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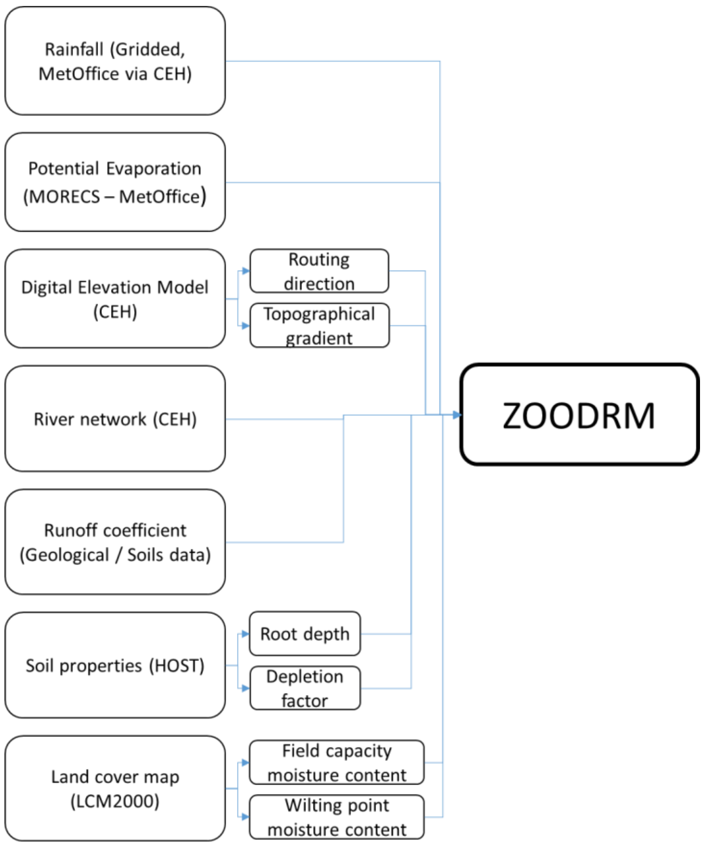
Application of the recharge model code ZOODRM to the British Mainland under conditions of climate change: scoping sources of uncertainty

Informatics Programme

Internal Report OR/18/021



BRITISH GEOLOGICAL SURVEY

INFORMATICS PROGRAMME

INTERNAL REPORT OR/18/021

Keywords

Recharge model; British mainland; climate change; uncertainty.

National Grid Reference

SW corner 40000,-10000
NE corner 680000,1010000

Front cover

Flowchart showing parameters used in the recharge model ZOODRM.

Bibliographical reference

HUGHES AG; MANSOUR MM. 2018. Application of the recharge model code ZOODRM to the British Mainland under conditions of climate change: scoping sources of uncertainty. *British Geological Survey Internal Report*, OR/18/021. 29pp.

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Keyworth, Nottingham British Geological Survey 2018

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Acknowledgements

This report has been produced as part of the CHANGE project. The CHANGE project lead, Anna Harrison is gratefully acknowledged for her support. Chris Williams is also gratefully acknowledged for his help with this work.

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Summary

This report summarises the likely sources of uncertainty associated with the GB recharge model and its application to the 11 ensembles of RCM produced for the Future Flow and Groundwater Level datasets. It identifies the sources of uncertainty in the base model as applied to historical data (1962-2010). The range of responses caused by the application of the 11 ensembles is presented and discussed. Recommendations for further work include quantifying the parametric uncertainty associated with the base model.

1 Introduction

The BGS authored recharge model ZOODRM and its application to the British mainland or Great Britain (GB) has been increasingly used on a number of BGS projects and to produce products. The Future Flow and Groundwater Level (FFGWL) ensembles have been run through it to examine the impacts of climate change. This has resulted in a number of outputs produced which have potential value for understanding how soil processes change under conditions of forecast climate change. However, there is a need to define the sources of uncertainty as part of model metadata, which will aid both its reliability and credibility.

This report briefly describes the recharge model and its application to the GB mainland and FFGWL ensembles and presents sample spatial output. The main data inputs are documented and a qualitative assessment of the uncertainty associated with each one is provided. Given that the 11 ensemble members each provide a source of uncertainty, the rainfall, potential evaporation and recharge from each is presented. Finally, recommendations are made for further work.

2 Description of recharge model code and its use

2.1 NATIONAL-SCALE RECHARGE MODEL

2.1.1 Model code

ZOODRM (Mansour and Hughes, 2004) is an Object Oriented model developed by BGS as part of the ZOOM suite of models. It is a distributed recharge model that simulates runoff and recharge processes and provides the output in a gridded form for use with groundwater flow models or on a catchment basis for water balance purposes. It has been applied in both the UK nationally (see Figure 1), regionally and overseas (e.g. West Bank; China).

2.1.2 Model Instance - application to the GB mainland:

The GB-wide recharge model was built using BGS' code ZOODRM. Potential recharge is calculated on a grid with 2 × 2 square kilometre cells over the area described by the following National Grid Reference: Bottom Left (40000, -10000) Top right (680000, 1010000). The model has been run for the period 1st January 1962 to 31st December 2010 and calibrated against the runoff component of river gauged flow. It calculates recharge on a daily basis and aggregates the recharge to a monthly value.

The calculation method used is the modified UN Food and Agricultural Organisation (FAO) as proposed by Griffiths et al. (2006). It uses the distribution of soil parameters and crop parameters obtained from the HOST soil data map, which includes 33 classes of soil types (Boorman et al., 1995), and the land cover map, Land Cover Map 2000 which includes 9 land use classes (Natural Environmental Research Council, 2000). The values of these parameters are obtained from the literature.

The model calculates potential recharge, which is the amount of water calculated to leave the bottom of the soil zone. It does not, therefore, take into account any modification of recharge resulting from the unsaturated zone and other, minor aquifers which may lie above the water table.

The implications for uncertainty for the model are discussed in Section 3.

