British
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Modelling the impact of climate change on groundwater in the UK

Stage 1 - Background, literature and available data review and selection of modelling techniques

Groundwater Systems and Water Quality Programme
Internal Report IR/01/58

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/01/58

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Bibliographical reference

Ó DOCHARTAIGH, B É, BLOOMFIELD, J P AND PRUDHOMME, C. 2001. Modelling the impact of climate change on groundwater in the UK. Stage 1 – Background, literature and available data review and selection of modelling techniques. *British Geological Survey Internal Report*, IR/01/58. 37pp.

Keyworth, Nottingham British Geological Survey 2001

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Summary

This report describes the background to and initial work on the joint BGS-CEH project "Modelling the impact of climate change on groundwater in the UK". The project aims to develop a flexible modelling methodology for assessing the impacts of climate change on groundwater resources at various scales. An overview of the current state of the art in developing future climate change scenarios is given. The relationships between groundwater and climatic conditions are discussed. Previous work on groundwater and climate change is reviewed. A set of four modelling approaches is selected to develop during the current project for application with future climatic data. Data requirements for groundwater modelling are considered. An overview of the hydrogeological characteristics of the major UK aquifers is given. A scheme of work is specified.

1 Introduction

The aim of the project is to develop a flexible modelling methodology for assessing the medium to long-term impacts of climate change on groundwater resources at borehole, catchment and regional scales. The model(s) which are developed as part of this methodology will be applicable to a range of aquifer types and adaptable to a range of hydrological and hydrogeological scenarios. They will be used to evaluate impacts to selected regions of the major UK aquifers using the current range of accepted future climate scenarios. The modelling methodologies will also be adaptable enough to be used where there are only limited data or with data of variable quality. They will highlight areas where additional research is required, and will provide guidance on data requirements related to climate change and on the future monitoring of groundwater resources under conditions of climatic uncertainty.

The methodology should be capable of identifying critical climatic factors and characteristic groundwater resource responses irrespective of assumptions regarding specific aquifers or recharge processes. It will act as a precursor to the development of climate change sensitive water resource models and groundwater management tools for specific aquifers and catchments.

Project deliverables include recommendations for flexible groundwater resource modelling methodologies, tested under a range of climate scenarios and calibrated for a range of catchment types; model code and supporting information developed during the course of the project; and a guidance note on the application of the method for use in water resource planning, including recommendations on data collection and monitoring of groundwater resources under conditions of climatic uncertainty.

2 Climate change in the UK

Climate varies naturally on many time scales, because of effects such as oscillations in the earth's orbit, changes in solar output, volcanic eruptions, changing ocean circulation patterns. The current UK climate, particularly the parameters rainfall and wind speed, is noted for its short-term variability around a relatively stationary mean, while sustained periods of very wet or very dry weather are relatively rare. Historical observations show that this pattern has been characteristic of the last two centuries. However, recent years have seen two phenomena which suggest either that this pattern may be changing, or that a pattern of climatic variation exists on a scale which the existing historical record is too short to reflect. One is a trend of rising temperature, at a rate which is unlikely to be solely due to natural climate variations. Analysis of natural climate variability on 30-year time-scales shows that mean seasonal UK temperatures vary by no more than +- 0.5 °C. However, the 1990s were almost consistently about 0.5 °C warmer than the 1961-1990 average, and four of the five warmest years in the 340-year Central England Temperature series occurred between 1988 and 1997 (Hulme and Jenkins, 1998). The other phenomenon is the increasing frequency (above that which could be expected by analysis of the historical record) of 'extreme' climatic events. Many of these events had significant hydrological effects, such as severe floods and extended periods of drought. One example is the extended (three months or more) and marked reduction in effective precipitation (precipitation minus actual evapotranspiration) across almost all of Britain during 1984, 1989 and 1995. According to historical example, such conditions would be expected only once in 200 years (Price, 1998). At the other end of the scale, the autumn and winter of 2000 was marked by prolonged rainfall leading to extended flooding across the UK. Seasonal groundwater level recovery was rapid and groundwater levels in many Chalk aquifers reached levels unprecedented in historical records, causing groundwater flooding from large numbers of high level springs which had been inactive for decades (CEH/Met Office, 2001).

