British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

Future Flows and Groundwater Levels: responses to project peer review

Groundwater Science Programme

Commissioned Report CR/12/091N

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

COMMISSIONED REPORT CR/12/091N

Future Flows and Groundwater Levels: responses to project peer review

C.R. Jackson

Keywords

Climate Change; Groundwater; R-Groundwater model.

Bibliographical reference

JACKSON, C.R. 2012. Future Flows and Groundwater Levels: responses to project peer review. *British Geological Survey Commissioned Report*, CR/12/091. 14pp.

Keyworth, Nottingham British Geological Survey 2012

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461
www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Contents

FIGURES

TABLES

Summary

This report summarises the changes to the lumped catchment R-Groundwater model that have been made in response to the issues raised by the Future Flows and Groundwater Levels project peer review panel. Presentations of the proposed models and modelling methodologies to be used within the project were made to the panel in a meeting at CEH Wallingford on 18th January 2011. The peer review panel made a number of recommendations in response to these with regard to processing of the baseline climate data, downscaling of climate model output, and surface water and groundwater model verification. This report considers the verification of the lumped catchment groundwater model only. The peer review panel was composed of:

- Prof Nigel Arnell, Director of the Walker Institute for Climate Systems Research, University of Reading
- Dr Adrian Butler, Reader in Sub-surface Hydrology, Imperial College London
- Prof Rob Wilby, Professor of Hydroclimatic Modelling, University of Loughborough

1 Introduction

Recommendations were made by the peer review panel for changes to the groundwater modelling methodology and for additional R-Groundwater model (Jackson et al., 2012) verification work. These related to the following six aspects of the modelling:

1. The soil moisture accounting procedure.
2. The calculation of runoff.
3. The representation of drought response and bypass flow within the simple groundwater model.
4. The identification of the groundwater catchment associated with an observation borehole.
5. The number and identifiability of model parameters.
6. The effect of model parameter uncertainty on the resulting estimates of changes in groundwater levels under climate change.

Changes have been made to the R-Groundwater model to address points 1 to 5 above. These are described in section 2. In section 3 the results of the calibration of the modified model to the Dalton Holme groundwater hydrograph are presented. Finally the effect of parameter uncertainty on simulated changes in mean monthly groundwater level (point 6) is discussed in Section 4.

2 Modification of the R-Groundwater model

2.1 SOIL-MOISTURE ACCOUNTING

The soil moisture accounting procedure used to calculate actual evaporation (AE) and potential recharge (or soil drainage) has been changed within the R-Groundwater model (Jackson et al., 2012). Previously it was based on the Penman-Grindley model (Penman, 1948; Grindley, 1967). This has been replaced by the FAO56 methodology (FAO, 1998) as implemented in CERF (Griffiths et al., 2007). Consequently, the R-Groundwater model and CERF use the same algorithm for calculating actual evaporation (AE) and *excess water* (EXW), the amount of water available for surface runoff and potential groundwater recharge.

The FAO56 methodology requires the specification of values of four parameters: field capacity (FC), wilting point (WP), rooting depth (Zr) and depletion factor (dp). The relationship between these parameters is described in the updated R-Groundwater model manual (Jackson et al., 2012). Zr and dp are calibration parameters and are adjusted in a Monte Carlo model calibration process. However, bounds on their calibration ranges are based on the grouped fields within CEH's LCM2000 land cover data set (Fuller et al., 2002), and on information gained during the calibration of CERF models of UK river catchments. FC and WP are based on HOST soils data (Boorman et al., 1995) and values are set to those applied in CERF.

2.2 RUNOFF CALCULATION

In the previous version of the R-Groundwater model runoff was defined as a fixed proportion of rainfall. This has been modified during the implementation of the FAO56 soil moisture accounting procedure. The soil moisture balance model generates *excess water* (EXW), which is the amount of water available for both surface runoff and potential recharge. This depends on the soil moisture content and is generated only after the soil moisture content reaches field capacity. A runoff coefficient parameter (RO) is defined to separate surface runoff from potential recharge. This is taken as one minus the base flow index (BFI) for the catchment and is not adjusted during model calibration. Potential recharge (PR) is defined as:

$$PR = EXW \times (1-BFI)$$

2.3 DROUGHT BEHAVIOUR AND BYPASS FLOW

The role of the unsaturated zone (UZ) in controlling the behaviour of groundwater levels in Chalk aquifers was discussed by the peer review panel. The processes operating in the Chalk UZ have been the topic of much recent research (Butler et al., 2012). The delay in potential recharge arriving at the water table is related to the thickness, hydraulic properties and degree of fracturing of the UZ, the nature of the soil and weathering of the land surface, and the intensity and duration of driving rainfall. These factors lead to differences in the response of the water table to a pulse of potential recharge, both across a catchment and in time. For example, it possible that the slow drainage of recharge through the matrix of a *thick* chalk unsaturated zone results in continuous recharge to the water table that persists through summer and maintains groundwater heads. By contrast, intense rainfall events over *thin* chalk UZs can result in rapid rises in the water table due to fractures rapidly transmitting water downwards.

