

# Climate change and chalk aquifer groundwater resources in West Norfolk, UK

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**Abstract:** Assessment of the significance of climate change on water resources presents a considerable challenge. This study investigated the impacts of climate change on the Chalk aquifer of West Norfolk using a combination of a groundwater model (MODFLOW) and a climate change model (Hadley Centre's climate change experiment, HadCM2). Two future climate change scenarios were selected from the HadCM2 model: (i) a Medium-high (MH) emissions scenario and (ii) a Medium-low (ML) emissions scenario of greenhouse gases. Two future periods were considered: 2020-35 and 2050-65. Climate-change impacts were evaluated by incorporating the monthly estimated recharge inputs within the transient flow model and comparing the relative changes of groundwater levels and river baseflow volumes over monthly and annual timescales. Two opposite trends are predicted from the modelling of climate change scenarios for the two future periods considered (2020s and 2050s). The 2050ML scenario predicts an annual decrease in recharge of up to 13 mm, a monthly decrease in groundwater levels of up to 70 cm and a monthly decrease of up to 11% in the baseflow volume of the River Nar while the 2020ML scenario predicts an annual increase in recharge of up to 8 mm, a monthly increase in groundwater level of up to 50 cm and a monthly increase of up to 7% in the baseflow volume of the River Nar.

**Abstrak:** Penilaian keberkesanan perubahan cuaca ke atas sumber air merupakan suatu cabaran yang agak besar. Kajian ini bertujuan untuk menyiasat impak perubahan cuaca keatas akuifer batuan berkapur di Norfolk Barat dengan menggunakan kombinasi model air tanah (MODFLOW) dan model perubahan cuaca (HADCM2- Pusat eksperimen perubahan cuaca Hadley). Dua scenario perubahan cuaca masa hadapan telah dipilih daripada model HADCM2: perlepasan gas-gas rumah hijau yang i) sederhana-tinggi (MH) dan ii) sederhana-rendah (ML). Dua tempoh masa hadapan telah dipertimbangkan: 2020-35 dan 2050-65. Impak-impak perubahan cuaca telah dinilai dengan cara menggabungkan input angaran imbuhan bulanan ke dalam model aliran transient dan membandingkan perubahan-perubahan secara relatif paras air tanah dan isipadu aliran dasar sungai mengikut skalamasa bulanan dan tahunan. Dua trend yang bertentangan telah diramalkan daripada pemodelan scenario perubahan cuaca untuk kedua-dua tempoh masa hadapan yang dipertimbangkan (2020an dan 2050an). Senario 2050ML meramalkan pengurangan imbuhan tahunan sehingga 13mm, penurunan paras air tanah bulanan sehingga 70 cm dan pengurangan isipadu aliran dasar bulanan Sungai Nar sebanyak 11%. Manakala scenario untuk 2020ML pula meramalkan peningkatan imbuhan tahunan sebanyak 8 mm, peningkatan paras air tanah bulanan sebanyak 50 cm dan peningkatan isipadu aliran dasar bulanan Sungai Nar sebanyak 7%.

## INTRODUCTION

Global warming is the general term given to the possible climatic effect of increasing concentrations of "greenhouse gases", primarily carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) in the atmosphere (Arnell, 1996). The gases are transparent to incoming short-wave radiation but block outgoing long-wave radiation. The increased concentration of these gases will increase both the radiation and temperature of the lower atmosphere which eventually leads to changes in climate locally and regionally. Human activities, primarily the burning of fossil fuels and change in land use and land cover are increasing the atmospheric concentrations of the greenhouse gases (IPCC, 1997).

During the past decade, there have been many studies examining the potential effects of climate change on the

hydrologic cycle with most of the research concentrating on river flows and surface water resources (e.g. Arnell and Reynard, 1989; Mimikou and Kouvopoulos, 1991; Arnell, 1992). It has been concluded that climate change would have a significant effect on water resources, but there are uncertainties in hydrological processes and inconsistencies in both climate and impact models

This paper presents a study of the effects of climate change on groundwater resources in a part of the Great Ouse catchment, eastern England. The study used the hydrological modelling method as summarised by Arnell (1992). Many hydrologists prefer hydrological models compared to the other methods (i.e. temporal analogues and regional analyses), for the purpose of estimating hydrological response to climate change. The use of a hydrological model offers important advantages over the

direct use of hydrologic output from the climate model, General Circulation Model, GCMs (Mearns *et al.*, 1990). The linking of two models enables hydrologists and water resource engineers to study a variety effects of climate change, including both equilibrium and transient responses, and hypothetical responses. Models also allow varying degrees of complexity for representing current and future climate conditions.