There is increasing evidence to suggest that at least part of observed climatic change is due to the human-induced rise in atmospheric concentrations of greenhouse gases since the industrial revolution. The inertia in global energy systems means that this climate-forcing is likely to continue during the next century, even if the rate of greenhouse gas release to the atmosphere is slowed.

The extreme climatic events of recent decades fit relatively well with current scenarios for human-induced climate change. This study will make use of climate change scenarios produced by the UK Climate Impacts Programme (UKCIP) and published in the report "Climate Change Scenarios for the United Kingdom" (Hulme and Jenkins, 1998). The scenarios are based on the results of climate modelling experiments performed by the Hadley Centre using a coupled ocean-atmosphere Global Climate Model (GCM) called HadCM2. This model has been extensively analysed and validated and represents one of the leading GCMs in the world. A new version of the model – HadCM3 – has since produced updated results which are currently being used to construct improved scenarios. The climatic modelling is based on scenarios of greenhouse gas emissions and concentrations provided by the Intergovernmental Panel on Climate Change (IPCC).

There is also a possibility of using climate change scenario data from Regional Climate Models (RCM), which are available through the LINK project (funded by the UK Department of the Environment, Transport and the Regions; contract reference EPG 1/1/68). Regional Climate Models were developed because regional climate change is strongly influenced by local features such as topography, which is not well represented in global models, because of the coarse resolution of the latter. RCM, with higher resolution (typically 50 km), cannot practically be used for global simulation over long periods of time. They are generally constructed for limited areas and run for short periods (typically 20 years). RCMs take their boundary and sea-surface temperature inputs from global GCMs (typically the HadCM2 model runs).

The UKCIP98 report describes four possible short-term climatic futures for the UK, spanning a range of greenhouse gas emissions scenarios and different climate sensitivities. The climate scenarios suggest that annual-mean temperatures over the next century will increase differentially across the UK, with a pattern of larger increases in the south-east than in the north-west. By the 2080s, annual-mean temperatures over south-east England may have increased by between 1.5 and 3.2 °C, while over Scotland the increase will be only 1.2 to 2.6 °C (all increases are described relative to the 1961-90 average). Warming will also be generally slightly more rapid in winter than in summer. Year-to-year temperature variability will increase in summer, but decrease in winter (Hulme and Jenkins, 1998). Changes in mean annual precipitation are likely to be less dramatic, with increases of between 0 and 10 percent over England and Wales, and between 5 and 20 percent over Scotland by the 2080s. However, seasonal differences in precipitation may be greater, with winters and autumns across the whole of the UK becoming wetter by up to 20 percent for some scenarios. During spring, and particularly summer, the south-east may see reductions in precipitation of 10 to 20 percent by the 2080s, while in the north-west summers may be wetter. The year-to-year variability in precipitation increases almost everywhere, even in seasons and regions when mean precipitation falls (Hulme and Jenkins, 1998

The scenarios also suggest changes in other climate factors: vapour pressure is likely to increase, while relative humidity remains stable or declines slightly. Patterns in changing cloud cover, and the inversely-related solar radiation, generally match those of precipitation. Mean wind speeds are predicted to change little, except for a slight increase in autumn. Potential evapotranspiration is likely to increase in all seasons, with the greatest relative increase in autumn and the smallest in spring, so that by the 2080s, summer potential evapotranspiration over southern England may have increased by 10 to 20 percent (Hulme and Jenkins, 1998).

The scenarios also suggest that the frequency of extreme precipitation will increase, with intense daily precipitation events becoming more frequent, especially in winter (Hulme and Jenkins, 1998).

The implications of these scenarios are that it is no longer possible to rely on relatively short (decades-long) sequences of past weather data in order to predict the probability of future climatic events (Hulme and Jenkins, 1998).

3 Groundwater resources and climate change

Groundwater resources depend to a great extent on spatially and temporally variable climatic parameters, largely precipitation and evapotranspiration, which may vary over a wide range of scales. Gross relationships between climatic variables and groundwater resources are generally understood, and there has been some progress in recent years in understanding recharge processes, usually related to specific aquifers, and/or types of soil cover and land-use. It is generally accepted that the global climate will become warmer overall and probably exhibit increasing variation, with extreme climatic events becoming more frequent. The potential impact of these climatic changes, particularly extreme events, on groundwater resources is highly uncertain. Climate change may have minimal impact on some aquifers, but a significantly deleterious effect on others. Consequently, there is a need to develop a robust methodology to investigate systematically the relationship between climate change and groundwater resources.