A representation of the complex processes operating in the UZ is not included in the R-Groundwater model, nor in any of the many existing models of UK Chalk aquifers. Consequently, some site specific features of an individual hydrograph may not be reproduced. However, given the complexity of the R-Groundwater model and the need to minimise model parameters an appropriate representation of the UZ has been included. Previous modelling has shown that the simple representation of the UZ contained implemented in the model, and described in the updated R-Groundwater model manual (Jackson et al., 2012), is able to match Chalk hydrographs well.

2.4 IDENTIFICATION OF THE GROUNDWATER CATCHMENT

The R-Groundwater model is calibrated against an observed groundwater hydrograph but outputs a time-series for three flow components: (i) groundwater flow beneath a point, p, on river, (ii) groundwater discharge to the "perennial" section of a river above p, and (iii) groundwater discharge to the "intermittent" section of a river, again above p. Each discharge, Q_i, out of the aquifer is governed by an equation of the form:

$$Q_i = \frac{T\,\Delta y}{0.5\Delta x}\Delta h_i$$

where Δh_i [L] is the difference between the groundwater head and the elevation of an aquifer outlet point, T is the appropriately calculated transmissivity [L^2T^{-1}], and Δx and Δy are the length and width of the aquifer [L], respectively.

The *a-priori* identification of the length of the aquifer, L, to set in the model is difficult. This is because a groundwater level hydrograph represents a point measurement. The characteristics of a groundwater hydrograph are controlled by the physical properties of the aquifer and the driving climate variables. However, they also depend on the position of the observation borehole within the catchment, and in particular the area of the recharge zone above it and its proximity to discharge points (e.g. a river). For catchments in which the borehole is not aligned perpendicular to a straight line river, the location of the discharge point that controls the groundwater level, within the framework of the simple R-Groundwater model conceptualisation of the system, is uncertain. Consequently, L is a calibration parameter of the model.

This means that it is generally not possible to relate the discharges simulated by the model to the flow at a river gauge directly. This is not ideal but an outcome of the approach of modelling a groundwater level time-series rather than a flow time-series with a lumped model. To model both a groundwater hydrograph and river flow at a gauge a distributed model would be required.

Whilst it is not ideal that it is difficult to compare the R-Groundwater model simulated river flows to observed flows, this is a fact of the modelling approach. However, calibration of the model has shown that the value of the L parameter is identifiable, when adjusted as part of a Monte Carlo calibration process.

2.5 MODEL PARAMETERS

The number of calibration parameters has been reduced as part of the R-Groundwater model modification process. The modified R-Groundwater model is described in full in the updated manual (Jackson et al., 2012). In summary it consists of three components:

1. An FAO56 based soil moisture balance model (FAO, 1998) producing a time-series of potential recharge (soil drainage).
2. A simple transfer function representing the delay in the time of the arrival of recharge from the base of the soil to the water table. Monthly potential recharge (soil drainage) rates are converted to recharge at the water table by distributing it over a number of months, n. The distribution is based on a 3-parameter Weibull distribution, in which n is one of the parameters.
3. A lumped catchment groundwater model based on a simple Darcian representation of flow out of three aquifer "outlets". The three outlets conceptually represent groundwater flow

beneath a stream, groundwater discharge to the perennial section of a river, and groundwater discharge to the intermittently flowing section of a river.

The structure of the model is shown in Figure 1. A full description of the model is provided in Jackson et al. (2012).

