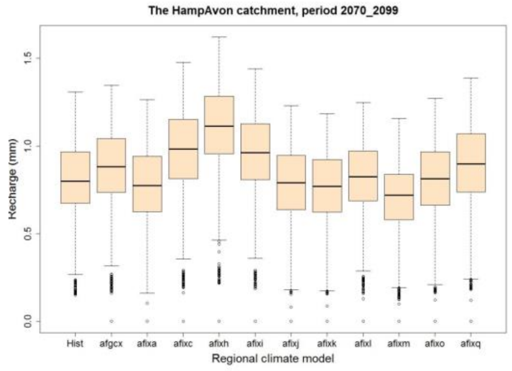
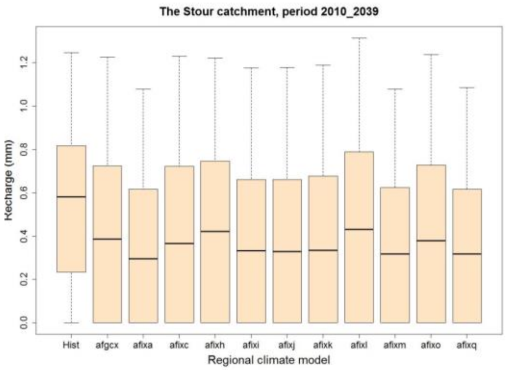
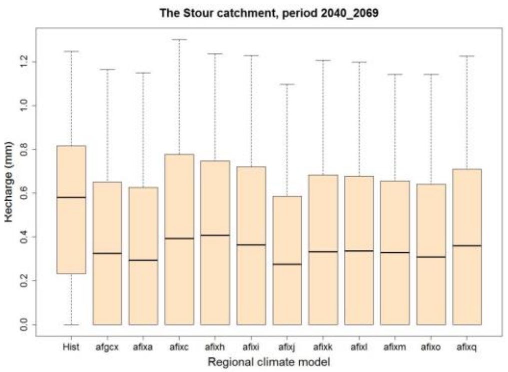
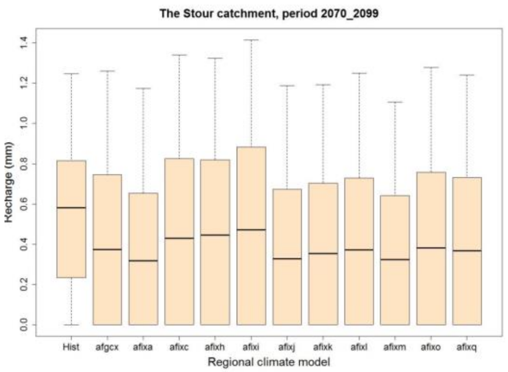
		
		
		

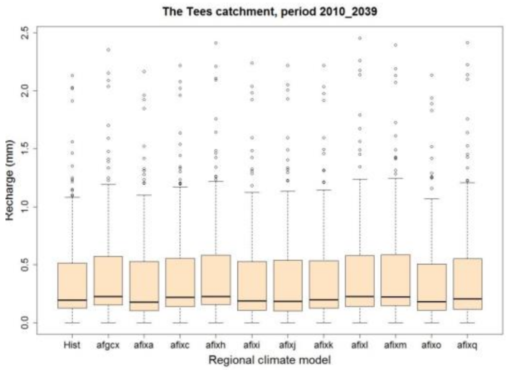
D: The Stour catchment

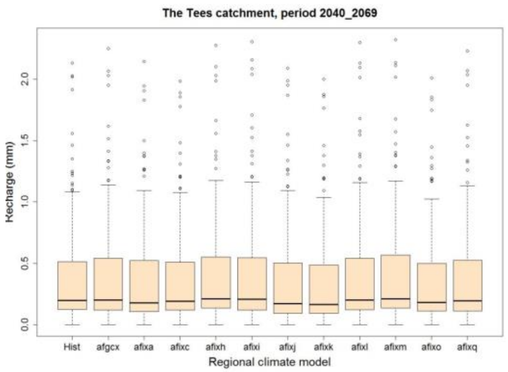


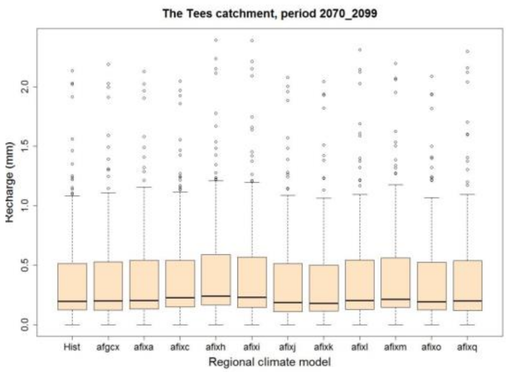




E: The Tees catchment







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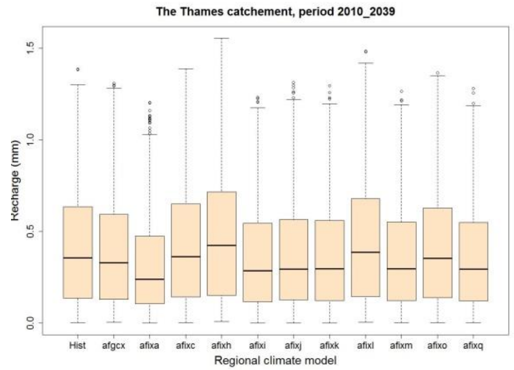
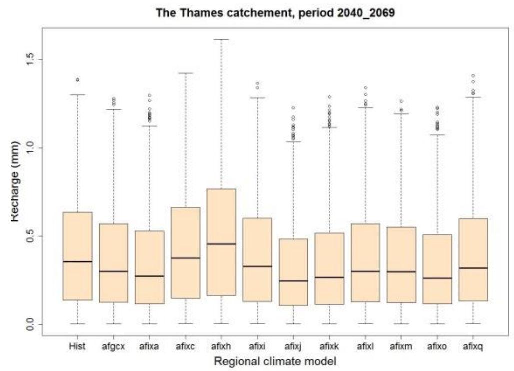
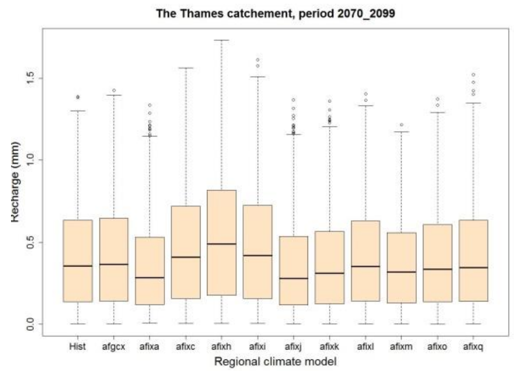