Groundwater systems may conceivably be affected in a number of ways by changing future climates, including changes in recharge volumes and seasonal and spatial distribution, changes in aquifer storage and transmissivity characteristics, changes in discharge volumes and distribution, and changes in groundwater quality. Quality issues are not considered in this study, although many aspects could be significant under changing climates, including microbiology. Changes in the physical and hydraulic properties of aquifer units are most difficult to forecast, because doing so requires good data on both potential future groundwater level changes and on the detailed physical structure of aquifers. The focus of this study is on changes in groundwater level fluctuations in response to changing seasonal patterns and volumes of recharge. The study will not directly investigate potential impacts of sea level rise on coastal aquifers.

Climatic events over the last few decades have had significant impacts on groundwater resources by modifying recharge patterns. During the late 1980s and throughout the 1990s, clusters of successive winters with low effective precipitation resulted in lower than average aquifer replenishment, with extended dry summers allowing intensified groundwater recessions. On a number of occasions groundwater levels fell to close to, or below, the lowest levels on record across many aquifers, particularly the Chalk (Marsh et al., 1994). The extremely wet winter of 2000/2001 led to record high groundwater levels in many aquifers, causing significant groundwater flooding. An underlying assumption of standard procedures for investigating extreme hydrological events such as these is that climate is relatively stationary: that is, climatic means and variances do not change over long time scales (Knox and Kundzewic, 1997). However, as climatic research, such as that of the UKCIP, suggests strongly that UK climate is no longer stationary, it is clear that it is not sufficient to use historical climatic data to assess the future behaviour of hydrological systems. One approach is to develop statistical methods which do not assume stationarity.

The identification of recharge mechanisms and the quantification of different recharge components is one of the most important parts of groundwater resource studies (Bradbury and Rushton, 1998). Despite its importance, there is no single accepted model for quantifying recharge. It cannot be measured directly, and so methods of estimation must be devised (Rushton and Ward, 1979). The choice of methodology may be based on local characteristics, but it is often primarily a function of training and personal preference, past practice, cost, and other extra-scientific factors.

4 Previous work on groundwater and climate change

Despite the importance of groundwater in the UK, and the increasing recognition that the UK climate is changing, there has been little assessment of the potential impacts of such climate change on groundwater resources, and particularly of the potential effects of more frequent extreme events. Most groundwater studies have formed part of broader investigations which generally concentrate on the potential impacts on surface water resources of site-specific catchments under future climate scenarios.

Climate change impact studies are restricted by the range of uncertainty in future climate scenarios. This uncertainty is partly a function of the different models used to represent climatic processes in different GCMs, and partly of the relatively coarse resolutions of GCMs. For example, in HadCM2, the UK land area is represented by just four grid cells, so that it is impossible to apply the model results directly at catchment scales. Another uncertainty is imparted by the difficulties in predicting how climatic forcing mechanisms, such as global greenhouse gas emissions, will change in the future. Recharge studies are further limited by the continuing imperfect understanding of how physical properties differ between aquifers, and how they may respond under different hydraulic conditions.

The results of existing studies highlight some of the issues involved in investigating groundwater resources under changing climatic conditions. Younger et al (1997) comment that studies of groundwater, as opposed to surface water, resources (e.g. Cole et al, 1994) tend to derive from rainfall-runoff assessments, and primarily address changing infiltration, and therefore groundwater recharge, equating this directly (if at all) with discharge. Younger et al examined changing patterns of flow and storage within aquifers directly, modelling recharge and applying this to a model of dual-porosity saturated flow, thus addressing the impacts on groundwater resources more directly. This study also investigated potential changes in recharge quality and the effect these may have on the geometry and hydraulic characteristics of carbonate aquifers.

The sensitivity of different UK aquifers to climate and recharge variations has not received much study. Wilkinson and Cooper (1993) examined changes in aquifer storage and baseflow in three aquifer types following changes in the volume and seasonality of rainfall and evaporation. They demonstrated that different aquifers show variable response times to climate changes, related to different aquifer properties. Cooper et al (1995) also modelled differential responses to warmer, wetter winters and drier summers in Chalk and Permo-Triassic sandstone. Other studies related to these issues include Calver (1997), Price (1998), and Ragab et al (1997).