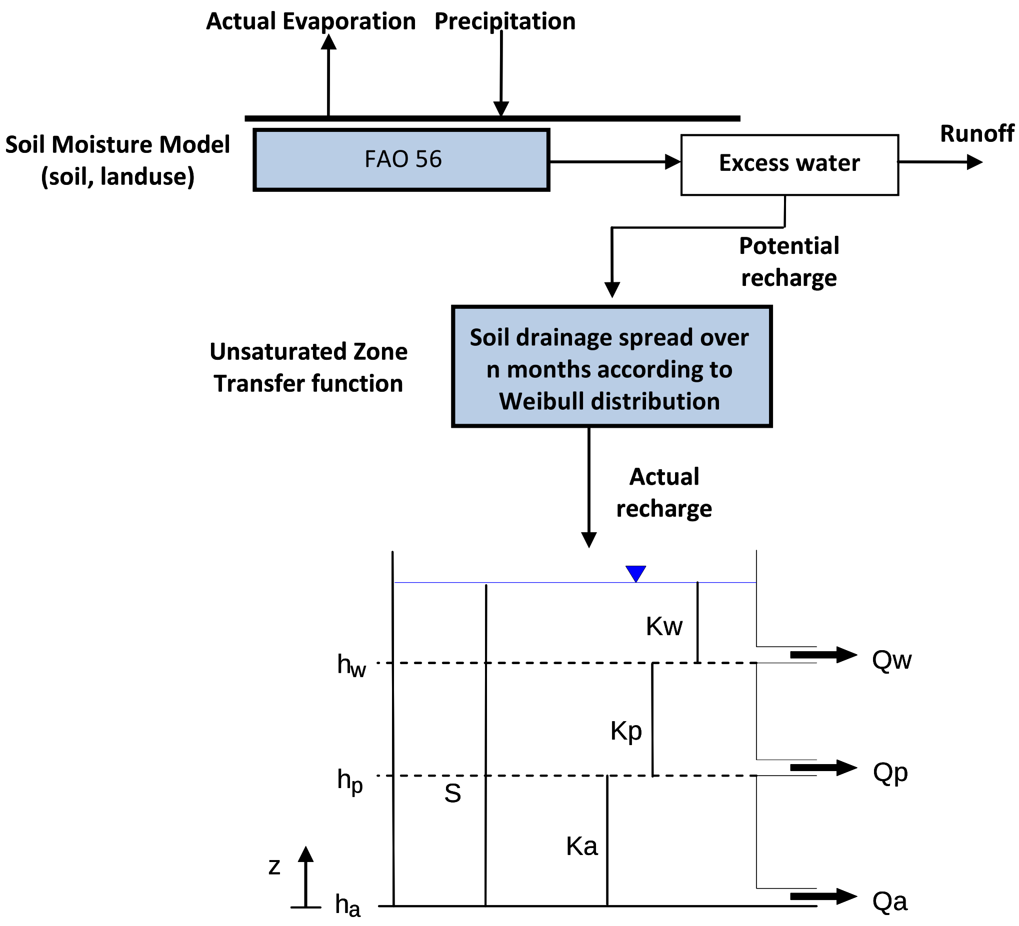


Figure 1 Structure of the R-Groundwater model

As a result of the R-Groundwater modification the number of model calibration parameters has been reduced to 10. Calibration parameters are listed in Table 1. Non-calibration parameters are listed in Table 2.

Table 1 Summary of model calibration parameters

Model component	Parameter	Data informing parameter estimation
Soil moisture balance	Maximum rooting depth, Z_r	FAO Irrigation and Drainage paper 56 (FAO 1998).
	Depletion factor, dp	FAO Irrigation and Drainage paper 56 (FAO 1998).
Unsaturated zone transfer	Weibull shape parameter, k	Calibration parameter but varied between values that allows a broad range of distributions to be tested.
	Weibull scale parameter, λ	Calibration parameter but varied between values that allows a broad range of distributions to be tested.
Saturated zone	Elevation of intermittent stream outlet, h_w	DTM elevation of intermittent streams.
	Elevation of Perennial stream outlet, h_p	DTM elevation of perennial streams.
	Hydraulic conductivity, of upper aquifer (above h_w), K_w	Calibration ranges based on pump test data and hydrogeological experience.
	Hydraulic conductivity, of middle aquifer (between h_w and h_p), K_p	Calibration ranges based on pump test data and hydrogeological experience.
	Hydraulic conductivity, of lower aquifer (between h_p and h_a), K_a	Calibration ranges based on pump test data and hydrogeological experience.
	Storativity of aquifer, S	Calibration ranges based on pump test data and hydrogeological experience.

Table 2 Summary of model non-calibration parameters

Model component	Parameter	Data informing parameter estimation
Soil moisture balance	Runoff coefficient, RO	River base flow indices (1-BFI).
	Field capacity, FC	As specified within the relevant catchments in the CERF model (Griffiths et al., 2007). FAO Irrigation and Drainage paper 56 (FAO 1998)
	Wilting point , WP	As specified within the relevant catchments in the CERF model (Griffiths et al., 2007). FAO Irrigation and Drainage paper 56 (FAO 1998)
Unsaturated zone transfer	Number of months over which to distribute potential recharge, n	Obtained from a cross-correlation of monthly groundwater levels and monthly rainfall.
Saturated zone	Elevation of groundwater discharge outlet, h_a	Determined from an assessment of the base of the aquifer as identified from geological and hydrogeological boreholes logs.

3 Dalton Holme calibration results

To test the modified R-Groundwater model code it was applied to simulate the groundwater level time-series at the Dalton Holme observation borehole (Figure 2). This was one of the 24 sites selected to be modelled as part of the Future Flows and Groundwater Levels project. Dalton Holme is located in the Yorkshire Chalk aquifer within the catchment of the River Hull. Observed groundwater levels were simulated over the period 1971-2009. The model was calibrated through a Monte Carlo process of 10^6 simulations in which calibration parameter values were randomly sampled from *a-priori* defined ranges informed by knowledge of the system and aquifer property data (Allen et al., 1997).