The Anglian region is regularly affected by dry conditions in the warmer months of the year; the region regularly accounts for 80% of the total spray irrigation used in southern and eastern England (Palutikof *et al.*, 1997). The main aim of this study was thus to highlight the possible effects of climate change on groundwater resources in the selected aquifer, the Chalk aquifer system in west Norfolk. The groundwater model simulations and the evaluation of the climate change impacts on groundwater resources, in terms of effects on recharge amounts, groundwater levels and baseflow volumes, are described.

## DESCRIPTION OF THE STUDY AREA

### Geology

A location map of the study area showing the general solid geology is shown in Figure 1. The Upper Cretaceous Chalk, a white, fine-grained, fissured limestone, dips gently east at less than 1°. The western margin of the study area is bounded by the impermeable Gault Clay. The eastern half of the study area is overlain by late Pleistocene glacial deposits of variable thickness and extent. These deposits include boulder clay (Lowestoft Till), a brown calcareous clay with clasts of chalk and flint, and with occasional

patches of glacial sands and gravels. The thickness of the boulder clay is generally between 15–30 m but it can be up to 60 m within sub-glacially eroded channels. In the main river valleys, alluvium and glacial sands and gravels cover the Chalk outcrop, especially in the River Nar valley.

### Hydrology

The average annual rainfall measured in the region from 1980–1990 is 582 mm with the average annual potential evapotranspiration being about 575 mm. Two major rivers drain the study area, the Rivers Nar and Wissey, and have estimated baseflow index values of between 0.7 to 0.9. The River Stringsides, a minor river, is a tributary of the River Wissey.

### Hydrogeology

The Chalk aquifer is the dominant hydrogeological unit; the Chalk groundwater catchment area corresponding approximately to the surface water catchment area. Previous work in the study area has divided the Chalk aquifer into unconfined and semi-confined regions in the west and east, respectively, with the division corresponding to the Pleistocene boulder clay cover (Foster & Robertson, 1977). In areas with thick boulder clay cover, the generally high piezometric surface produces confined aquifer characteristics. Unconfined or water table conditions can exist within the river valleys where there is no clay cover.

Within the Chalk aquifer, flow zones are more likely to occur within an interval of 30 m below rest water level, and within an interval of 50 m from the top of the Chalk (Wooton, 1994). A geophysical evaluation in the Rushall area, just to the east of the current study area (Foster & Robertson, 1977), suggested that flow in the Chalk aquifer

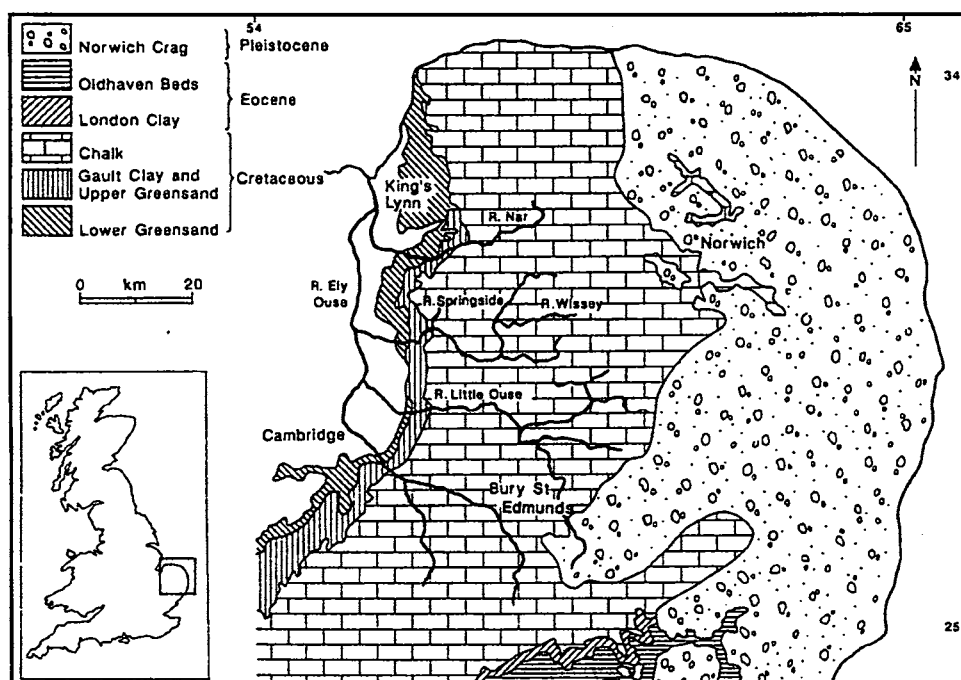


Figure 1. Simplified map of the solid geology of East Anglia showing the boundary of the study area.