Thomsen (1993) stresses the significance of natural seasonal and interannual climatic variability in recharge estimation, and the need for water resource planning to take short and medium term climatic variability into account. Vaccaro (1992), exploring the sensitivity of recharge estimates for a selected groundwater catchment to historical climate variability and predicted climate change, demonstrated that variability in recharge estimates is likely to increase with the length of forecast, making groundwater flow projection more uncertain with increasing time.

A number of recent studies have used simple process-based recharge estimation techniques, mainly soil moisture balances and semi-empirical transfer functions, to examine the water level response in individual boreholes to climatic parameters (Calver, 1997; Ó Dochartaigh, 1999; Seritella, 1996). Seritella's study went on to model the effect of changing climatic conditions on groundwater levels. In addition, Bennett (1996) explored the use of statistical methods for predicting UK groundwater levels from rainfall data. It may be useful to incorporate the results of these studies into larger scale hydrogeological models, and so perhaps to improve confidence in the applicability of such models to the individual borehole scale.

There is a need for reliable, easy to use and flexible models to examine how groundwater recharge and storage in different aquifers may be affected by climate changes as defined by

UKCIP and other scenarios. Such models should be capable of reliably reproducing observed hydrogeological and hydrological parameters. Climatic parameters derived from current climate change scenarios can be applied to these investigate the potential impacts of changing climate.

5 Selected modelling approaches

A set of modelling approaches will be selected, developed using historical data, and applied to data for future climate scenarios. The selected approaches will be based on existing modelling techniques which will be modified as necessary and used to simulate groundwater levels under different climate change scenarios. It is likely that all the approaches will be applied to unconfined situations only.

A preliminary list of four modelling techniques has been selected: a statistical model to predict groundwater levels, an unsaturated zone transfer model, a standard (EA-developed) soil moisture balance model, and a simple process-based model of an idealised aquifer/river system (Wilkinson & Cooper, 1993). This selection may be added to or modified as the project progresses. The approaches will be evaluated and the relative strengths and weaknesses assessed.

Approach 1. Statistical correlation between rainfall and water levels

This approach establishes a correlation between historical groundwater levels and rainfall using both multiple linear regression and linear regression models. It can be used to predict annual or monthly groundwater level minima. The model makes no assumptions regarding specific hydrological or hydrogeological processes, and so has general application over a wide range of hydrogeological settings. However, it assumes that the statistical relationships between rainfall and groundwater levels observed in the historical record will remain stationary under future climates. The model requires only two data sets: groundwater level and rainfall series. However, other potentially significant independent parameters, such as evapotranspiration or temperature, may also be included. The errors associated with simulated groundwater levels are easily quantified. A previous use of this approach is described in Bennett (1996).

Approach 2. Unsaturated zone transfer function model

This model uses an unsaturated zone transfer function to describe the annual oscillation of unconfined aquifer water levels in response to surface infiltration at single sites (i.e. boreholes). Previous work using this approach is described in Calver (1997) and Oakes (1981). These studies equate effective rainfall directly to infiltration, but a range of inputs could be used, from rainfall to a more complex water balance estimation of surface infiltration. A simple approximation of saturated zone behaviour is used: a value for aquifer specific yield to transform infiltration and groundwater outflow to a change in groundwater levels. The model approach is semi-process based, in that it takes into account the observed tendency for groundwater levels to be lagged behind rainfall input, and the role of aquifer properties (represented by specific yield) in influencing recharge. The model could therefore be used to investigate potential responses in different aquifer types, although specific yield may not be a sensitive enough variable to differentiate between aquifers. The approach is most appropriate where there is limited lateral unsaturated zone transfer, and where there is no great change in the influence of local abstractions.

Approach 3. Soil moisture balance model

Soil moisture balance techniques are simple and widely used methods for recharge estimation. They provide a simple conceptual model of the precipitation-recharge process: water is held in a soil moisture store; precipitation adds to the store, evapotranspiration depletes it. When the store is full, excess precipitation is routed to groundwater stores as recharge (Lerner et al, 1990). Actual evapotranspiration is difficult to measure, and in practice a conceptual quantity, potential evapotranspiration, is defined, which is converted to an estimated value for actual evapotranspiration by means of the soil moisture budgeting procedure. The Penman-Grindley model (Grindley, 1969; Lerner et al, 1990) is the simplest and most widely used soil moisture balance technique. As well as climatic factors, the model takes account of the effects of vegetation on evapotranspiration and soil moisture, by means of constants (the root constant and wilting point). It does not take account of geological and hydrogeological characteristics below the soil zone. The methodology was developed for humid climates, where there is a defined seasonal pattern of recharge, where precipitation is widespread and relatively uniform, and where there are well developed soils which do not dry completely.