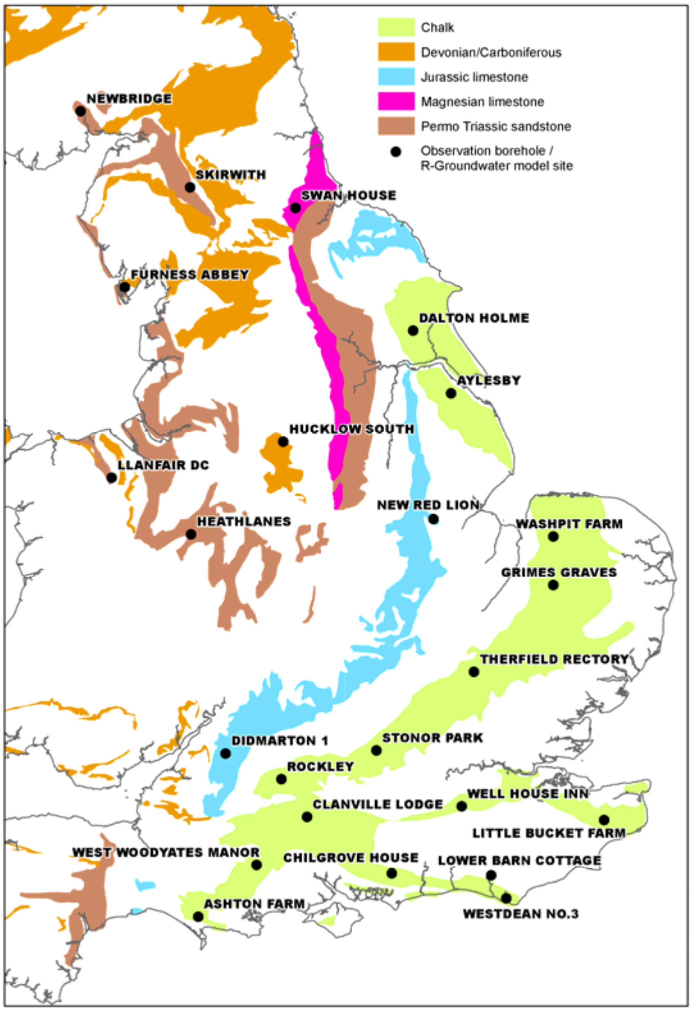
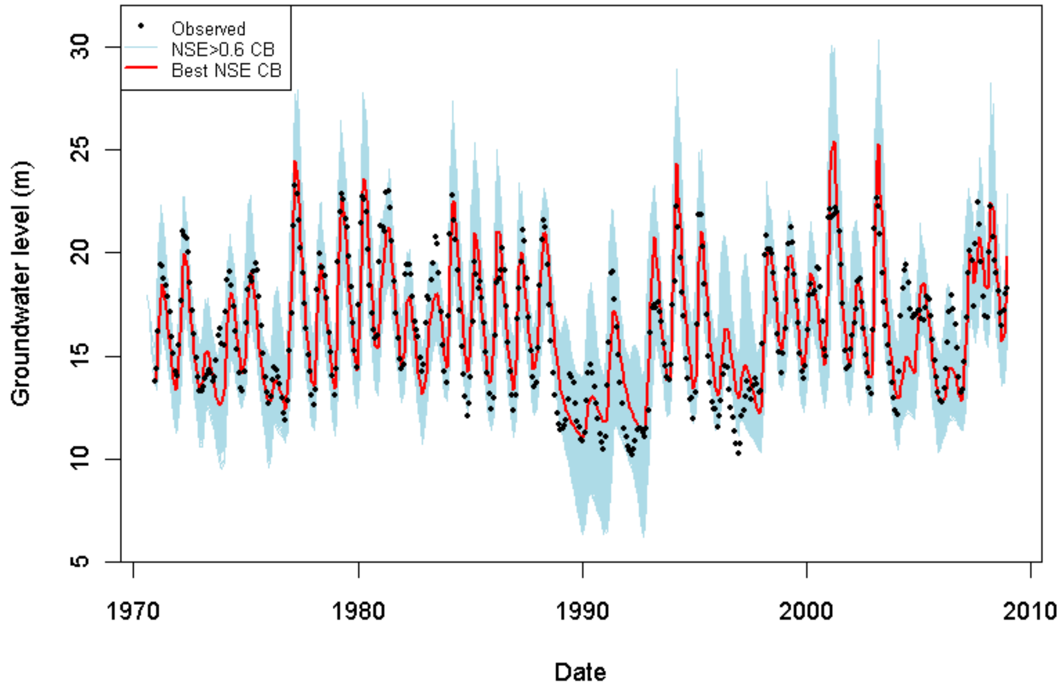
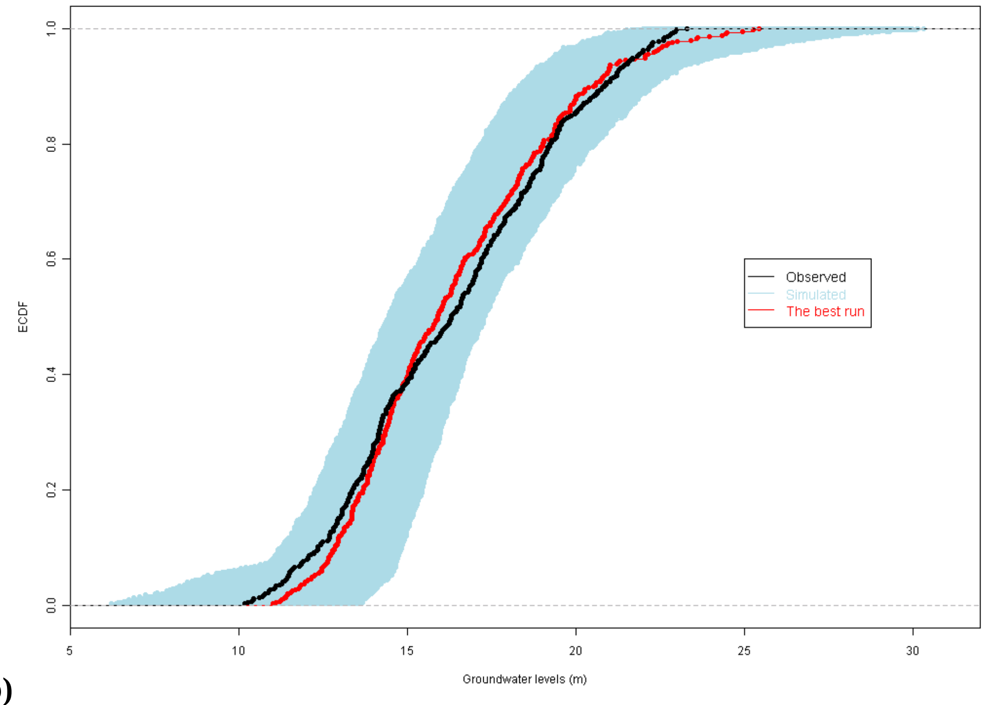