is mostly restricted to between  $-40$  m above Ordnance Datum (m AOD) and above, with the most significant groundwater flow largely above  $-10$  m AOD. In the Nar catchment, Chalk transmissivity values vary between  $2,000\text{--}3,000\text{ m}^2\text{ day}^{-1}$  in the valley zone, to less than  $100\text{ m}^2\text{ day}^{-1}$  in the interfluvial areas where the boulder clay cover has restricted groundwater flow and aquifer development (Toynton, 1983).

## GROUNDWATER MODELLING

A two-layer conceptual groundwater model was designed to investigate the likely impact of climate change on groundwater resources in the study area (Fig. 2). An upper, semi-confining layer of glacial deposits represents the glacial boulder clay, silts, sands and gravels. A lower layer, with an assumed effective thickness of 50 m, and bottom elevation of  $-20$  m AOD, represents the Chalk aquifer. The upper, boulder clay layer was estimated from borehole logs, the Hydrogeological map of northern East Anglia (IGS, 1976) and statements from selected reports (Aspinwall & Co., 1992; Boar *et al.*, 1994) to be 30 m thick and to lie in semi-hydraulic contact with the lower Chalk layer.

### Numerical Model

The conceptual model was converted into a numerical groundwater flow model using the Groundwater Vistas MODFLOW package (McDonald & Harbaugh, 1988) with a total area of  $2,250\text{ km}^2$ . The model domain was discretized into grid dimensions of  $1 \times 1\text{ km}$  and  $0.5 \times 0.5\text{ km}$  square cells, with the smaller cell size assigned to the active model area where rivers, springs and abstractions are simulated. In total, the model contains 95 rows and 78 columns of

cells, with 8,474 active modelling cells, of which 521 are river cells and 11 spring cells.

### Model boundary conditions

All the external boundaries for the upper layer (boulder clay) are no flow boundaries as shown in Figure 3a. The upper reaches of the Rivers Nar and Wissey, which continue to flow in the upper layer, were modelled with the 'River Package' of MODFLOW and assigned the same hydraulic conductivity as the underlying Chalk aquifer layer. Principal springs were also modelled with the 'Drain Package'. There is no groundwater abstraction from the upper layer. The boundary conditions for the lower layer (Chalk aquifer) are shown in Figure 3b. No flow boundaries are used to represent the northern and western boundaries which, respectively, follow a flow line and the western limit of the Chalk. A further no flow boundary was used for the eastern boundary to represent the estimated regional groundwater divide. The remainder of the eastern boundary was modelled as a river boundary. The southern boundary was modelled as a river boundary representing the River Little Ouse. The model is able to simulate unconfined-confining Chalk aquifer conditions. The top elevation of the Chalk aquifer layer was assigned as 30 m AOD, and any groundwater levels which exceed this elevation are considered confined water levels.

### Aquifer recharge

For the present west Norfolk Chalk aquifer model, it was decided, for ease of calculation in later climate change impacts modelling, to use the conventional method of Penman (Penman, 1949) and a soil water balance calculation method to estimate recharge to the aquifer. An outline of the method is given by Howard & Lloyd (1979). An average recharge, or effective precipitation, for 1980–1990 of  $3.43 \times 10^{-4}\text{ m day}^{-1}$  was calculated for the model area (Yusoff 2000).

## MODEL CALIBRATION

The modelling strategy used in this study was to calibrate the model to the steady-state condition for the period 1980–1990 and then to use the model output as the initial conditions for transient state simulations. A calibrated transient model would then be later used with the climate change scenarios. For the steady-state model, a 'trial and error' calibration process was used to match average field hydrogeological conditions (average groundwater levels and river baseflows) for the period 1980–1990. For the transient model, two calibration targets were chosen: groundwater levels for selected monitoring boreholes (two in the unconfined Chalk aquifer, two in the confined aquifer; see Fig. 4); and river baseflows of the Rivers Nar, Wissey and Stringsides. In estimating the groundwater contribution to river flow, or baseflow, the separation method outlined by Ineson & Downing (1964) was used.