Approach 4. Idealised aquifer/river system model

This model was developed by Wilkinson and Cooper (1993) to investigate the potential effects of climate change on aquifer storage and baseflow to rivers. It incorporates a simple one dimensional groundwater flow model. The response of the aquifer system is represented by a function incorporating transmissivity, storage and the average distance from groundwater divide to river discharge point. Recharge may be input from any recharge estimation module, or may be represented by a wave function with defined magnitude and periodicity. This model allows a much greater scope for examining the potential responses of different aquifer types to climate change. The combination of transmissivity and storage is a more distinctive definition of aquifer type than specific yield alone (as in Approach 2).

Summary

These four models provide a suite of techniques which can be used either alone or in tandem, depending on data availability and the need to use a given model. Recharge and other groundwater models make compromises between the accuracy of the results and the associated requirements for detailed data inputs, and adaptability to a variety of situations, such as the size of the area to be modelled, the length of time the model is to run, and the amount of data available. The modelling approaches selected therefore range from the simple, requiring few data and little input effort, to the more complex, requiring more (but still generally available) data. The modelling techniques use readily available meteorological and hydrological data, and are applicable to a variety of hydrogeological situations occurring in the UK.

The models selected are based for the most part on simple spreadsheet analysis, and sufficient documentation is available for each to reproduce the methods. The model code which will be used in Approach 4 is available at CEH.

The outputs of the models will be fitted to observed historical data, generally groundwater levels, but also possibly river flow records.

6 Data required for recharge, groundwater level and simple groundwater flow modelling

6.1 CLIMATIC, HYDROLOGICAL AND HYDROGEOLOGICAL PARAMETERS REQUIRED

Climatic parameters for estimating recharge are normally precipitation and evapotranspiration (estimating the latter variable involves factors such as temperature, air pressure, relative humidity and wind speed). Hydrological parameters may include stream flow, stream-aquifer connections, and soil properties, including infiltration capacity, where the latter may also be partly a function of general unsaturated zone properties. Hydrogeological parameters may include groundwater levels and the hydraulic properties of the unsaturated zone and aquifer. The parameters required by the four approaches detailed here are summarised in Table 1. Details of climatic and hydrological datasets available at CEH are given in Appendix 2, and of hydrogeological datasets at BGS in Appendix 3.

MODELLING APPROACH	1	2	3	4
PARAMETERS REQUIRED				
Rainfall	X	X	X	X
Effective Rainfall	x	X		
Temperature	x			
Evapotranspiration		x	X	
Groundwater levels	X	X		X
Stream flow/spring discharge	x			x
Soil properties (root constant, wilting point, field capacity)			X	
Aquifer specific yield		X		
Aquifer transmissivity				X
Aquifer storage coefficient				X
Aquifer dimension				X

Table 1 Data parameters required (X) or potentially applicable (x) for each of the four specified modelling approaches

The sensitivity of recharge estimation techniques to various input parameters has been considered by a number of authors. Howard and Lloyd (1979) investigated the sensitivity of the Penman approach to recharge estimation to the time scales of a selection of primary input variables, specifically precipitation, potential evaporation and root constants. They considered monthly, ten-daily and daily recharge calculations, and found that monthly recharge estimates underestimated recharge by over 20 percent compared to daily recharge totals, of which less than 3 percent could be attributed to differences in the potential evaporation figures used in the two estimates. Ten-daily estimates were found to agree more closely with daily totals, although as with monthly estimates, they generally failed to take account of sporadic episodes of summer recharge.

Finch (1998) considered the sensitivity of a similar simple water balance model, again estimating direct recharge, to land surface parameters, including vegetation type and cover and a set of soil parameters, particularly the maximum available water content, field drainable water content, rooting depth and root proportions, the bypass flow threshold and the proportion of bypass flow. He concluded that the variables field drainable water, maximum available water and rooting depth have the most significant impact on recharge estimates, as these parameters largely control when and for how long the soil is at field capacity, when most recharge occurs. Finch also showed that recharge estimates were relatively insensitive to vegetation canopy characteristics, although he made a distinction between permanent and annual short vegetation and forest cover.