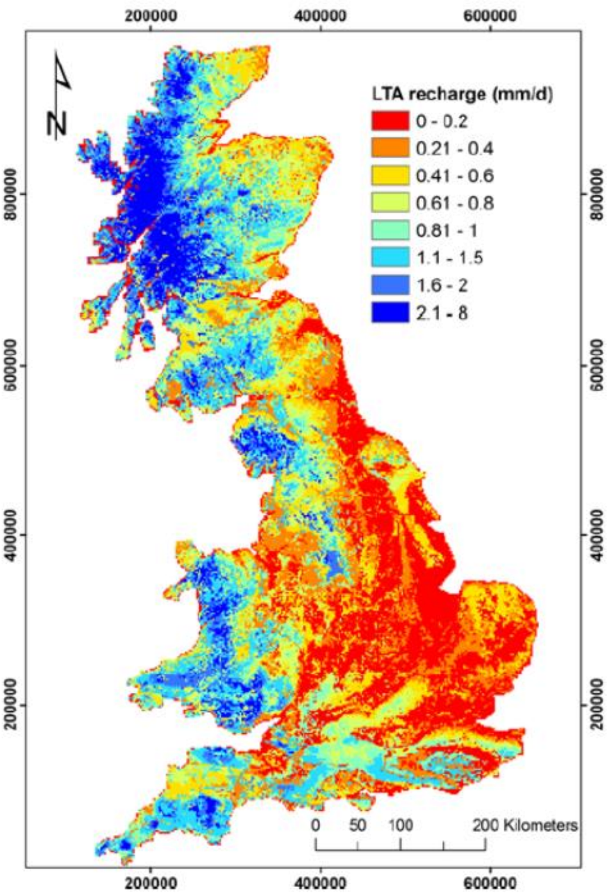

Figure 1. Long-term average recharge calculated for the GB landmass

2.2 CLIMATE CHANGE DATASETS – FUTURE FLOWS CLIMATE

Funded by DEFRA and produced in 2009, UKCP09 provides projections of climate change in the UK (Prudhomme et al., 2012; Murphy et al, 2007; Jenkins et al., 2009; Murphy et al, 2009). Based on the 11 variants of the Hadley Centre Regional Climate Model HadRM3-PPE, which underpins the UKCP09 scenarios, the Centre of Ecology and Hydrology (CEH) applied a bias-correction and downscaling procedure to produce 11 scenarios of Future Flow Climate data. The HadRM3 is used as a perturbed physics ensemble approach to produce the 11 ensembles (Prudhomme et al., 2012) with one unperturbed example (afgcx) and ten variants (aixfa – afixq). These data are 1 km gridded climate time variant projections of rainfall and potential evaporation and allow comparison of results across a range of scales and geographical regions. The data were produced as daily grids from 1st January 1950 to 30th November 2099. The 11 ensembles are named as follows:

1. afgcx (unperturbed)
2. afixa
3. afixc
4. afixh
5. afixi
6. afixj
7. afixk
8. afixl
9. afixm
10. afixo
11. afixq

The recharge model has been run with rainfall and potential evaporation for all 11 ensembles and the results processed as discussed in Section 4.

3 Qualitative assessment of uncertainty

3.1 STRUCTURAL UNCERTAINTY

Whilst the recharge model is itself a relatively simple model, relying on a soil water balance, there remain choices to be made for the model setup. The model grid and runtime period are 2 km and 1st January 1961 to 31st December 2010. The former was chosen as a compromise between the level of detail required and run times / data handling issues. The latter was chosen based on data availability. No work has been undertaken to determine the impact of changing either the grid spacing or the length of the model run. However, a 30 year period is chosen for running models driven by rainfall as this covers most of the climate extremes.

The model runs on a fixed time step of one day. However there is a choice of recharge calculation method. The modified FAO method was used (see above) which was a compromise between sophistication of soil processes and data availability. The model has been benchmarked against the results from other recharge models (see Mansour et al., 2018) which assist the understanding of its accuracy.

3.2 PARAMETRIC UNCERTAINTY

The main parameters for the GB recharge model are presented in Figure 2 and their provenance and main source of uncertainty is described in Table 1. Broadly the parameters fall into two categories: model results produced as grids or interpreted data involving human input and/or some form of algorithm.

Regarding rainfall datasets, Keller et al. (2015) state that further research is required to increase the confidence in certain areas for the CEH-GEAR rainfall estimates. They attribute the source of error to two regions, the first is in the North and West of the UK where they associate errors to rapid orographic rainfall enhancement with altitude. The second is in the South and East of the UK where the terrain is flatter resulting in poorer representation of convective storms, which typically occur in the summer months as a result of heating of the land mass. This leads to lower confidence and greater uncertainty in the rainfall distribution.

While there is no discussion related to uncertainty associated with the UK Met Office MORECS potential evaporation data (Hough and Jones, 1997), Kay and Davies (2008) discuss the application of two different formulations to derive PE for a set of climate models and they also compare MORECS PE dataset with these formulations. They conclude that the uncertainty introduced by the PE formulation is important for some applications but is less than that due to the climate model.

Geological and soil maps are prepared by delineating the boundaries of the different stratigraphic or lithological units based on field observations. Despite the recent developments in computer-based geological modelling, the geological boundaries mapped in two dimensions remain an important source of information that assist constraining the 3D geological models. The source of uncertainties associated with these boundaries can be conceptual or scale dependent (Lark et al., 2015) and is usually annotated by buffering the line or with text on maps. Because of the high resolution of the grid used to undertake the calculations, it is assumed that errors due to uncertainties associated with geological and soil mapping will be overshadowed by the errors introduced to the discretisation of the study area.

Land Cover Map LCM2000 is a vector land cover map of the UK based on satellite data. Land parcels were derived from image segments. Land cover is based upon UK Biodiversity Action Plan (BAP) Broad Habitats (Morton et al., 2011). The LCM 2000 product uses external datasets that were collected with different resolutions, with different levels of generalisation, and their own potential inaccuracies, so the final accuracy of LCM2000 depends in part on their reliability of these source datasets (Fuller et al., 2002).