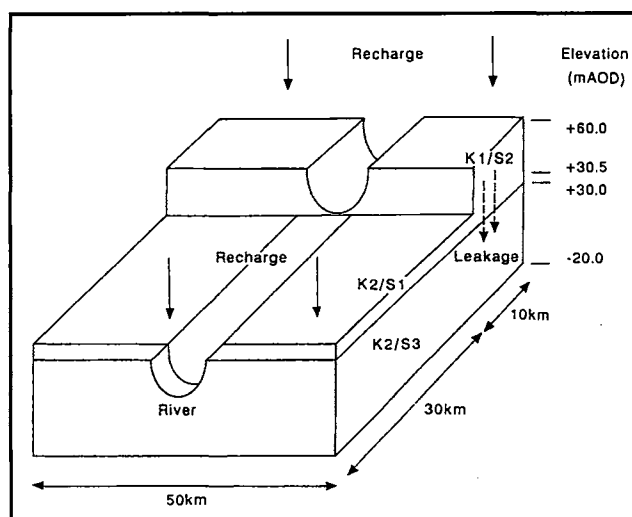


Figure 2. Conceptual model of the hydrogeological system of west Norfolk. The upper layer represents the Quaternary glacial deposits (principally boulder clay) and the lower layer the Cretaceous Chalk aquifer. Zones of hydraulic conductivity (K) and storage coefficient (S) are also shown.