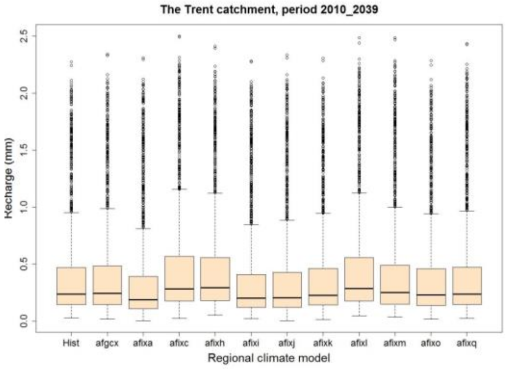
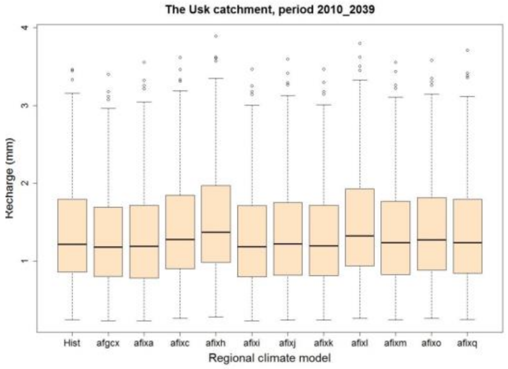
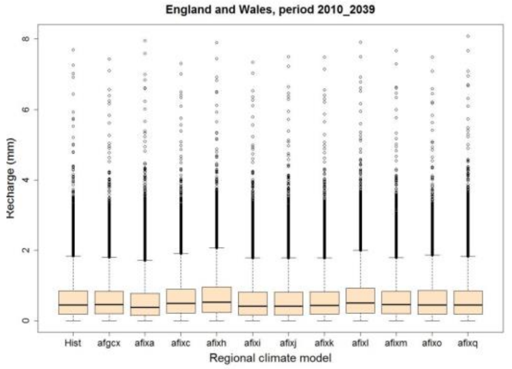
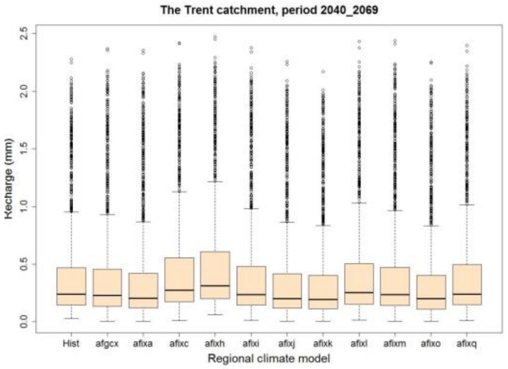
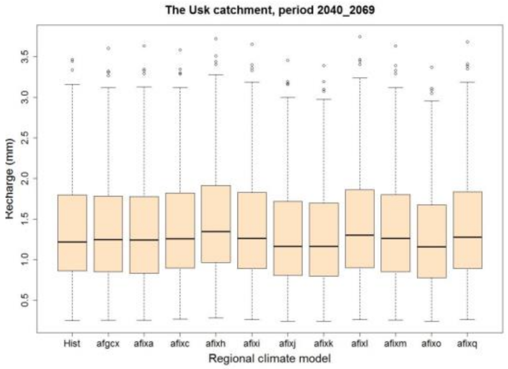
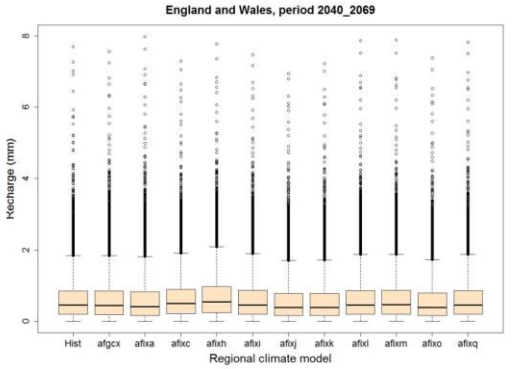
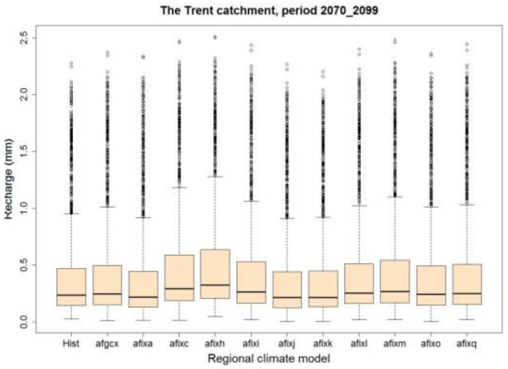
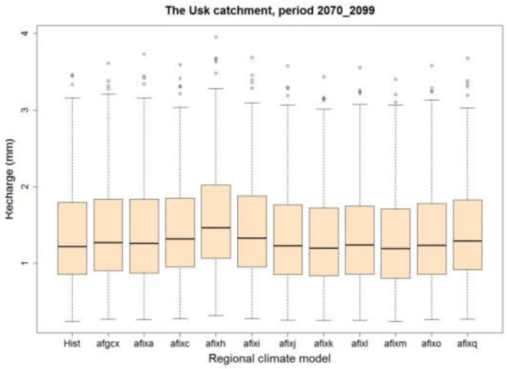
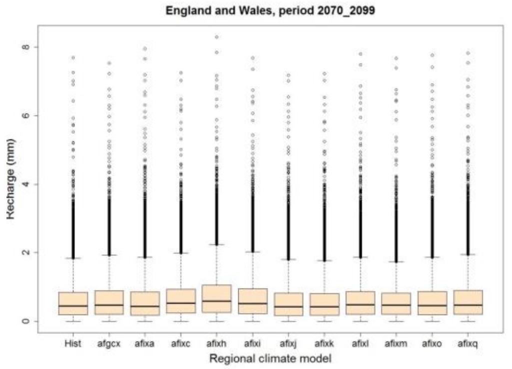
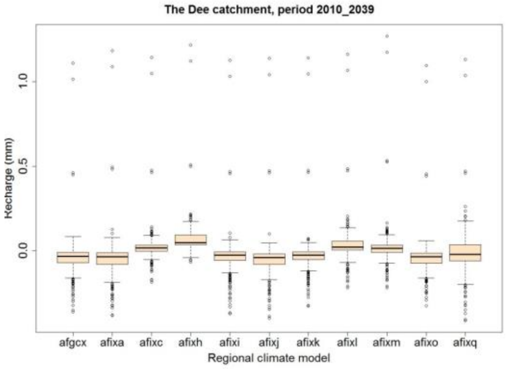
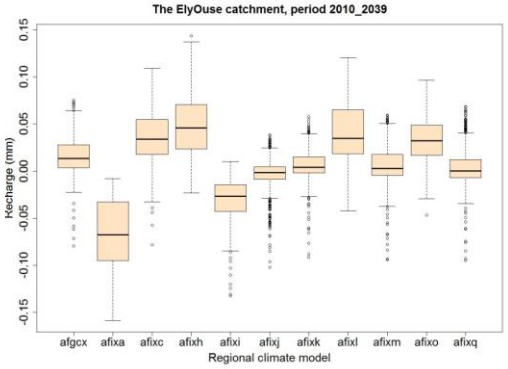
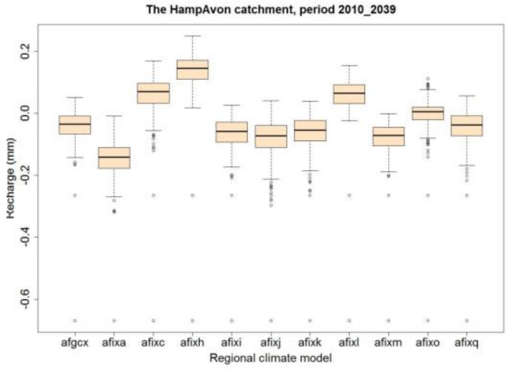
G: The Trent catchment	H: The Usk catchment	I: England and Wales
		
		
		

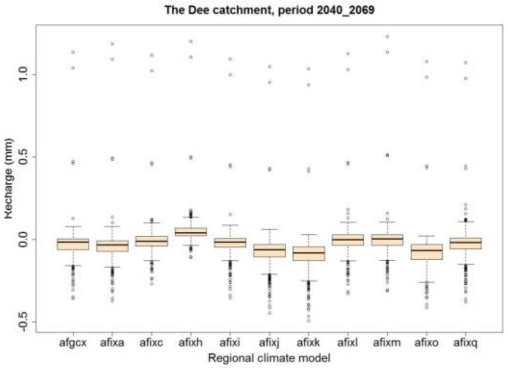
Figure 11. Plots of differences between simulated future LTA recharge values and historic LTA recharge values

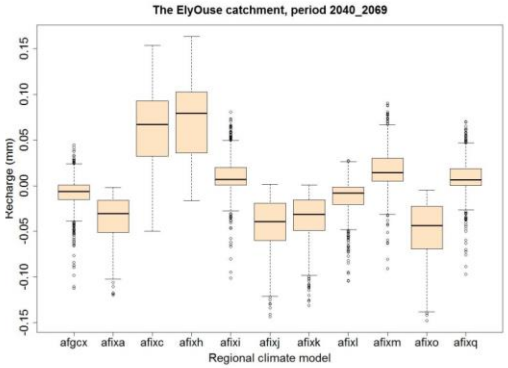
A: The Dee catchment	B: The ElyOuse catchment	C: The Hampshire Avon catchment