Table 1. Summary of the main parameters used as input for ZOODRM model of GB mainland

Parameter	Description	Sources of uncertainty
Rainfall	Daily 1 km^2 gridded rainfall available from CEH (modelled)	Measurement of rainfall; process of gridding (imputation)
Potential Evaporation	Monthly MORECS available on a 40 km2 gridded basis (Hough and Jones, 1997) (modelled)	Input parameters to the model; assumptions; interpolation from 40 km x 40 km grids
Digital Elevation Model	CEH gridded data (modelled)	Source data; assumptions; process of gridding (imputation)
River network	CEH – shapefile (NERC, 2003)	Source data; process of river centre line/thalweg creation – see Morris and Heerdegen (1988) for more details on automatic creation of river networks
Geological mapping	BGS (human interpretation)	Mapping process itself (heuristic/field interpretation); digitisation of outcrop linework; gridding of vector data
Soils mapping	Maculay Institute (human interpretation)	Mapping process
Soil properties	HOST (Boorman, 1995)	Source data; assumptions; interpretation
Land cover mapping	LCM2000, CEH (Fuller et al., 2002) (Interpreted from remote sensed data)	Source data; assumptions; process of gridding (imputation)

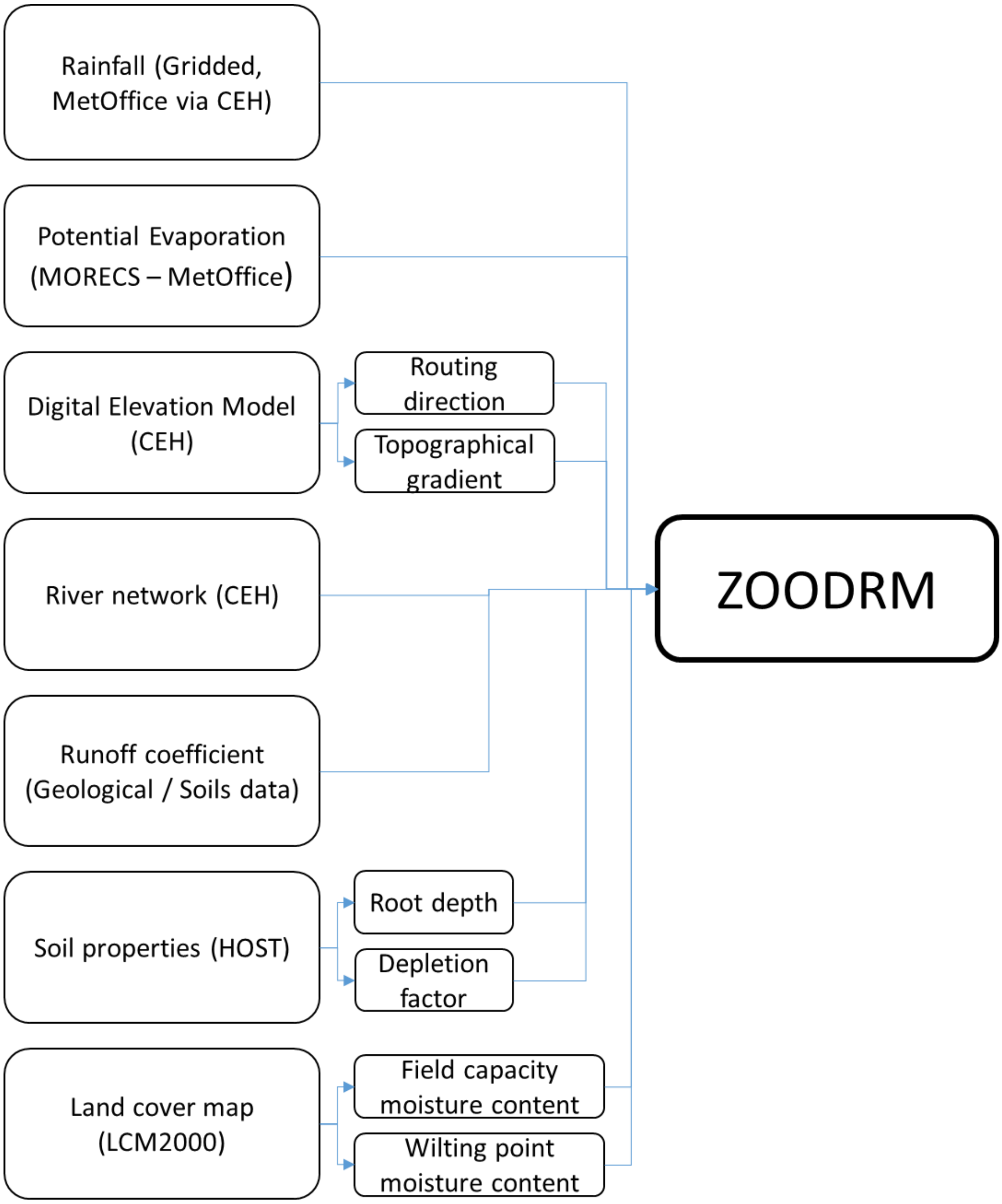

Figure 2. Flowchart illustrating input data for ZOODRM

3.3 CALIBRATION PARAMETERS

The only calibration parameter is the runoff coefficient, the split between runoff and recharge when excess water is produced at a node, and how this is obtained. River flow data was used to produce baseflow estimates and the remaining component, i.e. fast flow was used to compare with the recharge model results. The runoff coefficient was assigned to zones based on geological mapping and the runoff coefficient was optimised so that the modelled fast flow component matched the observed. More details can be found in Mansour et al., (2018).

Note that the river flows are themselves subject to both measurement and model uncertainty. The latter is due to the stage-discharge relationship. As well as this, base flow separation is, in itself, a modelling process and has an associated uncertainty.

4 FFGWL climate change ensembles

Following recharge model application to the GB landmass, one of its uses is for determining how climate change may impact potential recharge. However it is necessary to understand what the nature of the ensemble members are and how they may affect recharge. The following describes the output produced by running the recharge model with the 11 ensemble members and the resulting time series of rainfall, potential evaporation and potential recharge:

- Table 2, Table 3, and Table 4 present the total (GB landmass) for rainfall, potential evaporation and recharge for the 11 ensemble member.
- Figure 3 to Figure 5 show time series of the minimum, median, and maximum projected values of rainfall, evapotranspiration, and recharge together with the historical values for every month.
- Figure 6 to Figure 8 show time series of the 25th percentile, the median, and the 75th percentile of the projected values of rainfall, evapotranspiration and recharge.
- Appendix 1 show the time series of rainfall, evapotranspiration and recharge plotted for all months.

Figure 3 shows the minimum, maximum, and mean time series of the projected rainfall values. It is produced by running the 11 ensemble members through the recharge model and calculating total rainfall for the British mainland. It is clear that, for every month, the maximum rainfall is approximately 3 times greater than the minimum rainfall reflecting the degree of uncertainty associated with the future projection of rainfall data. It must be noted, however, that the time series of maximum or minimum values may not be produced from a single model, rather they are a collection of values obtained from different models. Comparing with observed historical rainfall values, it is clear that in most cases, the maximum and minimum projected rainfall values bound the historical ones except in couple of occurrences, e.g. the rainfall time series for February.