Figure 2 Location of observation boreholes for application of R-Groundwater model within Future Flows and Groundwater Levels project: Dalton Holme is located in the Yorkshire Chalk aquifer

The goodness-of-fit of the model to the Dalton Holme observed groundwater levels was assessed using the Nash-Sutcliffe Efficiency criterion. The fit of the model to the observed data is shown in Figure 3, for all those simulations in which the NSE was greater than 0.6.



(a)



(b)

Figure 3 (a) Observed and simulated Dalton Holme hydrograph for calibration period and (b) plotted as an empirical cumulative distribution function

Due to the time-scale of the project none of the modelling undertaken as part of the Future Flows and Groundwater Levels project was planned to be undertaken using multiple behavioural models. Rather a deterministic approach was planned and consequently one model was used at each river flow and groundwater level site modelled. Plots of the final simulation for Dalton Holme are shown in Figure 4. The full time-series, mean monthly levels and the level-duration curve are presented. The NSE of this model is 0.77 and the RMSE is 1.52 m. The model satisfactorily reproduces the inter-annual variability in the groundwater levels. Whilst it simulates the majority of the high and low groundwater levels reasonably accurately it does not simulate sufficiently low levels in summer between 1989 and 1993, and in 1996.

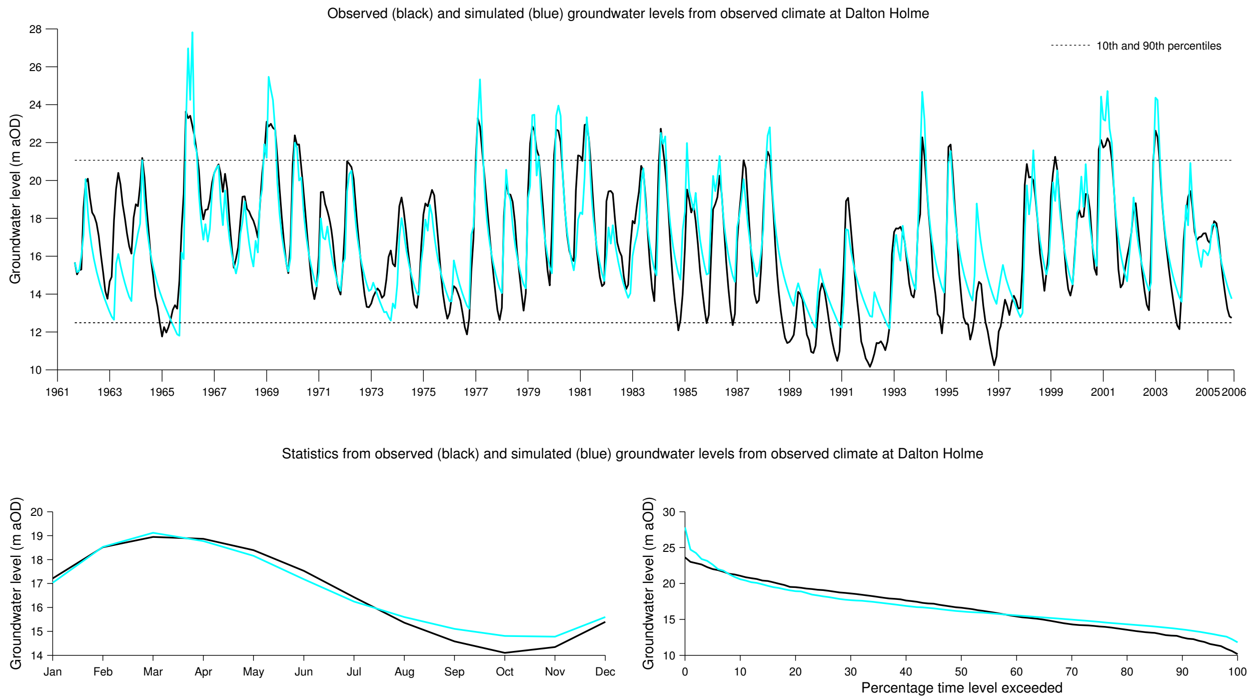


Figure 4 Comparison of observed and R-Groundwater model simulated groundwater levels for Dalton Holme. The full time-series, mean monthly levels and the level-duration curve are shown.