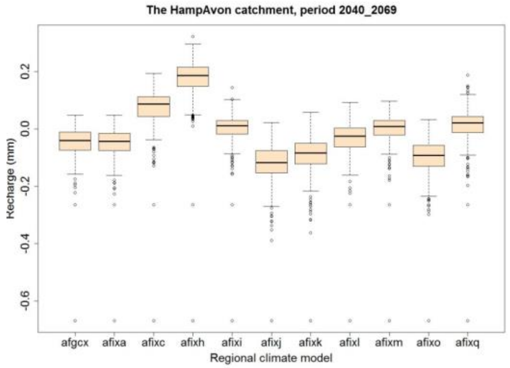


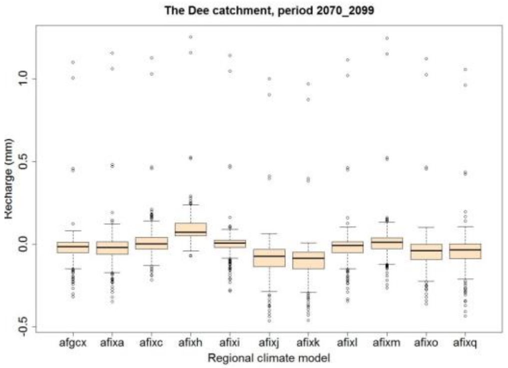


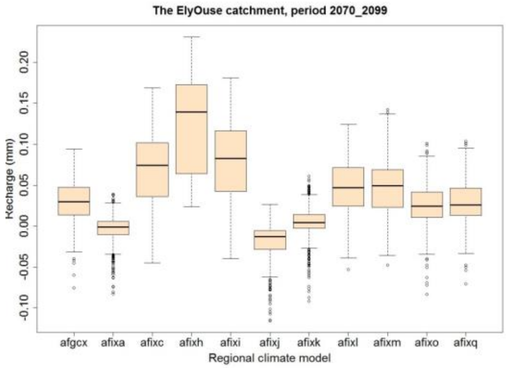


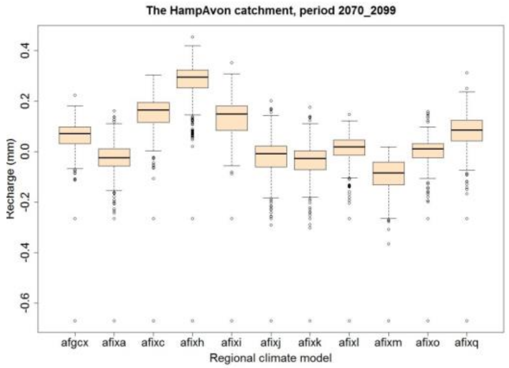




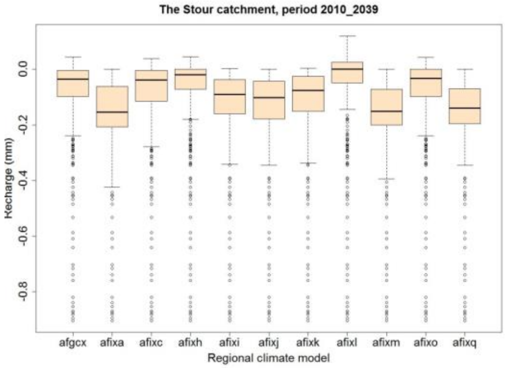


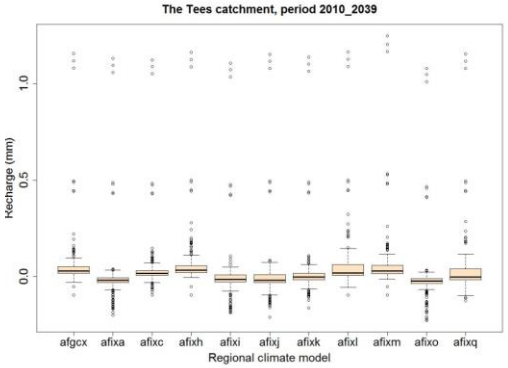


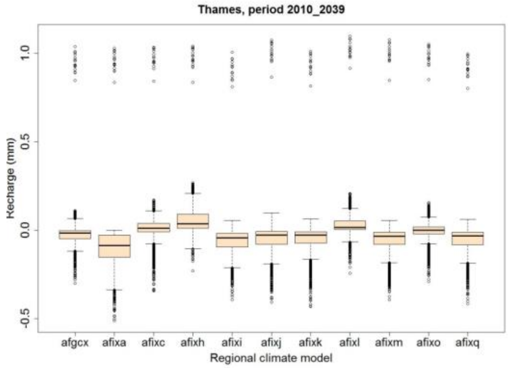


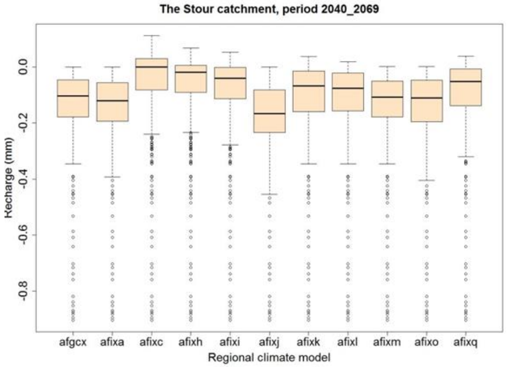


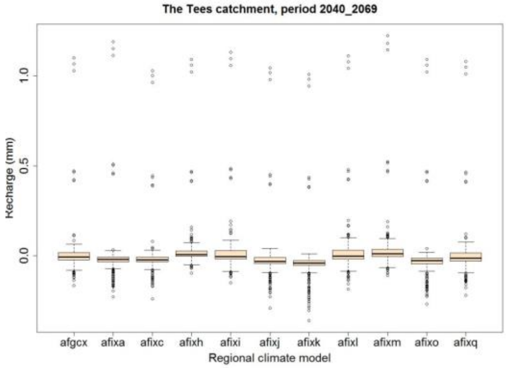
D: The Stour catchment	E: The Tees catchment	F: The Thames catchment

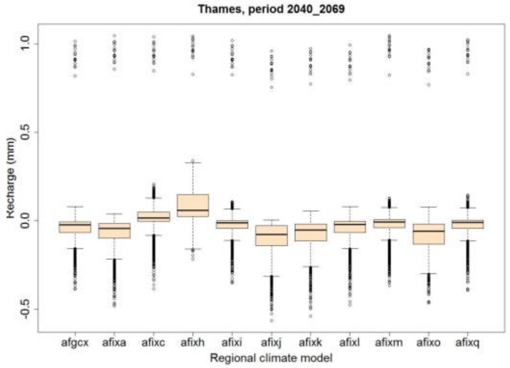


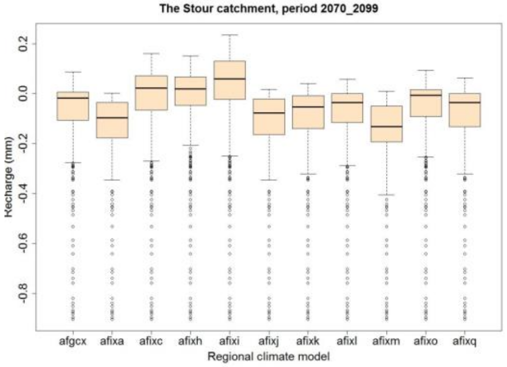


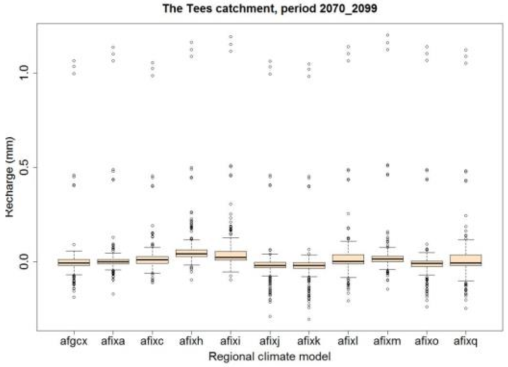


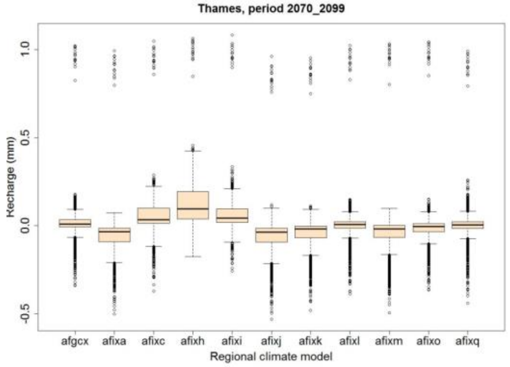




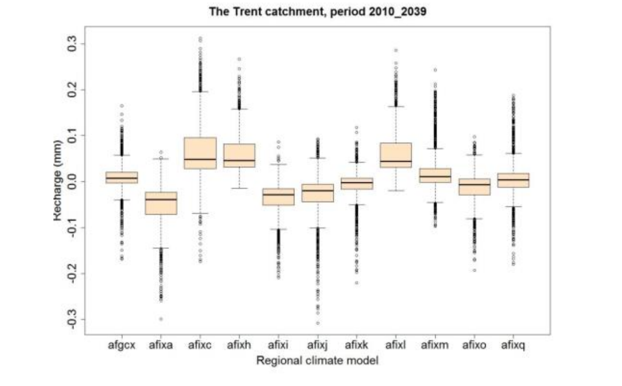


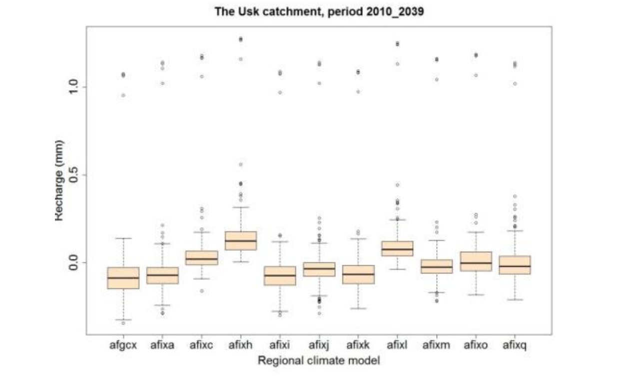


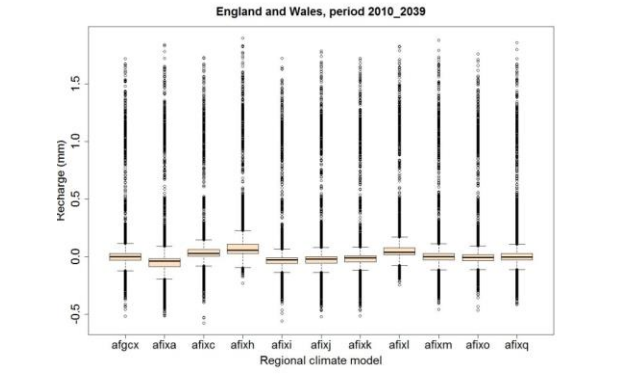


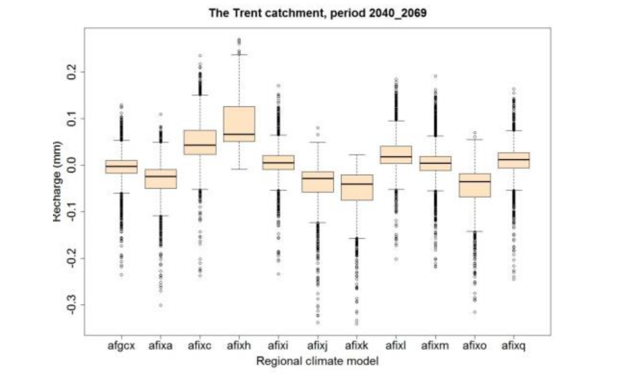


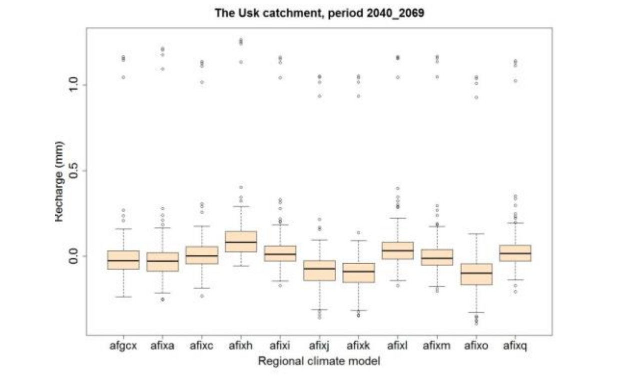
G: The Trent catchment	H: The Usk catchment	I: England and Wales