Figure 4 presents the evapotranspiration time series calculated using the projected and historical rainfall and potential evaporation data. Again it is produced by running the 11 ensemble members through the recharge model and calculating total potential evaporation for the British mainland. While the projected maximum and minimum values also bound the historical ones, it is clear that on average, the historical evapotranspiration values are higher than the projected ones. This applies especially to the months: January, March, April, November and December. Average historical values calculated over June, July and August are close to the average projected values, while the average historical evapotranspiration values for September are below the projected averages.

Figure 5 shows the recharge time series calculated using the recharge model from the driving data of historical and future predicted rainfall and potential evaporation data. Unlike the evapotranspiration time series, the recharge time series behave as the rainfall time series, i.e. the average historical values are aligned more to the average projected ones than those of the evapotranspiration values. Also there are a period of time in February where the historical recharge values are above the maximum projected recharge values. Figure 5 also shows that the minimum projected recharge values are approximately 4 times lower than the maximum projected recharge values illustrating, consequently, the significance of uncertainty in the calculated recharge values.

Figure 6, Figure 7, and Figure 8 illustrates clearly the trends in the used projected rainfall values and the calculated evapotranspiration and recharge values respectively. Figure 6 demonstrates that there is an increase in the trend of the rainfall values over the autumn and winter months (October, November, December and January, February,) and a decrease in the trend of rainfall values over May and the summer and early autumn months (June, July, August, and September) while the future values for March and April have little or no change. This observation applies to the time series of recharge values (Figure 8) but the changes in trends are a bit more subdued than for either rainfall or evaporation. For example, the recharge time series for October show almost flat trends as observed in the March and April time series. This behaviour can be also depicted in the seasonal summaries of recharge (Figure 9, Figure 10, and Figure 11). The greatest differences are shown by the seasonal recharge maps as time goes on 2020s to 2050s to 2080s with the winter recharge increasing at the expense of the summer values. The positive pattern within spring and autumn also becomes clearer through the time slices and suggests a move towards wetter winters and dryer summers.

The summary tables (Table 2, Table 3, and Table 4) show that the average values for each variable show differing results for each ensemble. All of the ensembles apart from afixk are wetter, i.e. have greater average rainfall than the equivalent historical simulation. For PE the picture is more mixed with afgcx, afixa, afixh, afixi, afixl, afixm and afixo showing increases and the rest of the ensemble decreases. This results in the changes in recharge to follow the rainfall pattern with only afixk showing a reduction in recharge from historical simulation to future climate.

In general, there is greater variability of the future climate compared to the historical simulation for each ensemble.

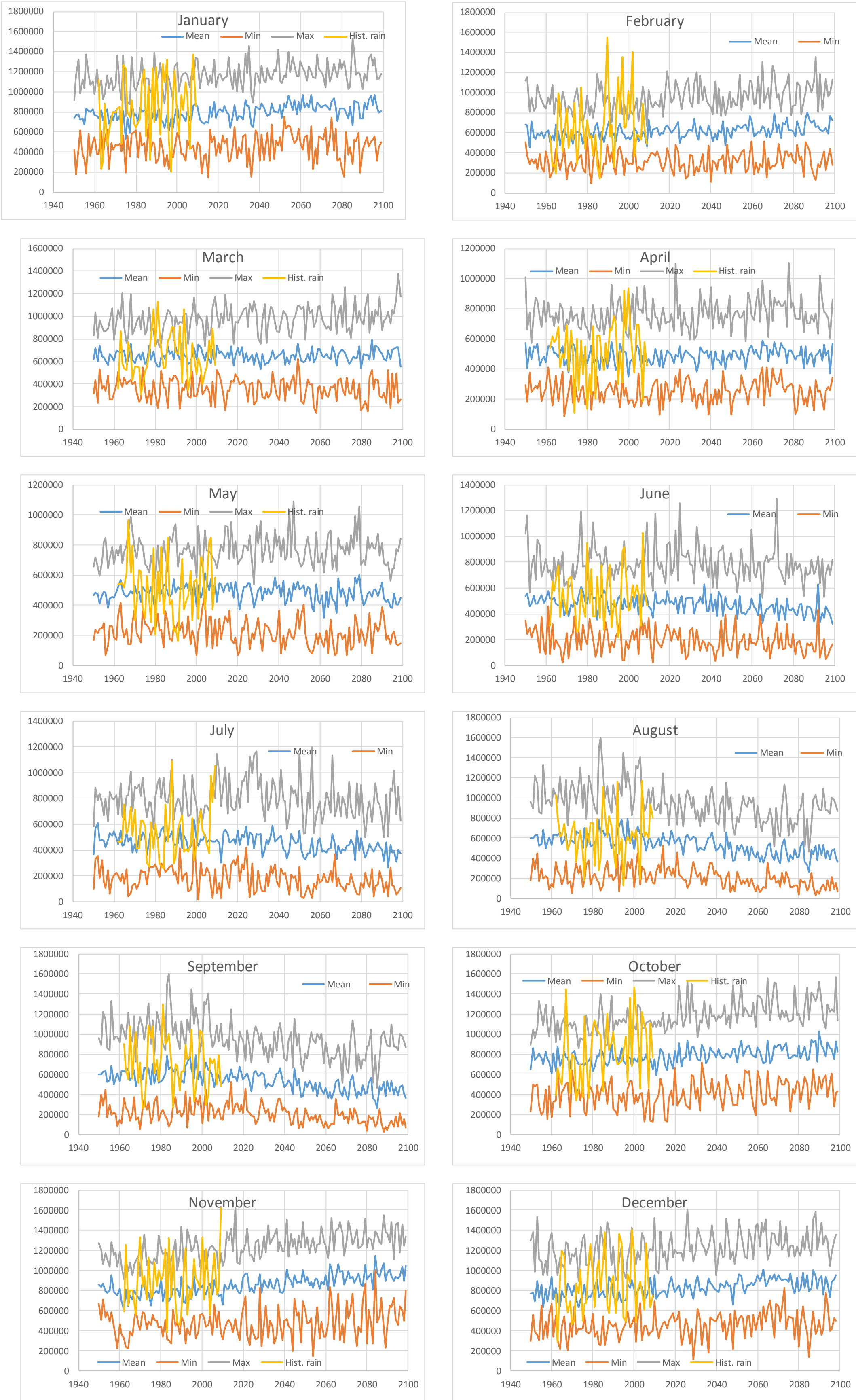

Figure 3. Minimum, mean, and maximum projected rainfall values and simulated historical rainfall values. Horizontal axis represents years and vertical axis shows rainfall in Ml/day.