6.2 DATA AVAILABILITY

Climatic data for the UK are available from a number of sources, including the Meteorological Office, Centre for Ecology and Hydrology (CEH) and the Environment Agency (EA). The Meteorological Office Rainfall and Evaporation Calculation System (MORECS) database holds daily and monthly average rainfall, potential evapotranspiration, actual evapotranspiration, effective rainfall and soil moisture deficit for 40 x 40 km grid squares covering Britain, for 1961 onwards (Hough and Jones, 1997). The National Water Archive at CEH Wallingford holds monthly catchment totals derived from a 1 km grid of rainfall values generated from all daily and monthly rainfall data available from the Meteorological Office. CEH Wallingford also holds records of potential evapotranspiration from grassland across the country. A large number of rainfall records from individual raingauges are also available, largely maintained now by the Environment Agency and also by water companies. Individual raingauges often provide the longest records. Many of these records are of monthly rainfall totals, although daily values are also common (see Appendix 2).

CEH Wallingford holds a wide range of hydrological data, including extensive streamflow data, digital catchment boundaries, and land cover. Hydrogeological data held by BGS include aquifer properties and groundwater level records from selected observation boreholes (see Appendix 3). Groundwater levels are still often measured manually either weekly or monthly, although a number are now equipped with continuous recorders.

7 Overview of the hydrogeological characteristics of the major UK aquifers

The modelling techniques will be applied to a range of representative sites on the following major UK aquifers: Chalk, Permo-Triassic sandstone and Lincolnshire Limestone. Any impacts of changing climate on these aquifers is likely to be important for groundwater resource management. The aquifers have contrasting hydrological, geological and hydrogeological characteristics, and may respond differently to changing climate. They therefore allow the model approaches to be tested under different conditions.

The three major UK aquifers, the Chalk, the Permo-Triassic sandstones and the Lincolnshire Limestone, are hydraulically complex and heterogeneous over a wide range of scales. However, it is possible to identify a range of broad physical characteristics for each aquifer, and on the basis of these observations make qualitative statements concerning the respective responses of each aquifer under conditions of climatic change.

The hydraulic complexity of the aquifers is to a large extent determined by the nature and extent to which they are fractured. Figure 1, from Allen et al (1997), shows the relationship between typical fracture size ranges and the predominant flow types in each aquifer, e.g. intergranular or fracture dominated flow (note that the Lincolnshire Limestone is one of the Jurassic Limestones). Fractures are present in all three aquifers, although they are less continuous and may be sediment-filled in the Permo-Triassic sandstones. Fracturing is pervasive in the Chalk and the Lincolnshire Limestone, and a preferentially enlarged component of the fracture network is responsible for locally high values of transmissivity in these aquifers. Tables A1 to A5 in Appendix 1 summarise transmissivity (T, m^2/d) and storage coefficients (S) for the three aquifers on a region-by-region basis, based on data given in the Aquifer Properties Manual (Allen et al, 1997).

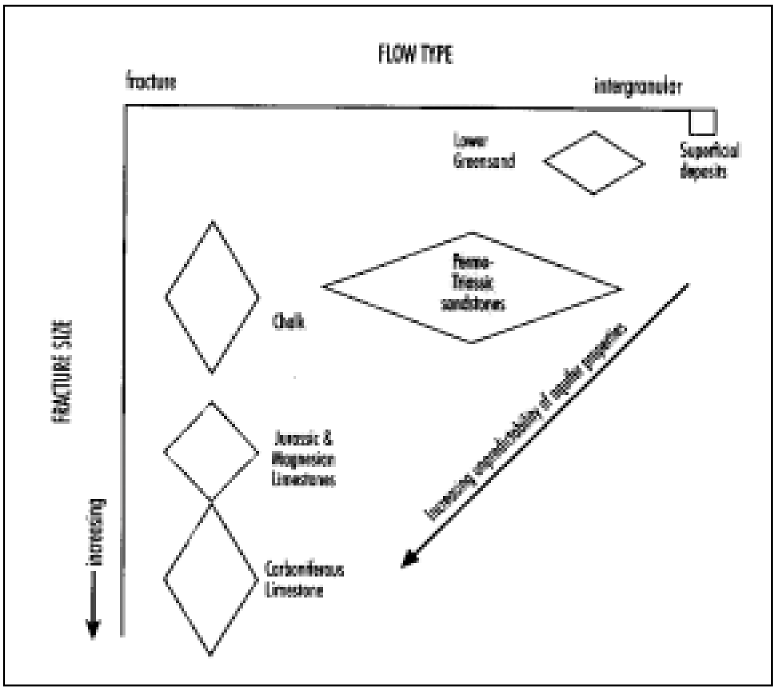

Figure 1 Flow types in British aquifers (from Allen et al, 1997)