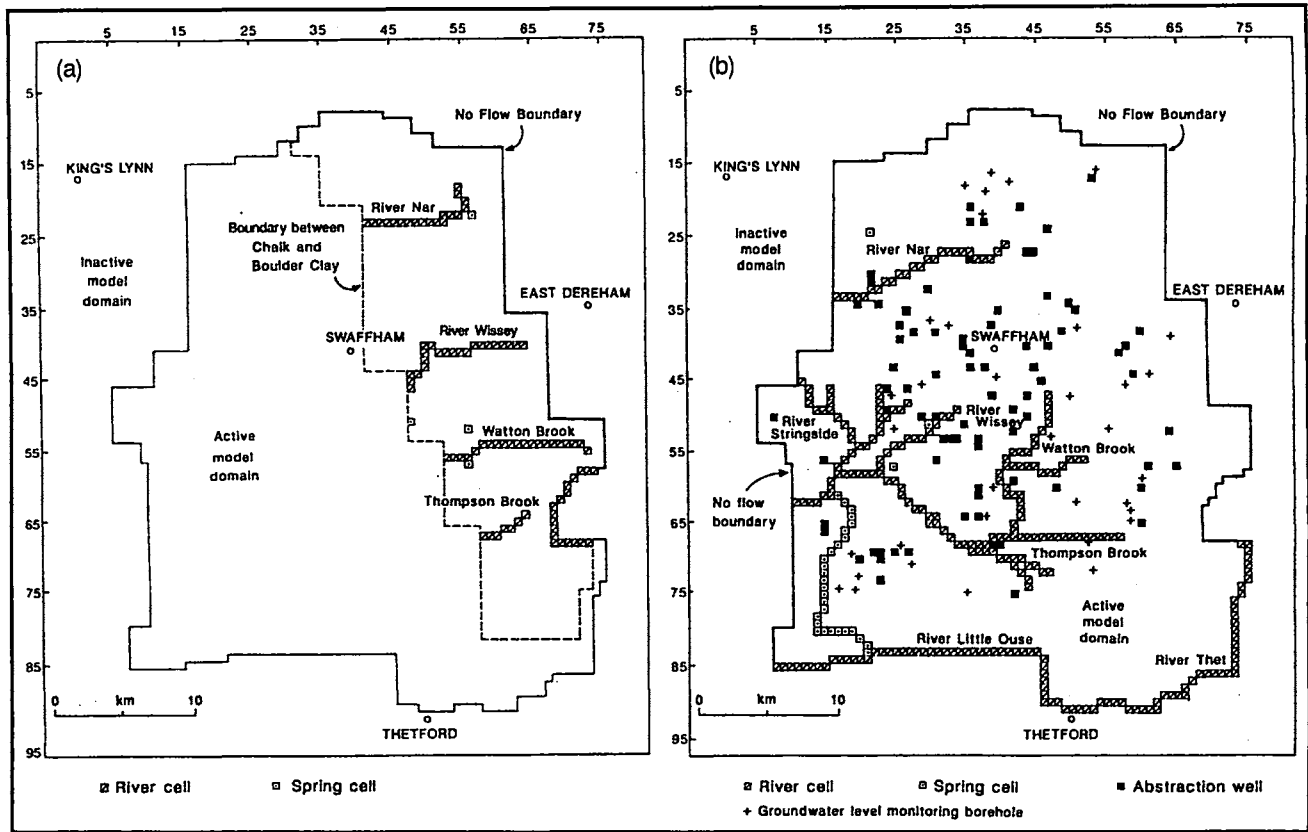


Figure 3. Boundary conditions for the two-layer MODFLOW numerical model of the west Norfolk Chalk aquifer system. In (a) boundary conditions for the upper (boulder clay) layer of the model are shown, and in (b) boundary conditions for the lower (Chalk aquifer) layer are shown.

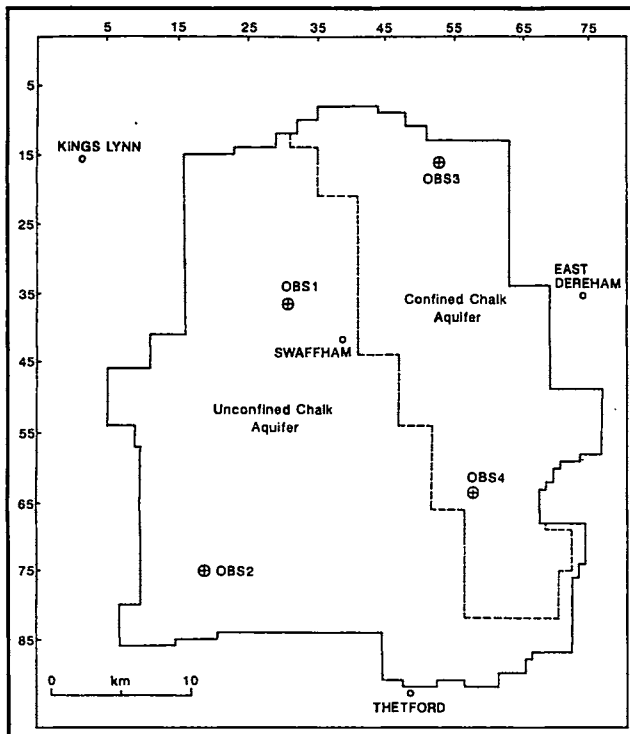


Figure 4. Locations of the four selected Chalk observation boreholes used for calibration of the transient state MODFLOW numerical model.

In the transient model, each month from 1980 to 1990 was treated as one stress period. Groundwater abstractions for each stress period remained unchanged, as monthly abstraction data were not available. The same MODFLOW solver package, the slice successive over-relaxation method, was used to solve the transient groundwater flow equation with an error criterion of 1% of steady-state recharge.

**Validation**

The final transient model was validated by extending the database used during the calibration process (1980–1990) by a further five years to 1995. In doing this, it is possible to study the effects of the initial conditions on model performance. In general, by starting the simulation period in 1980, the model provided a reasonable comparison to the independent dataset for 1991–1995, as shown by the selected groundwater and baseflow hydrographs given in Figure 5. As expected, the River Nar gave the best validation result using the calibrated model. At this point, the model was considered validated and ready for application in the prediction of hydrogeological conditions under future climate change scenarios.

## CLIMATE CHANGE SCENARIOS

Comprehensive reviews of climate change scenarios, including standards and construction, can be found in Yusoff (2000). In this study, results from the UK Climate Change Impacts Programme (UKCIP) were selected in constructing climate change scenarios. The scenarios represented the latest results from the HadCM2 climate change model experiments performed by the UK Meteorological Office's Hadley Centre. Given the difficulty of making firm predictions about future climate, the UKCIP approach is to present four alternative scenarios of climate change for the UK that span a reasonable range of possible future climates. The scenarios are labelled Low (L), Medium-low (ML), Medium-high (MH) and High (H) and refer to respective global warming rates in response to a doubling of atmospheric carbon dioxide concentration.

For the purpose of this study, only two climate change scenarios were selected, the Medium-high (MH) and Medium-low (ML) scenarios that represent the mid-range scenarios between the two extreme emissions scenarios (High (H) and Low (L)). For each of these scenarios, two future, 15-year periods (equivalent to the length of time of the available hydrological records in this study) were considered for modelling climate change impacts on groundwater resources: the 2020s (2020–2035) and 2050s

(2050–2065). This approach results in four climate change scenarios: 2020MH, 2020ML, 2050MH, 2050 ML.