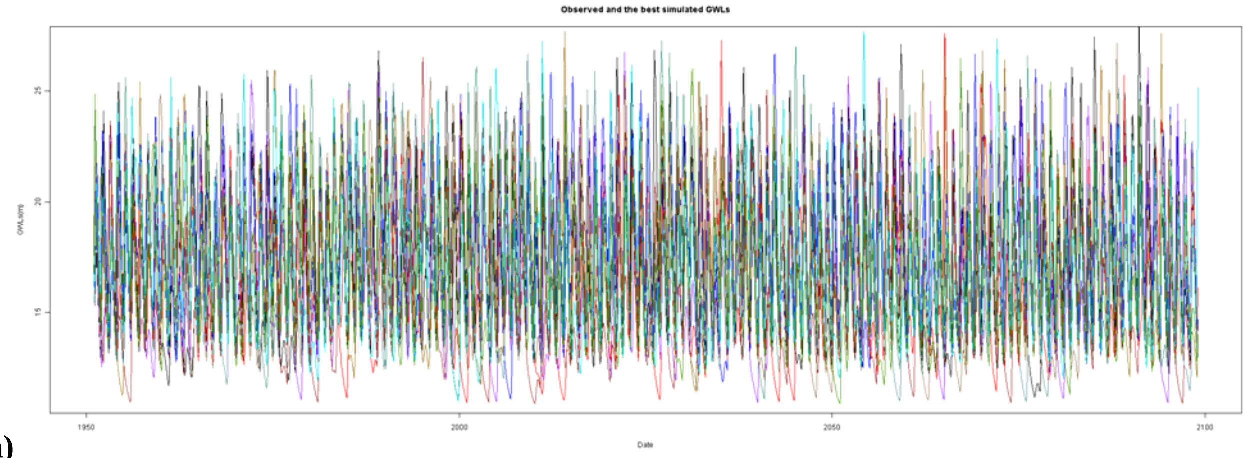
4 Model parameter versus climate uncertainty

In response to the peer review panel's suggestion that the effect of groundwater model parameter uncertainty on simulated climate change impacts should be explored, a number of additional simulations have been performed. These use the 43,245 Dalton Holme R-Groundwater models that achieved a calibration NSE of greater than 0.6 within the Monte Carlo run of 10^6 simulations. Each of these models is used to simulate groundwater levels for the period 1951-2098 based on the Future Flows Climate (Prudhomme et al., 2012) rainfall and potential evaporation time-series derived from each of the 11 ensemble members of the HadRM3-PPE-UK dataset (http://badc.nerc.ac.uk/data/hadrm3-ppe-uk/).

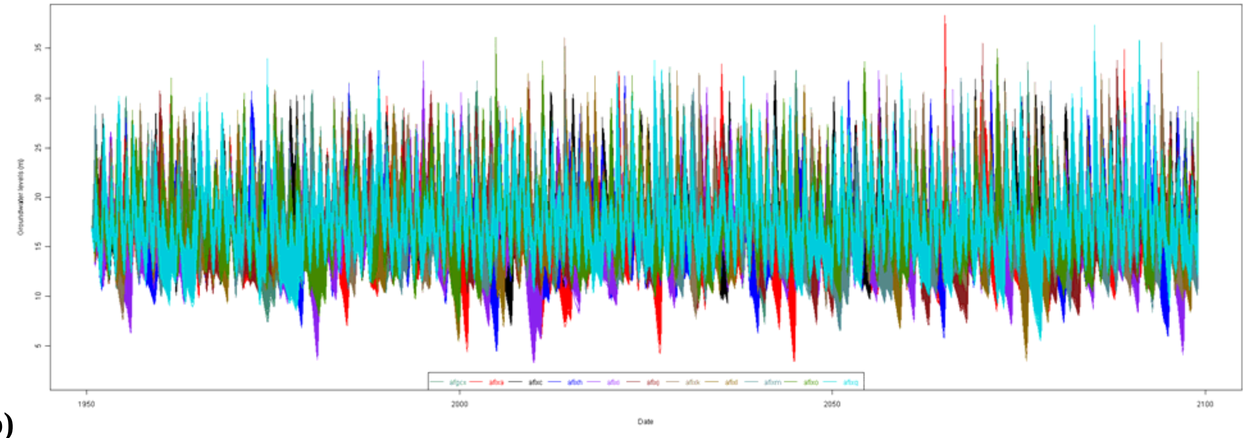
Figure 5 shows the simulated groundwater levels using each of the 11 climate time-series for the model with the highest NSE (the "best" model), and for all of the 43,245 behavioural models. Based on these Figure 6 shows the calculated changes in mean monthly groundwater levels for each of the 11 climate ensemble members, for the best groundwater model, and for a number of 30-year future time-slices. These illustrate the uncertainty associated with the projections of change within the 11-member ensemble, which is generally larger during late winter and spring (January to April) and smaller during summer and early autumn (July to October). The pattern of change factors across the months is also different from one 30-year time-slice to another. This illustrates the effect of variability in the simulated 150-year time series on the calculated change factors.

In Figure 7 the monthly change factors calculated using the best model are shown again for the 2080s. These are plotted next to a plot for each member of the 11-member climate ensemble, showing box-and-whisker plots of change factors calculated using all of the behavioural simulations. These plots illustrate the effect of model parameter uncertainty on the calculated monthly change factors. Monthly groundwater level change factors are also plotted for the best model. The spread of the change factors calculated using the best model and all 11 climate members is approximately the same as the spread of change factors derived from all the behavioural simulations. However, model parameter uncertainty is greater than climate uncertainty when groundwater levels are high (January to April) and smaller when groundwater levels are low (July to October). When considering the interquartile range (IQR) of the change factors (i.e. the box of the box-and-whisker plots) calculated using all the behavioural simulations, model parameter uncertainty is generally less than that of climate uncertainty. For example, the spread of change factors using the best model (climate uncertainty) is 1.66 m in February and 1.22 m in September. By way of comparison, the IQR of change factors for the afixo HadRM3-PPE-UK member and all behavioural simulations (model parameter uncertainty) is 1.11 m in February and 0.22 m in September.