The Chalk is the principal aquifer in the UK, providing about 55 percent of the total licensed groundwater abstraction in England and Wales. Hydraulically significant features of the aquifer include:

- A high porosity matrix with small pore-throat sizes. The matrix has a relatively low permeability, and groundwater flow in the saturated zone is primarily through fractures. Usable groundwater storage is concentrated in fractures, with only a minor contribution from the matrix.
- Significant vertical variation in hydraulic conductivity. Conductivity and storage coefficients are highest in the top 50 to 70 m of the Chalk and decline with depth.
- Marked horizontal variation in hydraulic conductivity, with relatively low conductivities over interfluves and areas of relatively high hydraulic conductivity associated with river valleys. This is due to the increased incidence of fracturing and fracture development associated with higher groundwater flux in the valleys.
- The highest conductivities are often associated with intervals of solution-enlarged fractures in the zone of water table fluctuation.
- Variations in aquifer properties that do not conform to topographic distribution can be observed where sub-karstic development is locally important.
- Seasonal, winterbourne, flow is characteristic of rivers fed by Chalk groundwater.

Any fall in base groundwater levels in the Chalk due to long term climate change may have a relatively significant affect on borehole yields. This is because the most transmissive part of the aquifer is the upper few tens of metres of the saturated zone, particularly the interval corresponding to the zone of recent/present-day water table fluctuation. Conversely, should groundwater levels rise above the zone of historic groundwater levels fluctuations they may continue to rise rapidly sue to relatively low storage in this zone. This phenomenon was observed during the wet winter of 2000-2001, when it contributed to groundwater flooding in a number of areas in southern England (CEH/Met Office, 2001). Because storage is dominantly affected by a range of macro- and micro-fractures, and only to a minor extent by the matrix, the response of the aquifer is generally more ‘flashy’ than that of the sandstones, but less rapid than that of the Lincolnshire Limestone where storage is essentially restricted to a few relatively large fractures.

The Permo-Triassic sandstones are the second most important aquifer in the UK, providing about 25 percent of the total licensed groundwater abstraction in England and Wales. A number of large towns, for example Manchester, Liverpool, Birmingham and Leeds, obtain their water supplies at least partly from the sandstones. Hydraulically significant features of the aquifer include:

- Highly variable lithologies with variable grain-size and pore-size distributions. The degree and nature of cementation varies locally and regionally and affects hydraulic conductivity and storage characteristics. The nature of fracturing also varies locally and regionally and may be related to lithology as well as burial history and tectonic structure.
- Hydraulic anisotropy due to sedimentary layering, which occurs over a wide range of scales from individual beds to whole aquifers. As a result saturated flow is often focused preferentially through high conductivity units. Lower conductivity units may act as leaky aquitards or as barriers to flow.
- Effective aquifer thickness may be considerably less than the full thickness of the aquifer due to the presence of low conductivity units.
- Compressible storage within the matrix as the principal component of storage in the sandstones.

A fall in base groundwater levels in the sandstones, due to long term climate change, may have a less significant affect on borehole yields than in the Chalk. This is because the conductivity of the sandstones is controlled by the distribution of high conductivity sands and is less a function of the zone of water table fluctuation. In addition, because storage in the sandstones is largely controlled by compressible storage within the matrix, they are less likely to exhibit a 'flashy' response to periods of rapid recharge. Thick unsaturated zones and variable low permeability drift cover also limit the potential for rapid groundwater level response.

The Lincolnshire Limestone is an important aquifer in central eastern England, outcropping for about 130 km between the Humber Estuary in the north to Peterborough in the south. Important aspects of flow in the Lincolnshire Limestone aquifer include (Rushton and Tomlinson, 1999):

- Low matrix porosity.
- Distributed and locally concentrated recharge.
- Variable transmissivity with saturated depth.
- The distribution of preferentially enlarged fractures, of major importance in determining the distribution of transmissivity.
- Vertical flow (upwards or downwards) through overlying beds in the confined part of the aquifer.