Figure 4. Minimum, mean, and maximum evapo-transpiration values calculated using projected rainfall data and simulated historical evapo-transpiration values. Horizontal axis represents years and vertical axis shows evapo-transpiration in Ml/day.

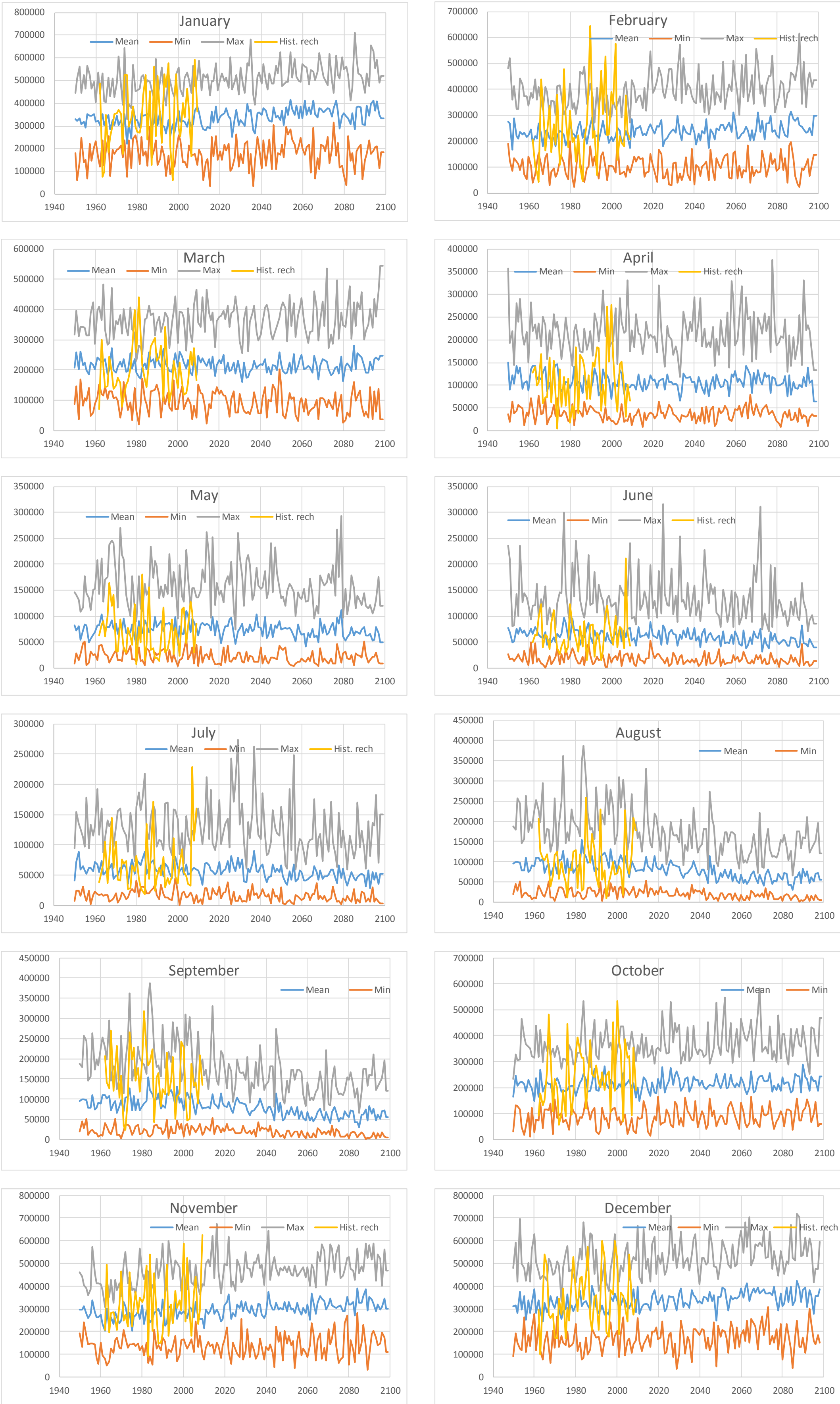

Figure 5. Minimum, mean, and maximum recharge values calculated using projected rainfall data and simulated historical recharge values. Horizontal axis represents years and vertical axis shows recharge values in Ml/day.

Figure 6. Mean, 25th and 75th percentiles of projected rainfall values. Horizontal axis represents years and vertical axis shows rainfall in Ml/day.

Figure 7. Mean, 25th and 75th percentiles of evapo-transpiration values calculated using projected rainfall data. Horizontal axis represents years and vertical axis shows evapo-transpiration in Ml/day.

Figure 8. Mean, 25th and 75th percentiles of recharge values calculated using projected rainfall data. Horizontal axis represents years and vertical axis shows recharge values in Ml/day.

Table 2. Summary of differences in rainfall – historical simulation to forecast climate

	afgcx	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
Av. Hist Sim	6.27E+05	6.33E+05	6.31E+05	6.32E+05	6.22E+05	6.29E+05	6.32E+05	6.31E+05	6.38E+05	6.15E+05	6.39E+05
Av. Fut. Climate	6.40E+05	6.46E+05	6.34E+05	6.63E+05	6.45E+05	6.31E+05	6.15E+05	6.57E+05	6.48E+05	6.31E+05	6.47E+05
Diff. Abs	1.29E+04	1.37E+04	3.27E+03	3.13E+04	2.36E+04	1.15E+03	-1.74E+04	2.65E+04	1.06E+04	1.64E+04	8.33E+03
Diff. (%)	2.05	2.17	0.52	4.96	3.79	0.18	-2.76	4.19	1.65	2.66	1.30

Table 3. Summary of differences in PE – historical simulation to forecast climate

	afgcx	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
Av. Hist Sim	2.53E+05	2.61E+05	2.46E+05	2.40E+05	2.48E+05	2.60E+05	2.58E+05	2.45E+05	2.57E+05	2.44E+05	2.56E+05
Av. Fut. Climate	2.56E+05	2.69E+05	2.42E+05	2.47E+05	2.53E+05	2.56E+05	2.53E+05	2.57E+05	2.66E+05	2.54E+05	2.56E+05
Diff. Abs	2.19E+03	7.88E+03	-3.61E+03	6.89E+03	4.56E+03	-3.73E+03	-5.42E+03	1.25E+04	9.29E+03	9.87E+03	-9.69E+01
Diff. (%)	0.86	3.02	-1.47	2.87	1.84	-1.44	-2.10	5.10	3.62	4.05	-0.04