This description of the relative magnitude of climate and R-Groundwater model parameter uncertainty is brief and relatively qualitative. It is recognised that the application of a single best model to calculate changes in groundwater level under future climates is not ideal but this has been necessary due to the constraints of the project. Ideally, the results of the project would contain quantitative information on both climate and model parameter uncertainty, for example, based on an application of the GLUE methodology (Beven, 2006).



(a)



(b)

Figure 5 Simulated groundwater levels for each RCM climate series for (a) the best simulation and (b) all behavioural runs

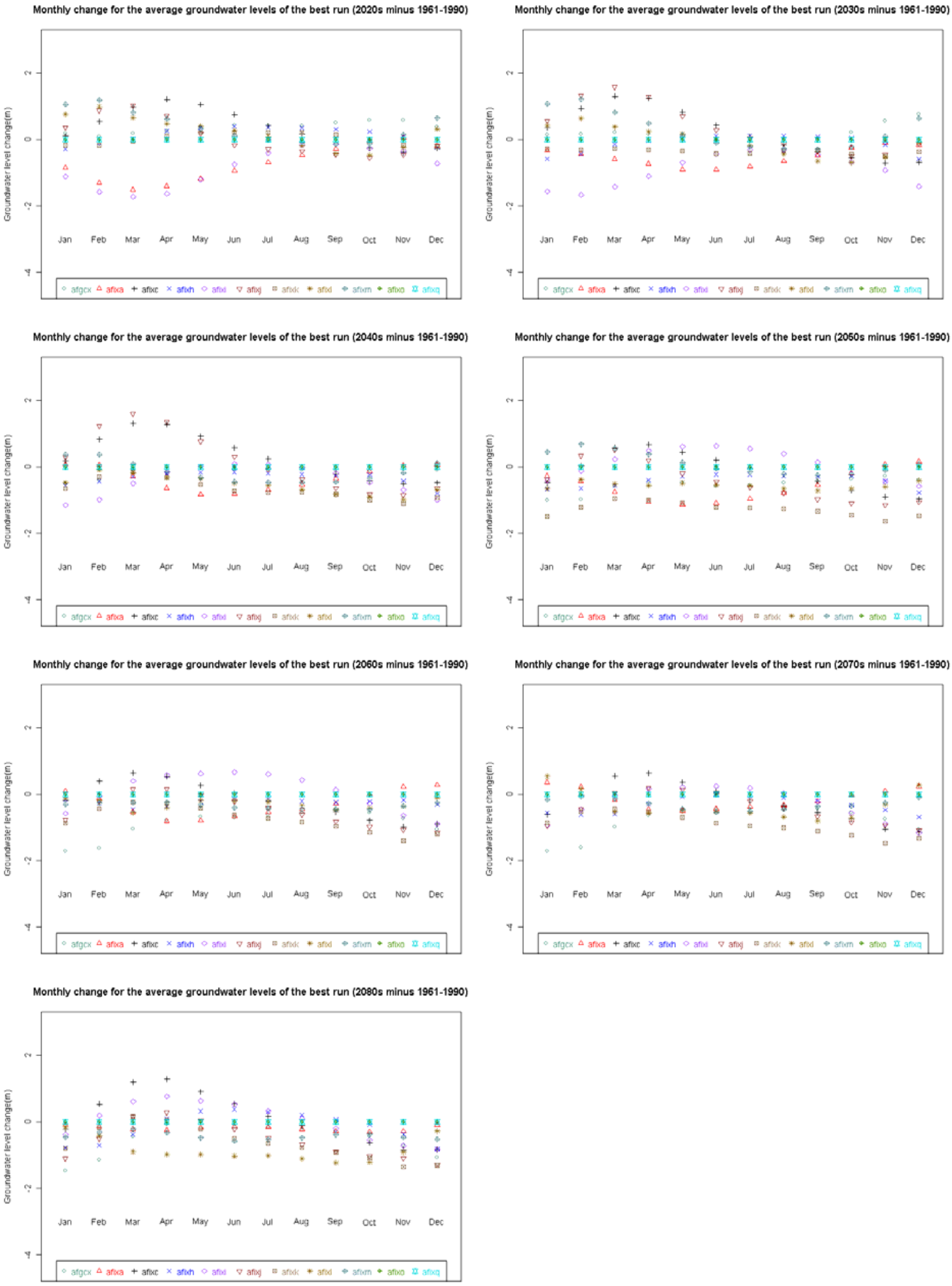


Figure 6 Simulated change in monthly mean groundwater level for all RCMs and each 30-year time slice centred on the seven decades from 2020s to 2080s