## MODELLING THE IMPACTS OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

### Changes in groundwater levels and baseflow volumes

Climate change impacts on groundwater resources were evaluated by incorporating the monthly estimated recharge inputs derived for the future climate scenarios on precipitation (P) and Potential Evapotranspiration (PE) into the validated transient model and comparing the relative changes (over monthly and annual timescales) in groundwater levels and river baseflow volumes. The results of the effect of climate change on groundwater levels and baseflows are presented in Tables 1 and Table 2 respectively. Although the model calibration process suggested that the baseflow of the River Nar is reasonably well simulated compared to the Rivers Wissey and Stringsides, the output for the latter two rivers is still of interest in this study in order to look at relative changes in baseflow volumes, as opposed to absolute values. Figure 6 shows a comparison

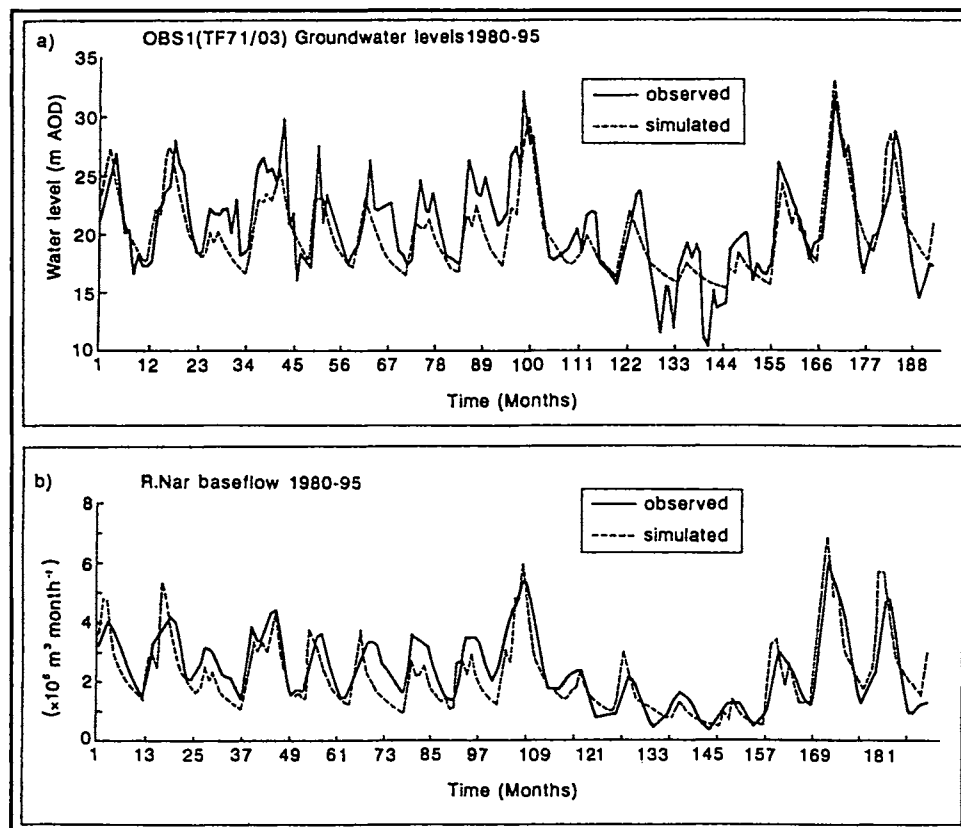


Figure 5. Comparison between (a) the observed and simulated groundwater levels for unconfined Chalk observation borehole (OBS1) and (b) the observed and simulated river baseflow runoff for the River Nar for the validated transient state MODFLOW model of the west Norfolk Chalk aquifer system.

Table 1. Comparison of monthly groundwater levels for the observed present-day climate and perturbed future climate states (2020 MH, 2020 ML, 2050 MH, 2050 ML).