Table 4. Summary of differences in recharge – historical simulation to forecast climate

	afgcx	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
Av. Hist Sim	1.76E+05	1.73E+05	1.81E+05	1.85E+05	1.75E+05	1.73E+05	1.75E+05	1.81E+05	1.78E+05	1.74E+05	1.80E+05
Av. Fut. Climate	1.80E+05	1.76E+05	1.85E+05	1.97E+05	1.84E+05	1.75E+05	1.69E+05	1.87E+05	1.79E+05	1.77E+05	1.83E+05
Diff. Abs	4.27E+03	2.17E+03	4.09E+03	1.22E+04	8.93E+03	2.02E+03	-6.11E+03	6.08E+03	4.98E+02	2.06E+03	3.64E+03
Diff. (%)	2.43	1.25	2.26	6.59	5.10	1.17	-3.48	3.36	0.28	1.18	2.02

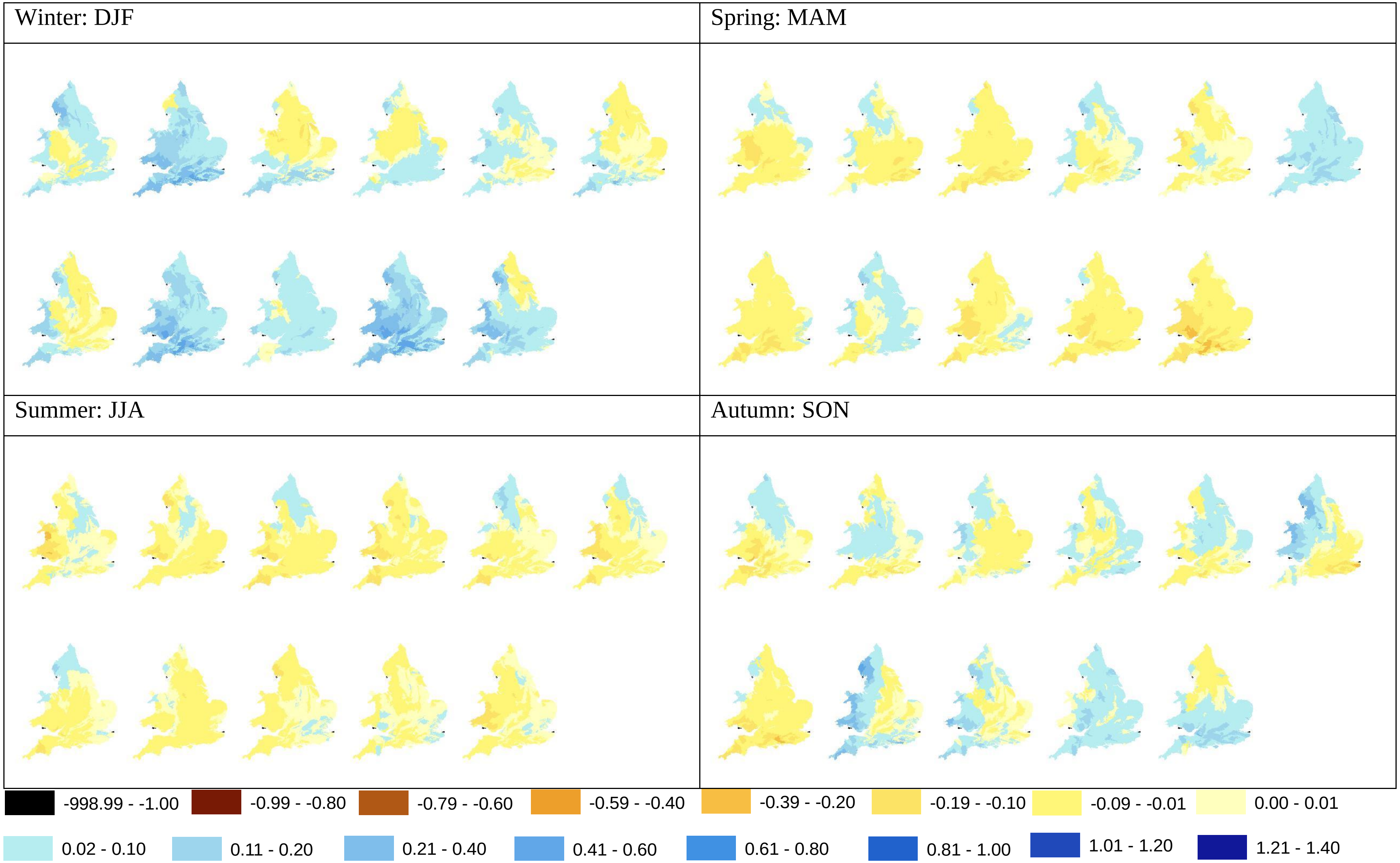

Figure 9. Seasonal changes in recharge values (2020s)