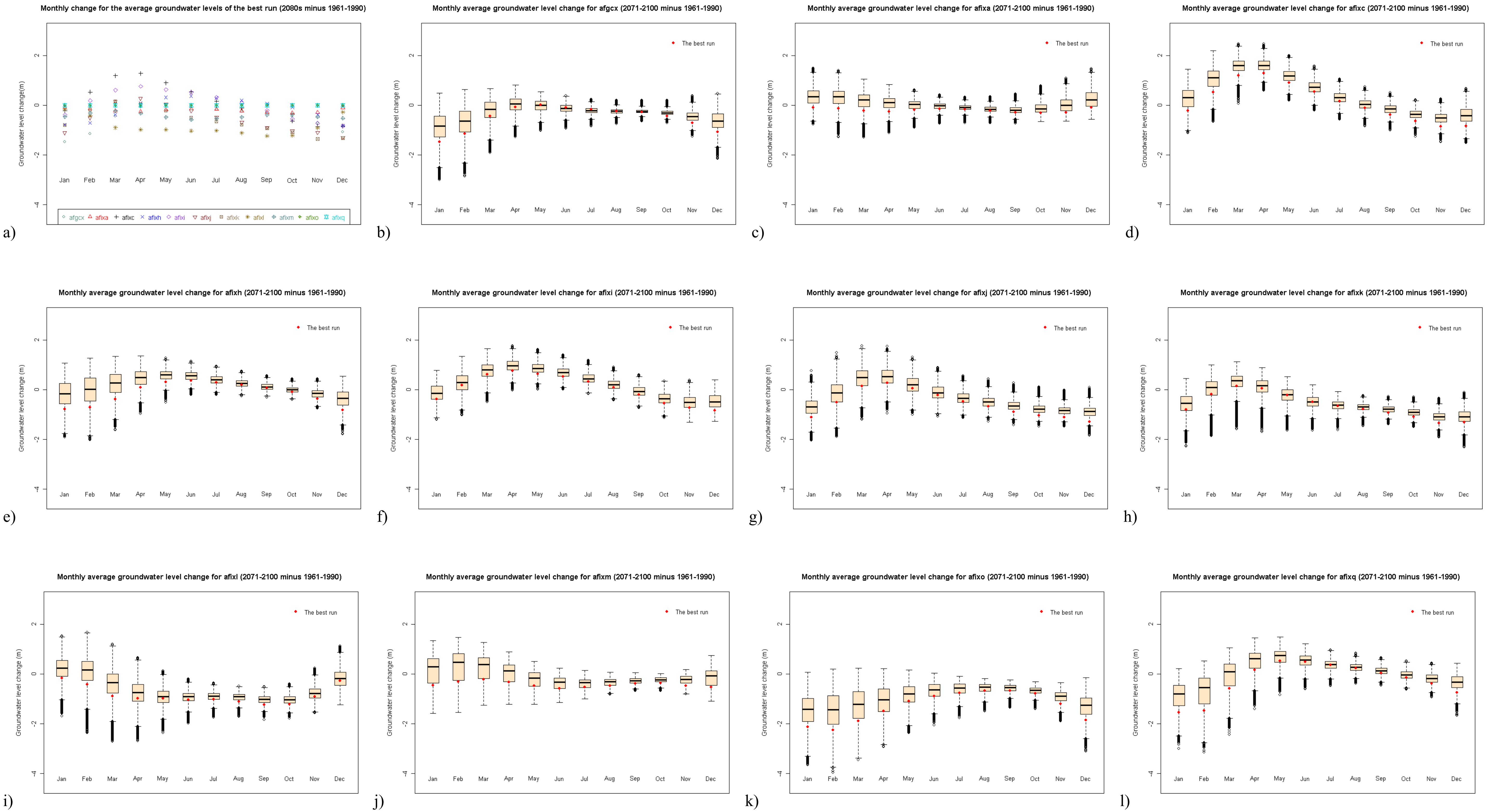


Figure 7 Simulated changes in monthly mean groundwater level for the 2080s for (a) the best calibrated model and all RCMs (climate uncertainty) and (b - l) for all behavioural simulations and each RCM (model parameter uncertainty)

References

ALLEN, D.J., BREWERTON, L.J., COLEBY, L.M., GIBBS, B.R., LEWIS, M.A., MACDONALD, A.M., WAGSTAFF, S.J. AND WILLIAMS, A.T., 1997. The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report. WD/97/34, Environment Agency R&D Publication, 8.

BEVEN, K.J. 2006. A manifesto for the equifinality thesis. Journal of Hydrology 320, p.18–36.

BOORMAN, D.B., HOLLIS, J.M., AND LILLY, A. 1995. Hydrology of soil types: a hydrologically-based classification of the United Kingdom. Report No. 126 Institute of Hydrology, UK.

FAO. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56.

FULLER, R.M., SMITH, G.M., SANDERSON, J.M., HILL, R.A., THOMSON, A.G., COX, R., BROWN, N.J., CLARKE, R.T. ROTHERY, P., AND GERARD, F.F. 2002. Countryside Survey 2000 Module 7: Land Cover Map 2000 Final Report. Centre for Ecology and Hydrology, Unpublished Report.

GRIFFITHS, J., KELLER, B., MORRIS, D., AND YOUNG, A.R. 2007. Continuous Estimation of River Flows (CERF) – Project Summary. Environment Agency Science Report W6 – 101.

PRUDHOMME C., CROOKS S., KELVIN J., AND JACKSON, C.R. 2012. Future flows and Groundwater Levels Final Report. Science Report/Project Note – SC090016/PN9. Centre for Ecology and Hydrology, Wallingford, UK.