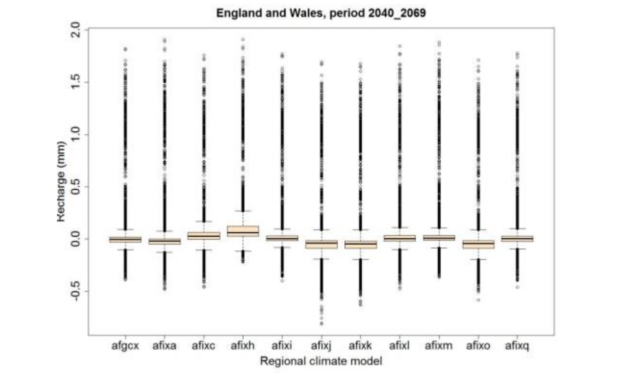


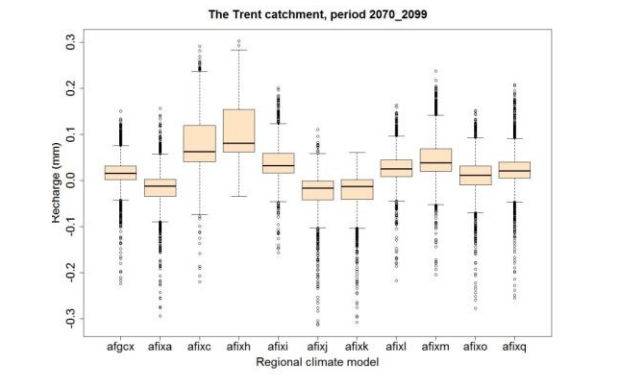


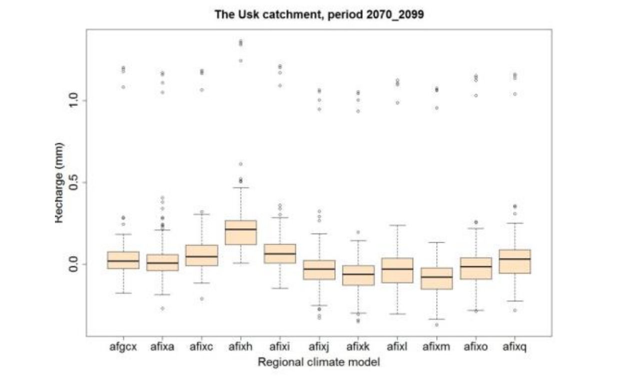


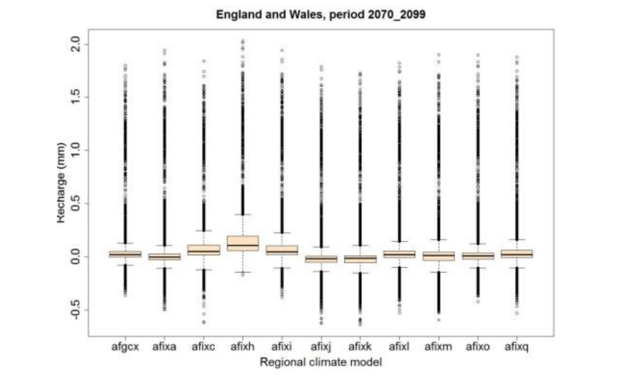












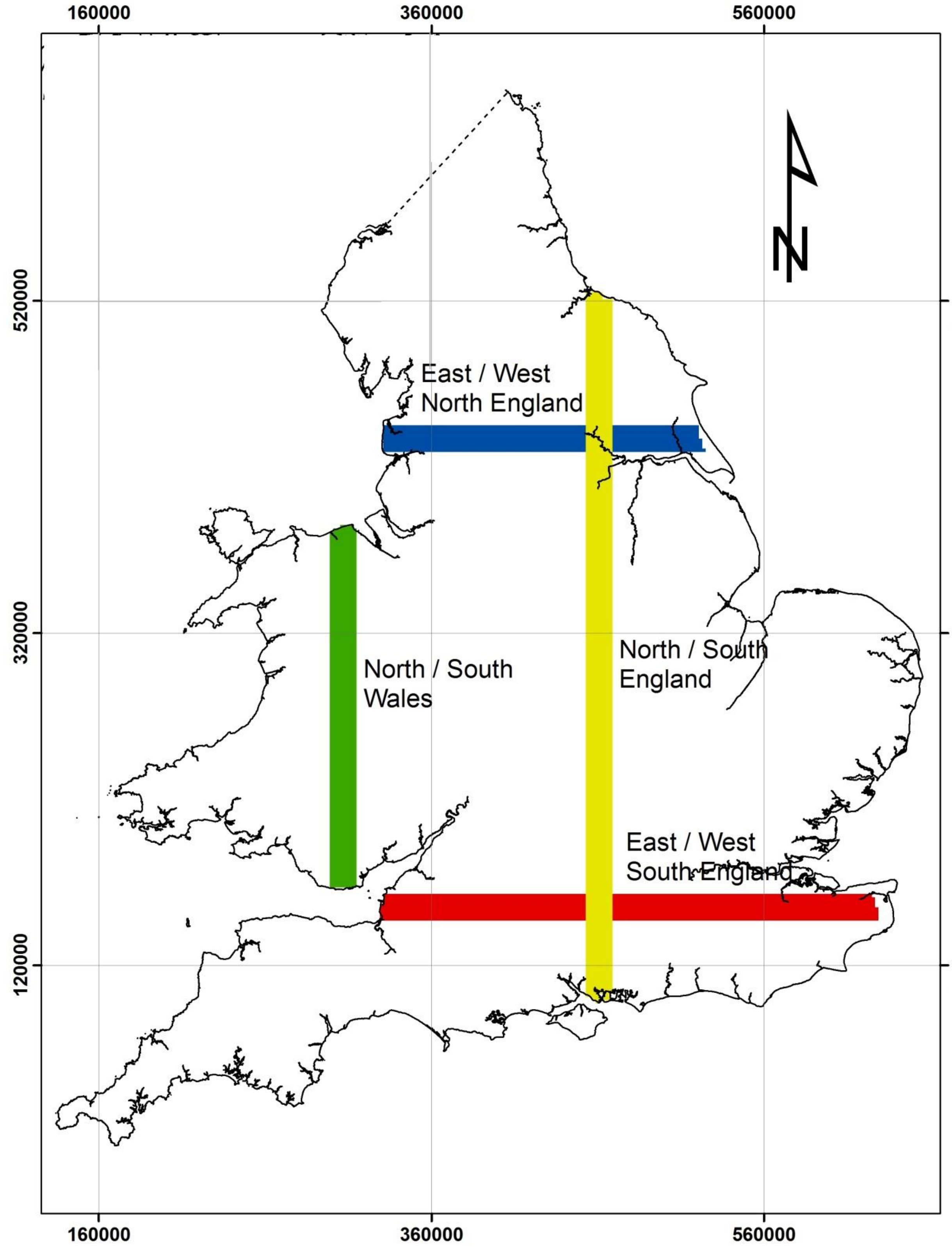
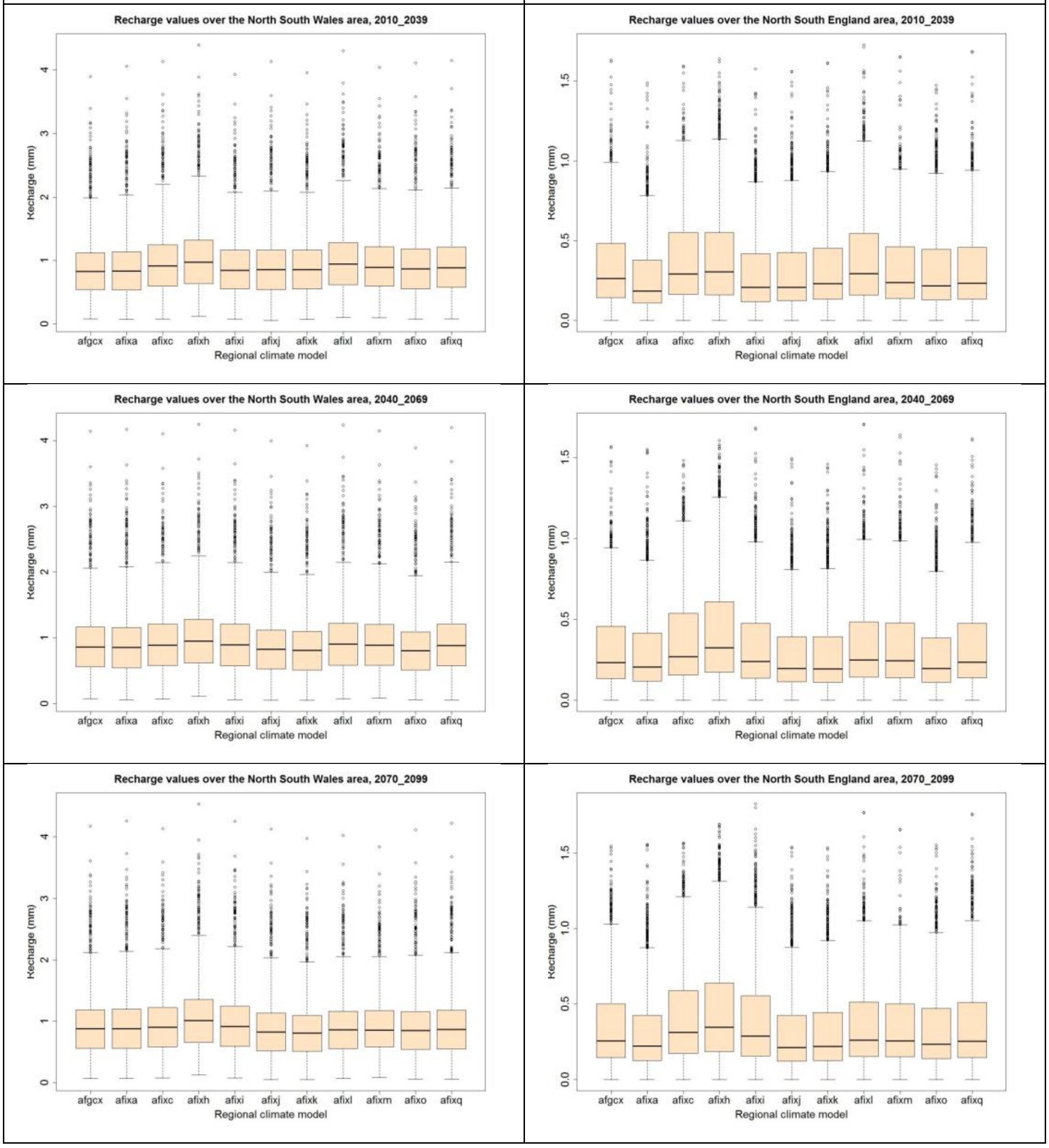