Observation borehole	Parameter (measure)	Obs. (m)	2020 MH	2020 ML	2050 MH	2050 ML
OBS1	Monthly average (% change)	20.1	-0.7	1.8	0.6	-2.7
	Change in groundwater level (m)		-0.1	0.4	0.1	-0.6
	Standard deviation (% change)	3.3	-1.5	5.8	3.6	-4.9
OBS2	Monthly average (% change)	2.8	-0.7	1.8	0.7	-3.2
	Change in groundwater level (m)		0.0	0.1	0.0	-0.1
	Standard deviation (% change)	0.7	-1.5	5.9	4.4	-2.9
OBS3	Monthly average (% change)	52.7	-0.2	0.8	0.3	-1.1
	Change in groundwater level (m)		-0.1	0.4	0.2	-0.6
	Standard deviation (% change)	1.9	-3.2	0.0	-2.7	-4.8
OBS4	Monthly average (% change)	37.3	-0.3	1.3	0.6	-1.7
	Change in groundwater level (m)		-0.1	0.5	0.2	-0.7
	Standard deviation (% change)	1.6	-1.8	-0.6	-3.1	-1.8

**Note:** OBS = Observation borehole

Obs = Observed present-day with averages based on 1980–1995

Table 2. Comparison of monthly and annual river baseflow volumes for the observed present-day climate and perturbed future climate states (2020 MH, 2020 ML, 2050 MH, 2050 ML).

River	Parameter	Obs. (m <sup>3</sup> month <sup>-1</sup> )	2020 MH % change	2020 ML % change	2050 MH % change	2050 ML % change
River Nar	Monthly average	2.21 x 10 <sup>6</sup>	-2.1	7.3	2.4	-10.9
	Standard deviation	1.22 x 10 <sup>6</sup>	1.7	7.4	3.9	-6.7
	Annual average	2.65 x 10 <sup>7</sup> m <sup>3</sup> year <sup>-1</sup>	-2.1	7.4	2.4	-10.7
River Wissey	Monthly average	3.12 x 10 <sup>6</sup>	-1.4	5.3	2.3	-6.8
	Standard deviation	1.16 x 10 <sup>6</sup>	-2.0	9.0	5.4	-7.3
	Annual average	3.74 x 10 <sup>7</sup> m <sup>3</sup> year <sup>-1</sup>	-1.4	5.3	2.4	-6.7
River Stringside	Monthly average	8.48 x 10 <sup>5</sup>	0.0	0.1	0.0	-0.1
	Standard deviation	4.38 x 10 <sup>5</sup>	-3.1	15.1	6.9	-4.6
	Annual average	1.02 x 10 <sup>7</sup> m <sup>3</sup> year <sup>-1</sup>	-2.3	5.2	1.5	-6.1

**Note:** Obs. = Observed present-day with averages based on 1980–1995.

of percentage changes in monthly average groundwater levels in an unconfined Chalk observation borehole (OBS1) and baseflow volume for the River Nar between the observed present-day and future climate states.

In general, two future trends in groundwater levels are produced and, as expected, are similar in trend to the pattern of future recharge. The first trend is shown by the 2020MH and the 2050ML scenarios and the second trend by the 2020ML and 2050MH scenarios. The first trend shows a decrease in monthly groundwater levels of up to 70 cm (see Table 1). The second, opposing, trend shows a relatively smaller increase in monthly groundwater levels of up to 50 cm. The changes in groundwater levels are relatively greater for the confined section of the aquifer (OBS4) than the unconfined area.

Overall, the 2020ML scenario predicts the prospect of an increase in groundwater levels in the future, while the 2050ML scenario predicts a decrease in groundwater levels compared with the present-day. In terms of the two future periods modelled, the 2020s represent a period of relatively higher groundwater levels compared to the 2050s.

As with changes in groundwater levels, the river catchments in the study area show different magnitudes of response to the future climate change scenarios. Two future trends in baseflow volumes are detected using the monthly and annual output from the groundwater model. The first trend is shown by the 2020MH and 2050ML scenarios that produce monthly and annual decreases in baseflow volumes for all timescales (see Table 2). The second trend is shown by the 2020ML and the 2050MH

scenarios that produce monthly and annual increases in baseflow for all timescales.

Monthly and annual changes in baseflow volume are very similar for the Rivers Nar and Wissey (see Table 2). The smallest catchment, the River Stringside, shows larger annual than monthly changes in baseflow. The River Nar has the highest monthly decrease (11% for 2050ML) and increase (7% for 2020ML) for all the proposed scenarios.

## CONCLUSIONS

The results of modelling the impacts of climate change on groundwater resources should be treated with caution given the shortcomings of the HadCM2 model, for example in simulating present-day climate conditions. Although a simple approach has been adopted in this study, with the application of climate change factors to the historic record to represent future climate conditions, the model outputs are, however, considered representative of potential climate change impacts on groundwater resources in the Chalk aquifer system in west Norfolk.