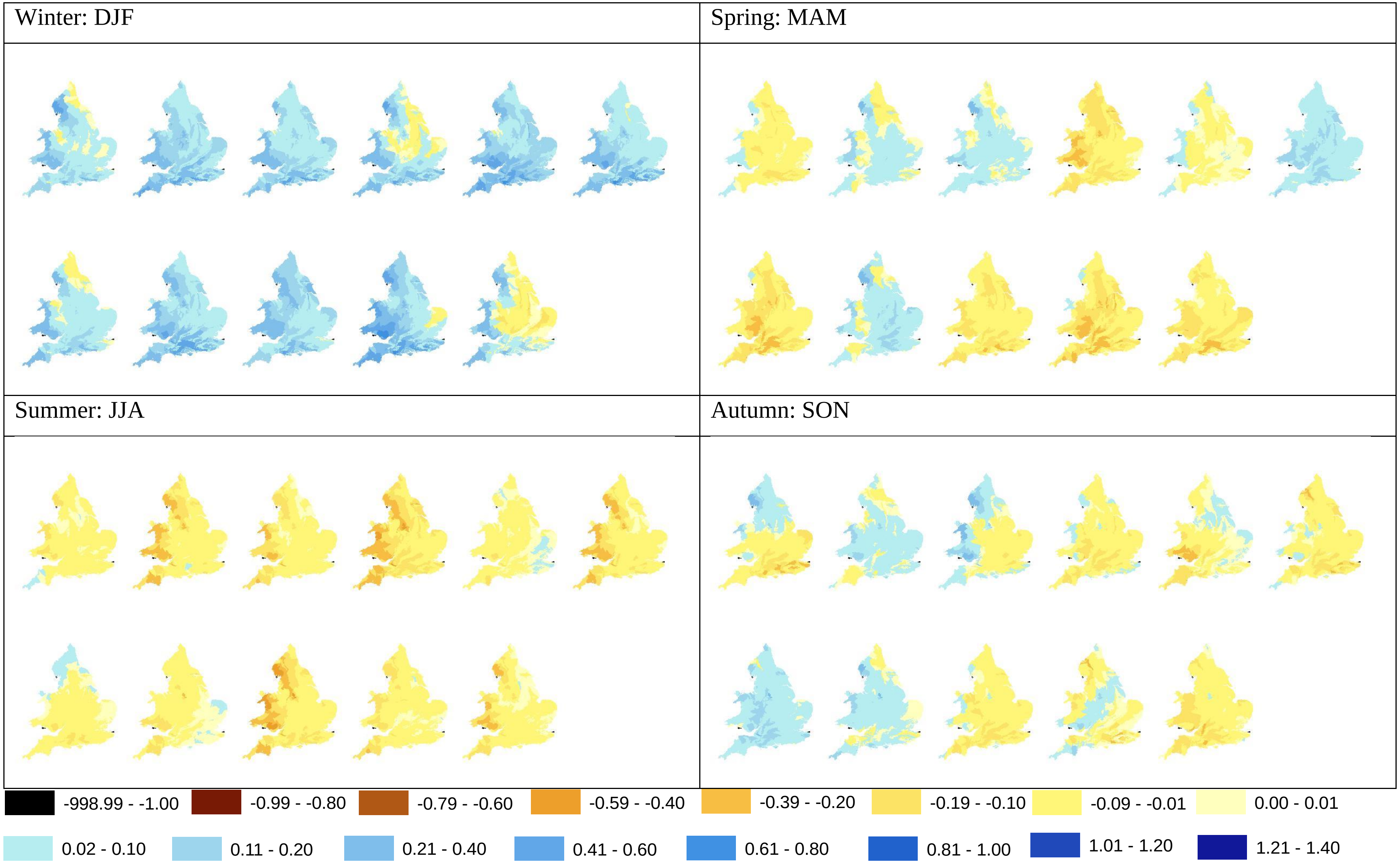

Figure 10. Seasonal changes in recharge values (2050s)

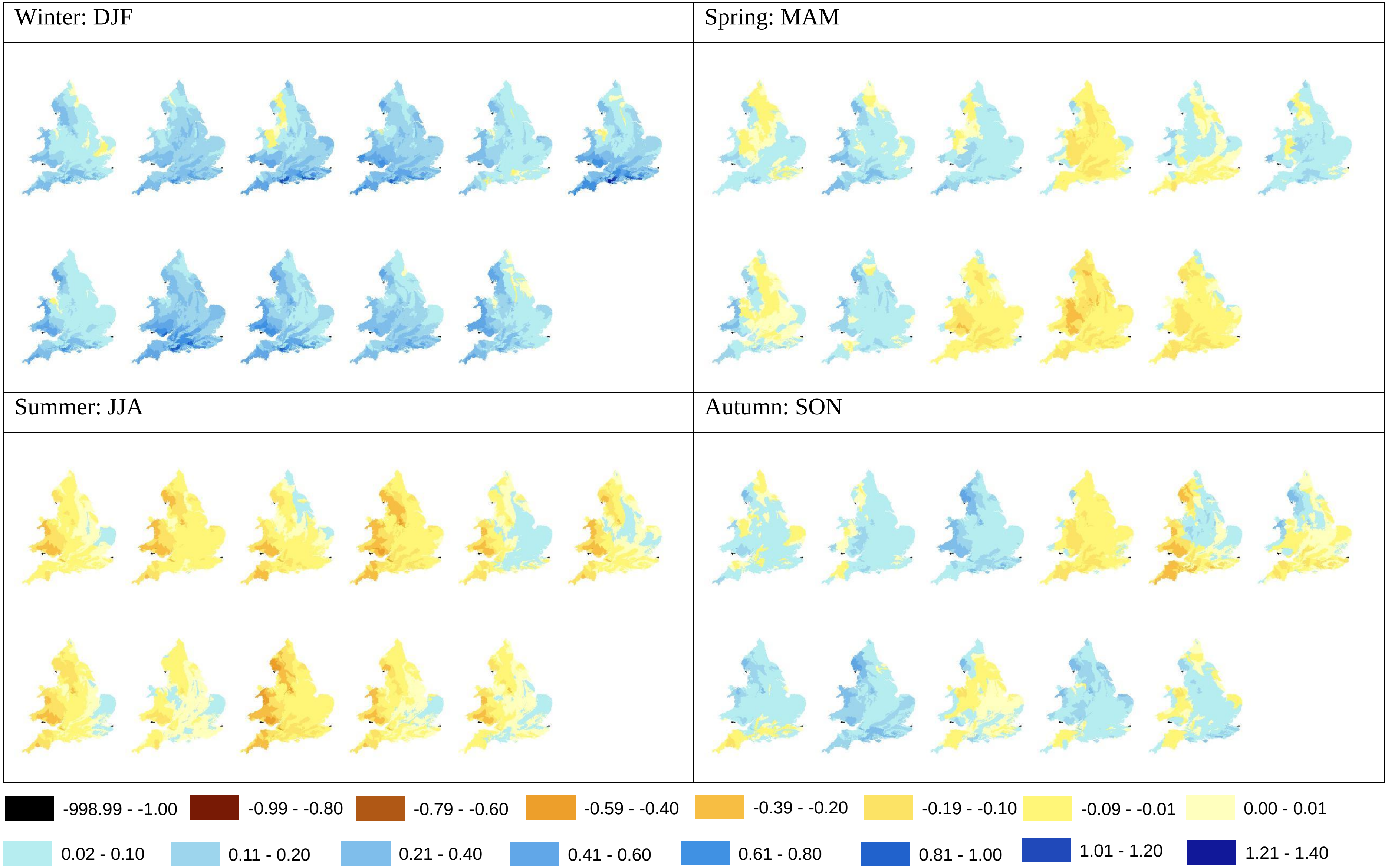

Figure 11. Seasonal changes in recharge values (2080s)

5 Summary and recommendations

5.1 SUMMARY

This report has outlined how the recharge model code ZOODRM has been applied to the GB land mass. It has presented sources of uncertainty, showing that even input data consists of those which are modelled and those that involve human interpretation. To understand the variability of the FFGWL ensembles then examples of the output from the 11 ensembles have been presented.