Figure 12. Position of east-west and north-west stripes

Figure 13. Plots of future recharge values over selected stripes

A: North south stripe over Wales	B: North south stripe over England



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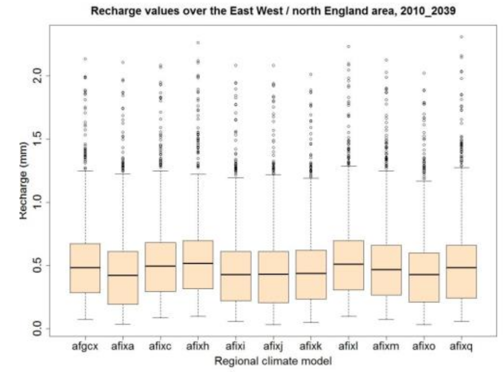
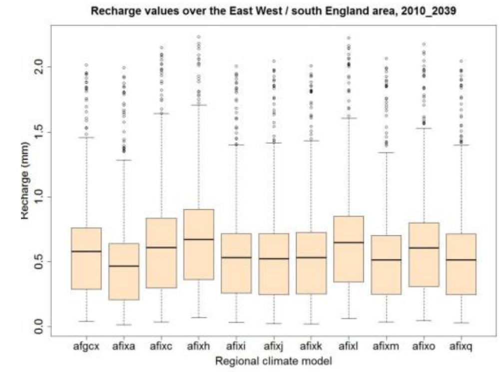
<tr><td>
</td><td>
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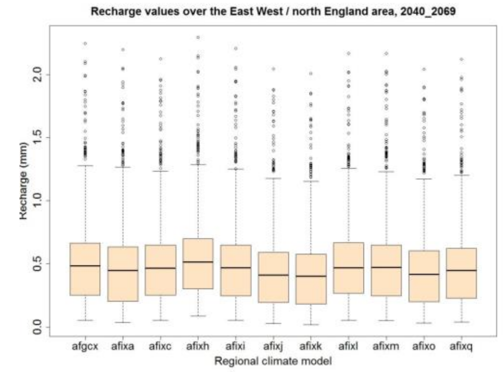
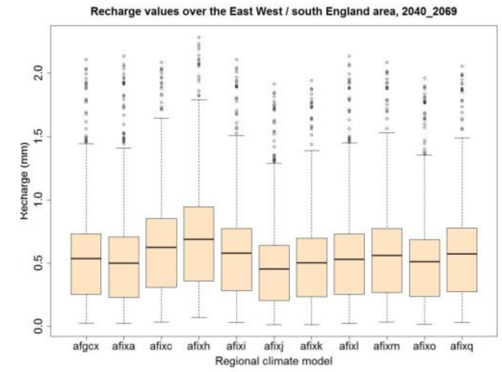
<tr><td>
</td><td>
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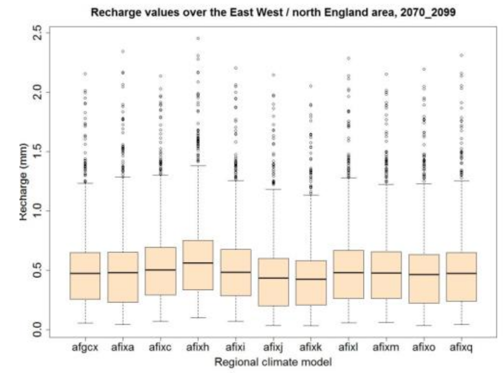
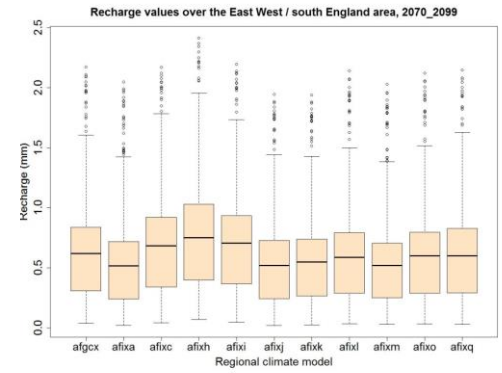
<tr><td>
</td><td>
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3.5 LAND USE CHANGE

3.5.1 Long-term averages for England and Wales

Two figures have been produced to illustrate the spatial changes in LTA recharge produced by modifying land use (Figure 14 and 15). Both figures show the LTA recharge from the historical simulation (top left of the diagram). Figure 14 presents the change resulting from modifying the land cover mapping from LCM2000 to LCM2007. The LTA recharge produced using LCM2007 is presented in the bottom left and the differences shown in the centre of the figure. The results from modifying land use to either woodland, arable or grass are presented in a column on the right-hand side of Figure 14. Figure 15 presents the results from modifying land use at the appropriate spatial location. Here the results are presented in two columns and show the LTA recharge where 50% land use is modified from one type to another.

Examining Figure 14 shows that comparing the recharge produced by using LCM2007 vs LCM2000 provides overall very little difference, but locally these are significant changes. These changes are mostly prevalent in the West of England and Wales and represent a reduction in recharge. For the more radical changes to land use, the following can be observed:

- Woodland: covering the country in trees significantly reduces potential recharge (see Houghton-Carr et al., 2013) – as trees generally use more water than other crops (maximum root constant specified as 2 m), but there are subtleties (e.g. Roberts et a., 2005)
- Arable: covering the country in crops (a representative crop type that has a maximum root depth of 0.75 m and a crop depletion factor of 0.8 is used) increased recharge in urban areas and reduces it over the Welsh hills (change in routing depth)
- Grass: covering the country in grasslands significantly increases potential recharge (significantly reduced crop coefficients with maximum root constant of 0.12 m).

A more subtle approach involves changing one land use type with another at the grid cell where it occurs (Figure 15). This is undertaken for 50% of the overall land use being converted from one type to another. There are 10 landuse types specified in the model using 10 arrays of data. These arrays have the same size and their values represent the percentages of landuse types so at each location the sum of the ten values from these arrays must add up to 100. In the subsequent runs, a 50% of a landuse type is replaced by another landuse type buy halving its percentage value and increasing the percentage value of the replacement landuse type by the same amount. The three land use type (arable, grass and woodland) are paired up with each other to undertake these changes. Of these pairs, the most significant changes are as follows:

- Arable to woodland: significant reduction in the east of England "bread basket effect"
- Grass to woodland: reduction in potential recharge over the whole country but predominantly in the western half
- Grass to arable: reduction in Wales and western England where managed grassland and semi-natural grass predominates

3.5.2 Catchment summaries using Box-Whisker plots

Figure 16 shows potential impact of complete (i.e. countrywide) land use change to either arable, grass, or woodlands on the calculated recharge values by using Box-Whisker plots. The differences between the LTA recharge values calculated using these land use types and the LTA recharges calculated using the dominant LCM 2000 land use are used to produce Box-Whisker plots. A whisker plot for the differences between the LTA recharge values calculated using the dominant LCM2000 and those calculated using the LCM2007 is also shown in Figure 16. All the plots share a common expected trend, and confirm the observations noted in Figure 14, that is the change of land use to woodlands results in significant reduction in recharge values and the change of land use to grass causes increase in recharge values compared to the values calculated using the dominant LCM2000. The use of land use arable has the lowest impact on the recharge values. This is because arable root depth falls between that of the grass and woodlands root depths, which consequently produces almost identical average recharge values. In general and on average the changes in land use from year 2000 to year 2007 did not cause significant impact on the calculated recharge values with the Dee and Usk catchments the only catchments showing wide range between the upper and lower limits of the Whisker plot. All plots show a number of outliers in the calculated differences. The maximum absolute change in recharge values calculated by replacing LCM2000 by LCM2007 over England and Wales is 0.6 mm/day.