Two opposite trends are predicted from the modelling of climate change scenarios for the two future periods considered (2020s and 2050s). Of these two trends, the first produces larger changes, as follows:

- (i) the 2050ML scenario predicts: an annual decrease in recharge of up to 13 mm; a monthly decrease in groundwater levels of up to 70 cm; an increase in the annual frequency of low groundwater levels by up to 12%; a monthly decrease of up to 11% in the baseflow volume of the River Nar; and an increase in the annual frequency of low river baseflow volumes in the River Nar by up to 24%;
- (ii) the 2020ML scenario predicts: an annual increase in recharge of up to 8 mm; a monthly increase in groundwater level of up to 50 cm; a decrease in the annual frequency of low groundwater levels by up to 12%; a monthly increase of up to 7% in the baseflow volume of the River Nar; and a decrease in the annual frequency of low river baseflow volumes in the River Nar by up to 12%.

From the point of view of managing future groundwater

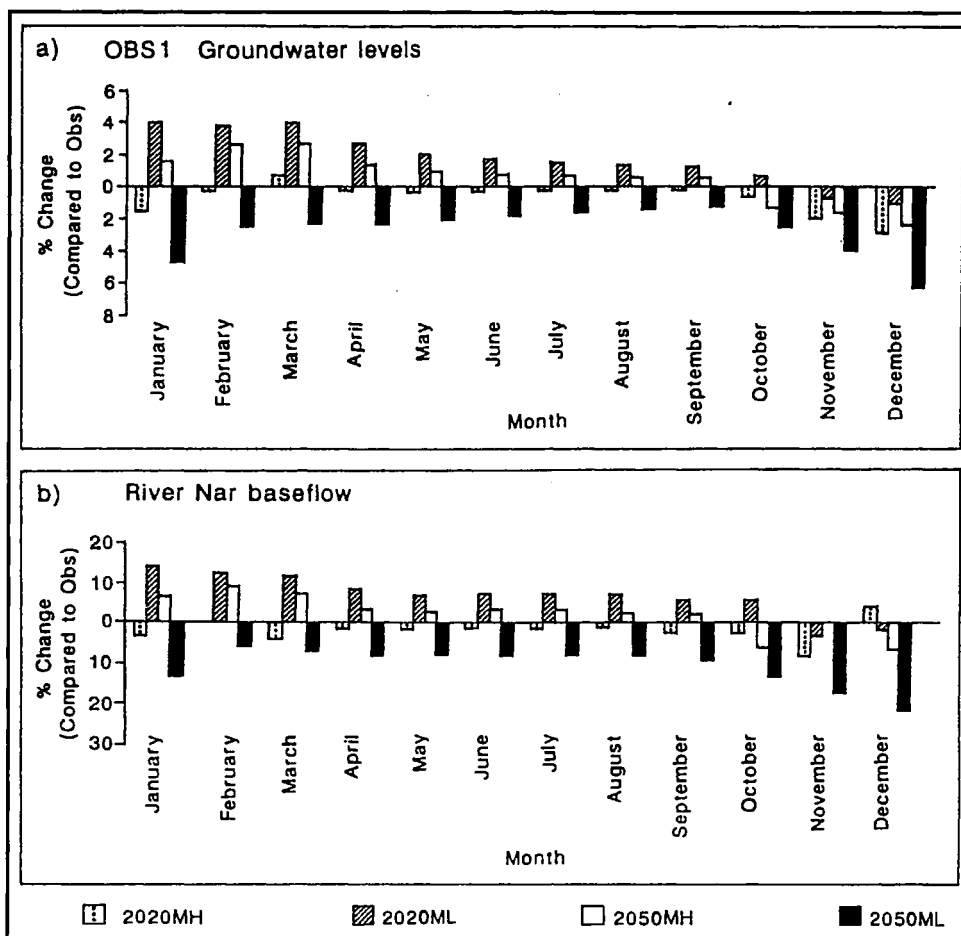


Figure 6. Graphs comparing percentage changes in (a) monthly average groundwater levels at Chalk observation borehole OBS1 and (b) monthly average baseflow volume for the River Nar between observed present-day climate and future climate predicted using the calibrated transient state MODFLOW model. Note: Obs. = Observed present-day climate.

resources, the most optimistic outcome is produced by the 2020ML climate change scenario, where the annual recharge amount is predicted to be 6% greater than the present value (1980–1995 average); while the worst outcome is produced by the 2050ML scenario in which the annual recharge is predicted to be 10% less than the present value. A 10% decrease in recharge by the middle of this century compares with a projected increase in household water demand of greater than 70% by 2025 for the least sustainable water use pattern.

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