5.2 RECOMMENDATIONS

The following recommendations are made to improve the understanding of uncertainty within the application of the model to the BGS landmass as follows:

- Understand the sources of uncertainty in the datasets used and to investigate whether quantification of uncertainty has been undertaken. This should lead to the creation of an uncertainty model which can then be used to quantify the uncertainty for any model outputs.
- Draw on previous work, e.g. Defra land use project (Mansour and Hughes, 2014) and extend this to undertake a sensitivity analysis to determine the parameters that control the calculation of recharge
- Determine the impact on model structure. i.e. grid resolution, on recharge values
- Understand the impact of different recharge calculation methods on the results
- Produce the time series of rainfall, evaporation and recharge for catchments and geological outcrops related to the main aquifers in Britain (Chalk, Permo-Trasssic Sandstone and Jurassic Limestone)

One source of uncertainty is that the model calculates potential recharge (soil drainage) rather than that which reaches the water table (actual). Therefore, work should be undertaken to include the effect of Quaternary deposits on recharge so as to calculate actual recharge rather than just potential.

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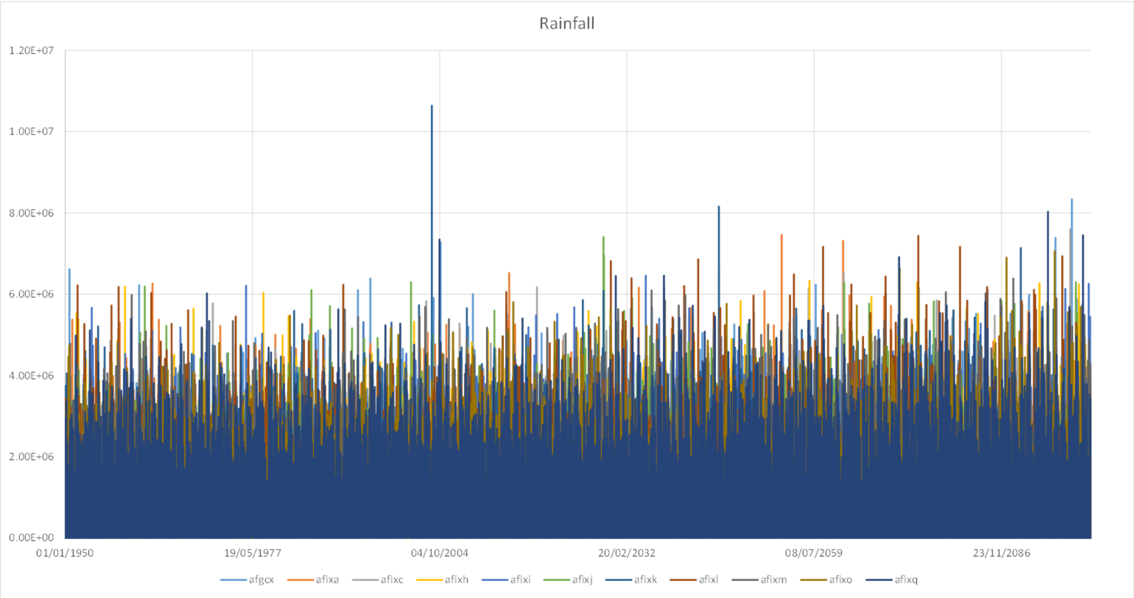
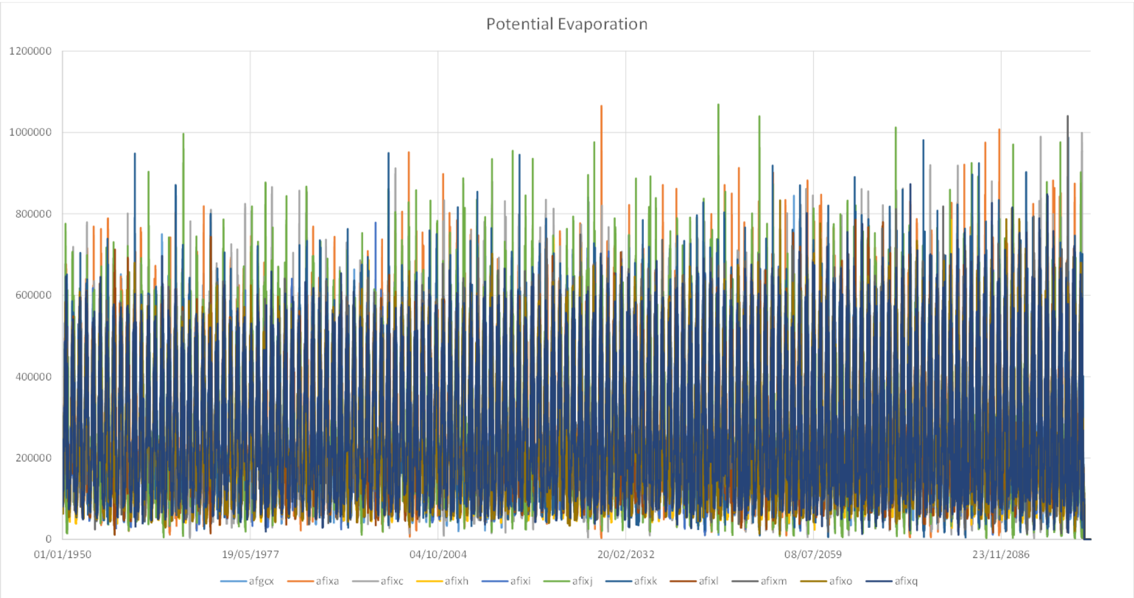
Appendix 1

This appendix shows time series of the total values of rainfall, evapo-transpiration, and recharge calculated over the whole study area.

TIME SERIES OF TOTAL RAINFALL FOR EACH ENSEMBLE



TIME SERIES OF TOTAL EVAPO-TRANSPIRATION FOR EACH ENSEMBLE



TIME SERIES OF TOTAL RECHARGE FOR EACH ENSEMBLE