The land use impact on the calculated recharge values is also investigated by varying the percentage land use classes of the percentage LCM2000 data by replacing 50% of one class by another class at a time. Figure 17 shows the Whisker plots of the differences between the recharge values calculated from these runs and the run using the percentage LCM2000 for all the catchments. This figure indicates that changing the land use from grass to forest causes the most significant reduction in recharge. On average, the reduction in recharge values is 0.26 mm/day using the recharge values calculated over England and Wales. However, this figure also shows that on average replacing 50% of arable by grass causes more recharge than replacing 50% of forest by grass. This depends on the extent of the area covered by the different land use types. On average the increase of recharge caused by replacing 50% of arable by grass is 0.022 mm/day but the maximum calculated increase in this case is 0.12 mm/day using the recharge values calculated over England and Wales. The increase in recharge values caused by replacing forest by grass is 0.012 mm/day but the maximum calculated increase in this case is 0.22 mm/day.

National maps of annual long term average recharge totals and differences, in mm/a simulated by ZOODRM (for various dominant land use runs, all assuming historic climate)

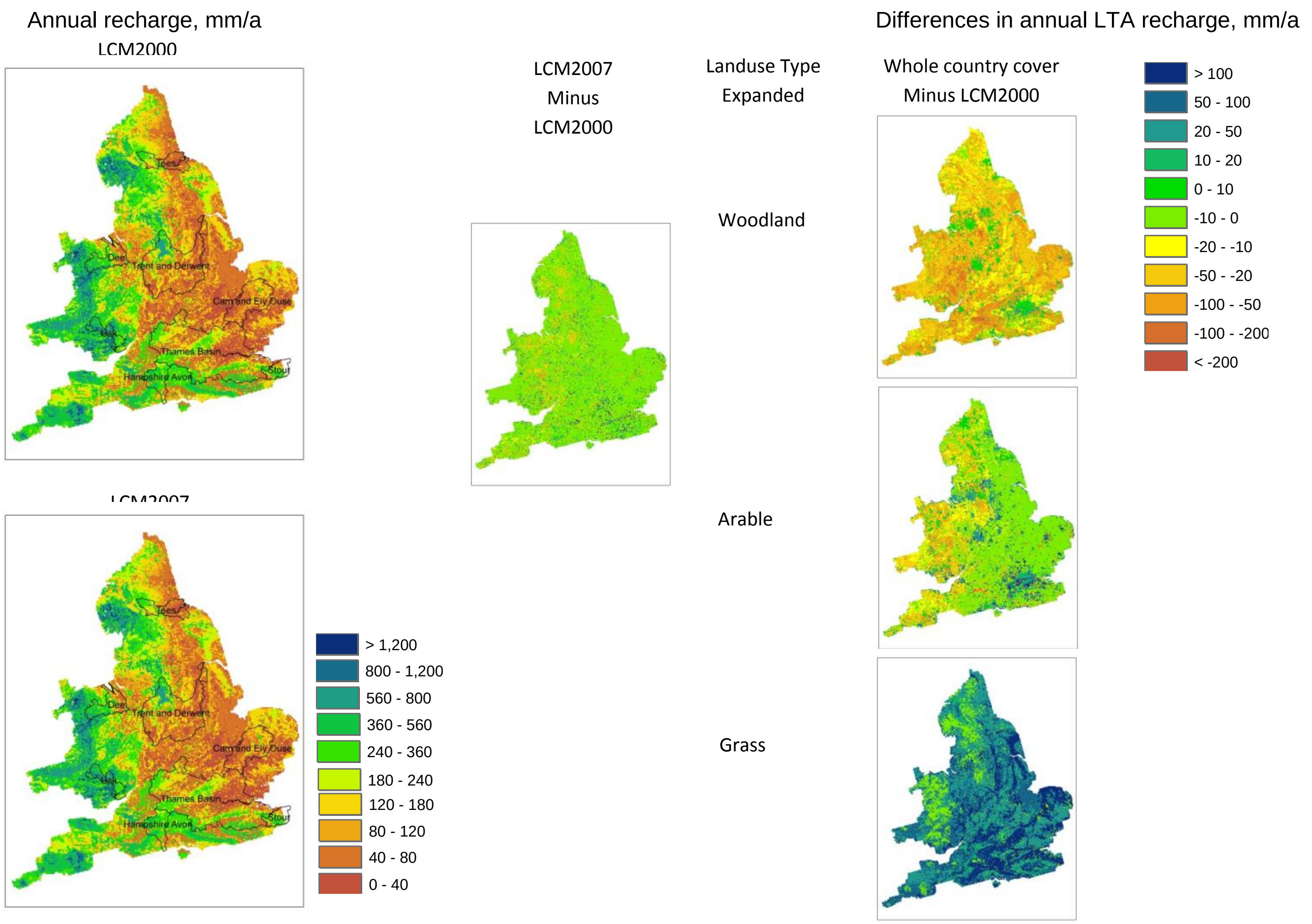


Figure 14. LTA recharge for changes to land use: LCM and single type coverage

National maps of annual long term average recharge totals and differences, in mm/a simulated by ZOODRM (for various percentage land use runs, all assuming historic climate)

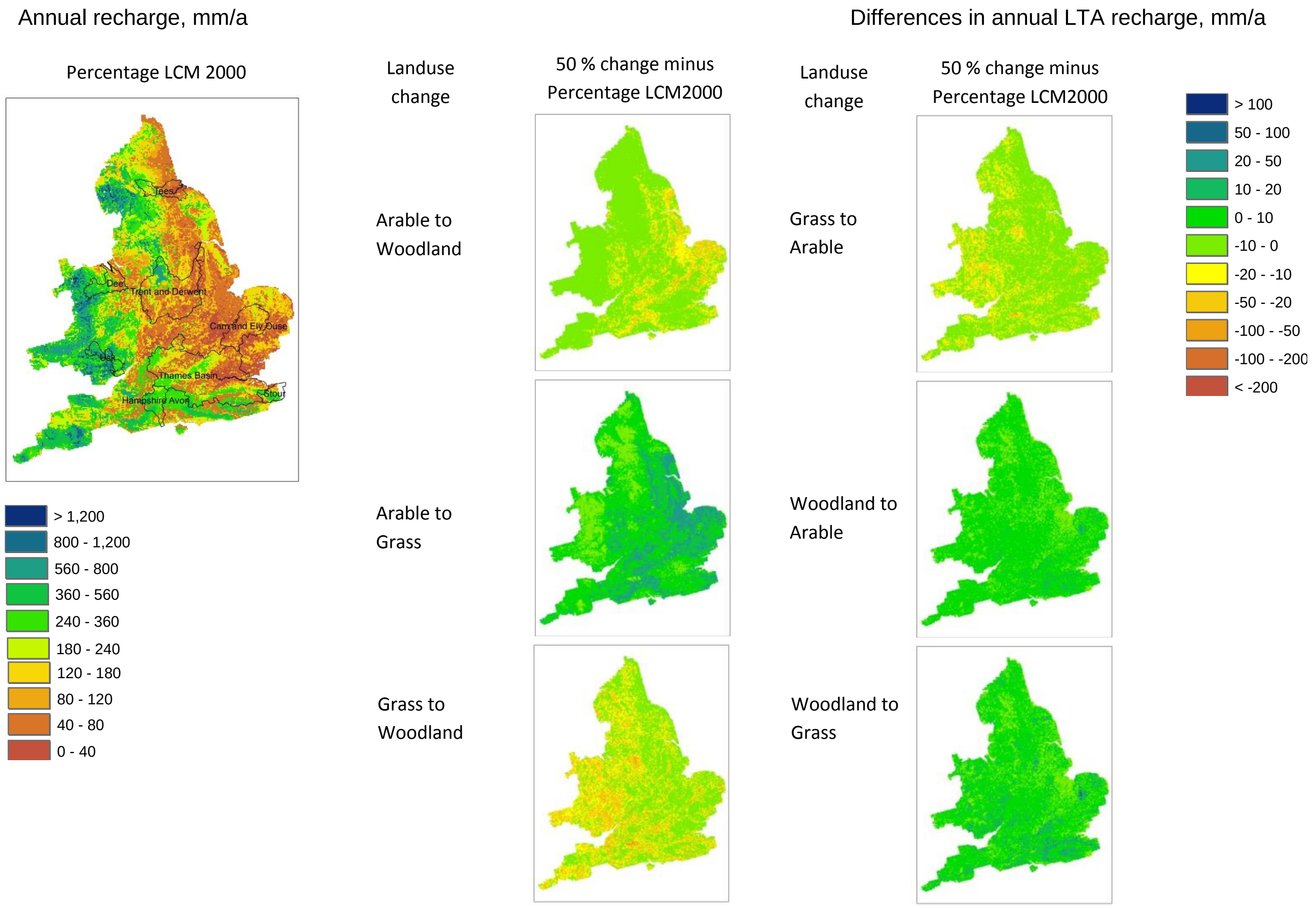


Figure 15. LTA recharge for changes to land use: like for like changes

Figure 16. Plots of differences between recharge values calculated with selected dominant land use types and those calculated with actual dominant LCM 2000

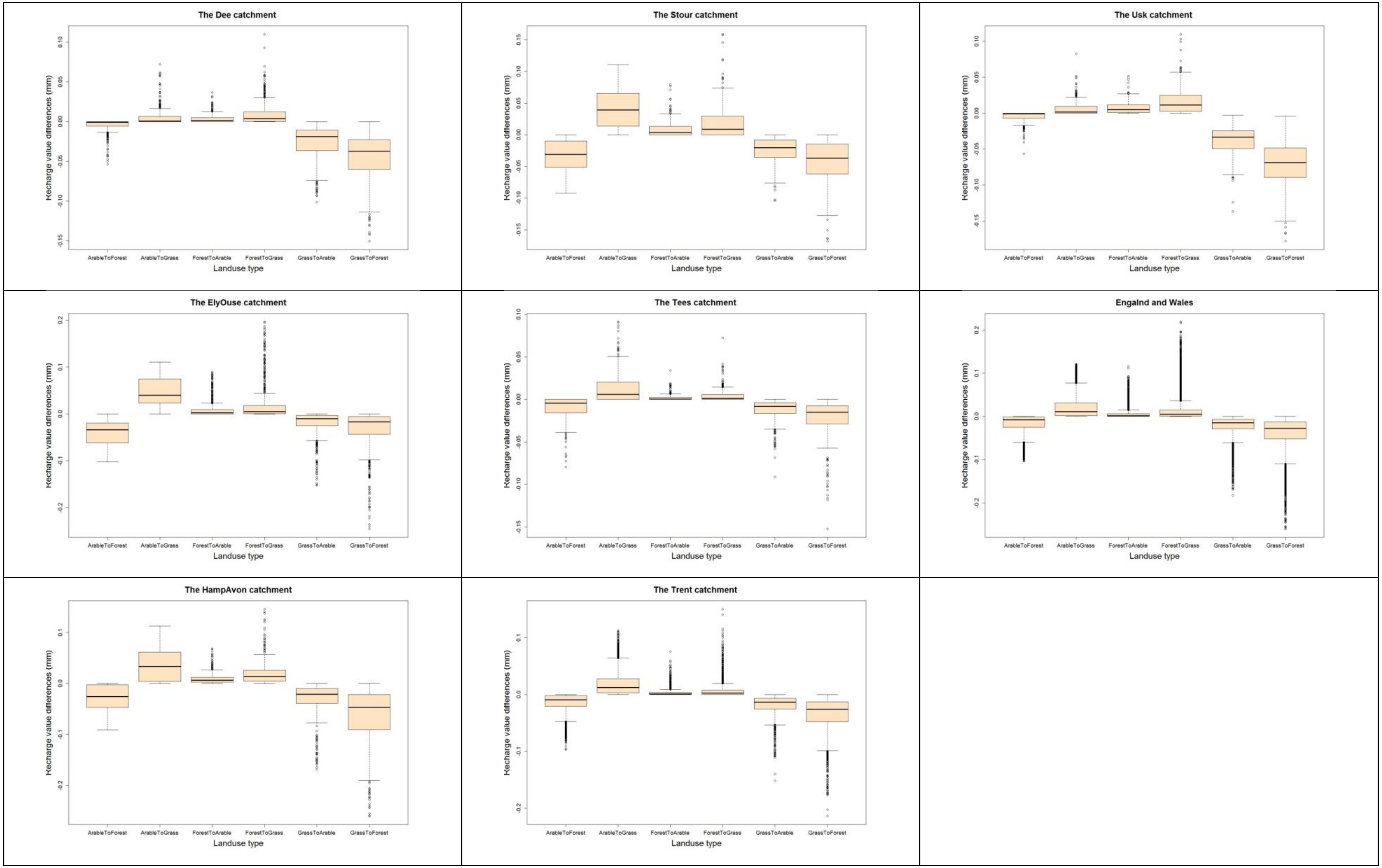
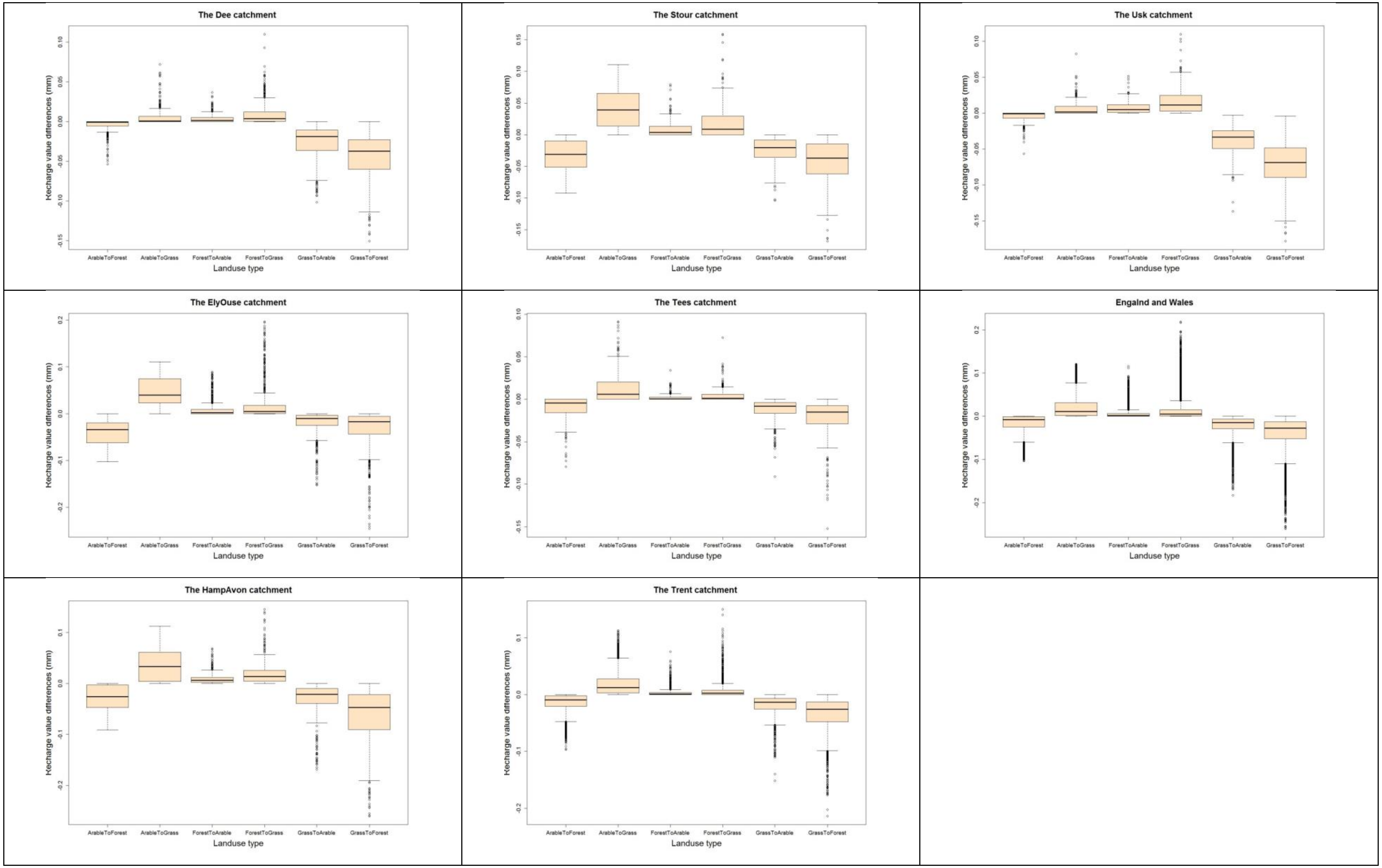

The Dee catchment
The Stour catchment
The Usk catchment
The ElyOuse catchment
The Tees catchment
Engalnd and Wales
The HampAvon catchment
The Trent catchment
Recharge value differences (mm)
ArableToForest
ArableToGrass
ForestToArable
ForestToGrass
GrassToArable
GrassToForest
Landuse type

Figure 17. Plots of differences between recharge values calculated with selected variations in percentage LCM 2000 and those calculated with actual percentage LCM2000


The Dee catchment
The Stour catchment
The Usk catchment
The ElyOuse catchment
The Tees catchment
Engalnd and Wales
The HampAvon catchment
The Trent catchment
Recharge value differences (mm)
ArableToForest
ArableToGrass
ForestToArable
ForestToGrass
GrassToArable
GrassToForest
Landuse type

4 Summary and conclusions

4.1 SUMMARY

To investigate how land use and climate change can affect potential recharge, 11 RCMs from the FFGWL project have been fed into the recharge model ZOODRM. This has produced potential recharge for the whole of England and Wales for three time slices (2020s, 2050s and 2080s). Allied to this, the historic rainfall and potential evaporation time series has been run for both historic and "extreme assumed" land use change. The recharge model was run using LCM2000 and LCM2007 datasets as well as three scenarios: all arable, all grass and all forested. A more subtle change in land use was investigated by swapping 50% of one land use for another, e.g. arable to forested. This ensured that land use was modified where such changes are likely to occur, and avoided problems with land use changes in unlikely places, growing crops on mountain tops, for example.

The results have been presented for the Abstraction Reform (AR) catchments (Dee, Ely-Ouse, Hampshire Avon, Stour, Tees, Trent and Derwent) as well as the Thames and results summarised for England and Wales. To investigate variability due to catchment orientation, then two east-west and two north-south strips were also examined. The results have been presented as both difference maps of LTA recharge and box and whisker plots for both the absolute values of recharge and the differences between the modified run and its basecase (historical simulation).

4.2 MAIN CONCLUSIONS

The output presented in this report is produced using a national-scale model that includes a range of simplifications and inherent assumptions. The results must be discussed, therefore, with these assumptions and simplifications in mind. In addition, the model uses a relatively coarse grid resolution (2 km by 2 km), which means its results are more relevant for water management at a regional scale rather than at local scale.

The pattern for England and Wales is generally increased recharge with significant outliers of greater recharge. However, the results show that generally the 2050s have reduced recharge with the 2080s producing predominately greater recharge. Spatially the most significant changes tend to occur in the west of England and in Wales (see Figure 9).

The catchments chosen have a range of sizes and are located in different climate conditions around the country. The response to climate change reflects this with recharge decreasing or increasing depending on the RCM used for the input data and time slice. It has been recognised that considering the variability of RCMs in any recharge study (Holman et al., 2011). For this study, a single climate model has been used to produce 11 different but equally likely futures. This approach has allowed a range of equally plausible futures to be considered (wetter or dryer). However one problematic feature is the relationship of the recharge calculated for the historic simulation 11 RCMs and that produced with observed data. These are different, with the historic simulation typically dryer (lees recharge) than for the observed data which suggests that the future predictions underestimates any increase in recharge.

Examining the plots produced (Figure 10 and 11) the following generalisations by catchment can be made:

- Dee – lower recharge in general with increasing recharge through the time slices
- Ely-Ouse – very slight increase in recharge which increases through the time slices
- Hampshire Avon –variation depending on the RCM; no significant change across the time slices
- Stour – reduction in recharge
- Tees – reduction in recharge which decreases through time slices

- Thames – variation depending on the RCM; significant outliers with increased recharge in the 2080s
- Trent – variation depending on the RCM; increased recharge through the time slices
- Usk – increased recharge; consistent over time slices

In terms of the results for climate change for the strips – there is greater variability E-W as opposed to N-S. This suggests the influence of Atlantic derived frontal systems and how these may change in the RCMs.

In terms of the effect of land use change then variation due to subtle 'real changes' in historic land use (between LCM 2000 and LCM 2007) is small. Extremes of land use change are predicted to result in significant change but these scenarios are very unlikely to be realised. For the Dee, Hampshire Avon, Tees and the Usk the change in recharge for land use change to climate change is comparable with the Ely-Ouse and Trent less and the Stour and England and Wales as a whole greater. This was investigated further by swapping out different land use types, i.e. arable to forested and showed much less variation than for the single land use runs.

The original question that the modelling work was to address relates to the relative changes in recharge related to climate change as opposed to land use change. Taking England and Wales as a whole then the order of change in recharge due to land use variation is: socio-economic land use (LCM2000 w.r.t. LCM2007) is less than spatial replacement whose magnitude of change in recharge is less than wholesale replacement (i.e. all one land use type for England and Wales). Comparing the magnitude of these changes with those resulting from climate change show that variation of recharge related to climate change variation falls in the middle of land use change. However, the variation of recharge due to the use of different RCMs is comparable with the overall variation of land use change, although this is tempered by the underestimation of recharge by the RCMs.

4.3 POSSIBLE FUTURE WORK

Further work that would help improve the conclusions are an improved understanding of the underlying assumptions regarding the RCMs used by FFGWL. Particularly the change in weather that these predictions incorporate, i.e. does rainfall reduce to the east of the country? This would have implications for understanding the behaviour of some of the catchments. Allied to this then would be an improved representation of drought frequency and the role of "blocking" in controlling weather systems.

Whilst the work has shown that land use change can produce greater variability than climate change current rates of land use change (i.e. decade to decade) do not result in significant modification of recharge. To properly quantify this, it will be necessary to include land cover scenarios such as those produced by the National Ecosystem Assessment work which may then show change closer to the magnitude observed for the climate change scenarios.

Potential recharge on its own does not give the whole story in terms of the hydrological cycle and the groundwater balance. To address this, the recharge model has to be used in conjunction with a groundwater model, ideally a distributed one. This work should, therefore, be linked to a groundwater balance. Possible solutions to this is linkage with the modelling undertaken by Risk Solutions/HR Wallingford for the AR work, comparison with existing studies of the imapcts of climate change on groundwater, i.e. Marlborough and Berkshire Downs (Jackson et al., 2010) and the work on the Otter Sandstone currently undertaken by AMEC (2013a, b).

The statistical analysis of the results presented here must be treated with caution. This is because small changes in recharge values may result in significant volumes of recharge over a catchment. It would be useful to discuss the impact on the water resources as volume as well as recharge depth after accounting for other processes such as changes in the flow regime in rivers and abstractions. Further work on the results such as presenting monthly averages of potential recharge and comparison between the results from different RCMs would be desirable.

Other work that could be undertaken to benefit the study is a better understanding of the uncertainty in the recharge results. The uncertainty analysis of the undertaken work could be highly complex because of the nature of processes we are dealing with. For example the complexity of weather modelling, the complexity of prediction and representation of the future socio-economic scenarios, and the uncertainty associated with the modelling tools applied. More rigorous sensitivity analysis to the impact of these processes on the estimated volume of water could be useful to address the uncertainty associated with the results. This must include other unforeseen processes such as high intensity events and long drought spells.

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Appendix 1 – Description of FAO56 calculation within ZOODRM

The simplified FAO calculates the evapo-transpiration based on the level of the soil moisture deficit (SMD) on a daily basis. It is assumed that crops draw water from soil at the full potential evaporation rate when the SMD value fluctuates between zero and the value of readily available water (RAW). Crops draw water from soil at a reduced rate if the SMD value fluctuates between RAW and total available water (TAW). Finally, crops are not able to draw water from soil if the SMD value reaches the value of TAW. The soil moisture deficit value cannot go beyond the value of TAW.

Total available water (TAW in mm) is calculated by the following equation:

$$TAW = 1000(\theta_{FC} - \theta_{WP})Zr$$

Where:

θ_{FC} is the moisture content at field capacity

θ_{WP} is the moisture content at wilting point

Zr is the root depth (m)

The readily available water RAW (mm) is calculated using the following equation:

$$RAW = dp \times TAW$$

Where dp is the depletion factor.

Soil storage is given as the difference between TAW and SMD

$$Soil\ storage\ = TAW - SMD$$

Appendix 2 – List of gauging stations and their locations used to calibrate the recharge model ZOODRM

Table A2_1. List of gauging stations used to calibrate the recharge model ZOODRM

River name	Station name	Grid reference	Eastings	Northings
Tavy	Lopwell	SX 475652	247500	65200
Tamar	Gunnislake	SX 426725	242600	72500
Torridge	Torrington	SS 500185	250000	118500
Taw	Umberleigh	SS 608237	260800	123700
Otter	Dotton	SY 087885	308700	88500
Frome	East Stoke Total	SY 866867	386600	86700
Stour	Throop	SZ 113958	411300	95800
Avon	Knapp Mill	SZ 156943	415600	94300
Avon	Bath ultrasonic	ST 738651	373800	165100
Blackwater	Ower	SU 328174	432800	117400
Rother	Hardham	TQ 034178	503400	117800
Ouse	Barcombe Mills	TQ 433148	543300	114800
Medway	Teston	TQ 708530	570800	153000
Thames	Kingston	TQ 177698	517700	169800
Lee	Lee Bridge	TQ 352872	535200	187200
Roding	Redbridge	TQ 415884	541500	188400
Chelmer	Rushes Lock	TL 794090	579400	209000
Stour	Stratf'rd	TM 042340	604200	234000
Waveney	Ellingham Mill	TM 364917	636400	291700
Ely Ouse	Denver Complex	TF 588010	558800	301000
Nene	Orton	TL 166972	516600	297200
Glen	Kates Bridge	TF 106149	510600	314900
Trent	North Muskham	SK 801601	480100	360100
Severn	Haw Bridge	SO 844279	384400	227900
Wye	Redbrook	SO 528110	352800	211000
Usk	Chain Bridge	SO 345056	334500	205600
Taff	Tongwynlais	ST 132818	313200	181800
Tywi	Nantgaredig	SN 485206	248500	220600
Teifi	Glan Teifi	SN 244416	224400	241600
Dee	Chester Suspension	SJ 409659	340900	365900
Weaver	Ashbrook	SJ 670633	367000	363300
Mersey	Westy	SJ 617877	361700	387700
Ribble	Samlesbury	SD 587314	358700	431400
Lune	Halton	SD 503647	350300	464700
Kent	Sedgwick	SD 509874	350900	487400

Derwent	Camerton	NY 038305	303800	530500
Eden	Sheepmount	NY 390571	339000	557100
Went	Walden Stubbs	SE 551163	455100	416300
Aire	Beal Weir	SE 535255	453500	425500
Ouse	Skelton	SE 568554	456800	455400
Derwent	Buttercrambe	SE 731587	473100	458700
Tees	Low Moor	NZ 364105	436400	510500
Wear	Chester le Street	NZ 283512	428300	551200
Tyne	Bywell	NZ 038617	403800	561700
Annan	Brydekirk	NY 191704	319100	570400
Nith	Friars Carse	NX 923851	292300	585100
Ayr	Mainholm	NS 361216	236100	621600
Clyde	Daldowie	NS 672616	267200	661600
Tweed	Sprouston	NT 752354	375200	635400
Forth	Craigforth	NS 775955	277500	695500
Tay	Ballathie	NO 147367	314700	736700
Beauly	Erchless	NH 426405	242600	840500
Conon	Moy Bridge	NH 482547	248200	854700
Spey	Boat o Brig	NJ 318518	331800	851800
Deveron	Muiresk	NJ 705498	370500	849800

Figure A2_1. Locations of gauging stations used in the calibration of the distributed recharge model ZOODRM