It is difficult to predict the effects of a fall in base groundwater levels caused by long term climate change on the Lincolnshire Limestone. This is because transmissivity is so strongly dependent on the local development of enlarged fractures within the limestone. Enlarged fractures may be associated with present-day local flow systems, or may also reflect past groundwater flow regimes. Any changes in mean or extreme groundwater levels may initiate unpredictable changes in local aquifer behaviour. Because storage is essentially restricted to the fractures, the Lincolnshire Limestone can be expected to show the most 'flashy' response of all the three aquifers under consideration.

8 Scheme of work

The following scheme of work has been adopted for the project:

- Select the boreholes or areas to be modelled.
- Obtain the input data required to develop and run the models.
- Develop and fit the models for historical data.
- Generate synthetic future climate data.
- Run the fitted models for synthetic future climate data.
- Investigate the sensitivity of the different models and different aquifers to various future climatic data.

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Appendix 1 Selected aquifer properties data for the major UK aquifers

Table 2 T, S and aquifer length (L)[1] values for the Permo-Triassic sandstones on a region-by-region basis (from Allen et al, 1997)

Region	Parameter	Geometric mean	Median	Range	Suggested range of appropriate values (m)	Comments
North-East	T (m^2/d)	201	206.5	12 - 5000	-	Approx. log-normal distribution
	S	0.0021	0.001	$1x10^{-4}$ - 0.31	-	Modelled values 0.1-0.15 (unconfined), 1-$5x10^{-4}$ (confined)
	L (m)	-	-	-	15,000	cf. pages 171-172, Allen et al. 1997
West Midlands	T (m^2/d)	151	158	2 - 5200	-	Approx. log-normal distribution
	S	$2.5x10^{-3}$	$1.6x10^{-3}$	$2x10^{-4}$ - 0.15	-	Modelled values 1-$5x10^{-4}$ (confined)
	L (m)	-	-	-	2,000 - 5,000	cf. pages 191-192, Allen et al. 1997
Shropshire	T (m^2/d)	200	240	9 - 4770	-	Approx. log-normal distribution
	S	$7.9x10^{-4}$	$9.4x10^{-4}$	$2.3x10^{-8}$ - 0.19	-	Approx. log-normal distribution. Low values of S are for confined aquifers.
	L (m)	-	-	-	~ 10,000	cf. pages 204-205, Allen et al. 1997
Cheshire & S Lancashire	T (m^2/d)	220	250	0.9 - 4900	-	Approx. log-normal distribution
	S	$1.1x10^{-3}$	-	$1.2x10^{-5}$ - 0.09	-	Approx. log-normal distribution
	L (m)	-	-	-	15,000 - 20,000	cf. pages 214-217, Allen et al. 1997
Fylde	T (m^2/d)	260	360	26 - 1100	-	T varies widely over very limited areas
	S	0.0015	0.0015	8.1x10-5 - 0.17	-	-
	L (m)	-	-	-	5,000 - 70,000	cf. pages 233 & 238, Allen et al. 1997

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Region	Parameter	Geometric mean	Median	Range	Suggested range of appropriate values (m)	Comments
North-West England	T (m^2/d)	240	263	8 - 3300	-	Sig. var. across region and between formations, depending on fracturing.
	S	$1.7x10^{-4}$	$4x10^{-4}$	$4.5x10^{-8}$ - 0.12	-	-
	L (m)	-	-	-	5,000 - 10,000	Cf. pages 240, Allen et al. 1997
Vale of Clwyd	T (m^2/d)	130	130	20 - 1200	-	Large range related to degree of fracturing
	S	$3.8x10^{-4}$		$1x10^{-4}$ - $2x10^{-3}$		Representative confined value of $4x10^{-4}$
	L (m)	-	-	-	2,000 - 5,000	cf. page 261, Allen et al. 1997
South-West England	T (m^2/d)	95	105	2.9 - 2033	-	Approx. log-normal distribution
	S	0.0013	$9x10^{-4}$	$1.3x10^{-4}$ - 0.15	-	-
	L (m)	-	-	-	2,000 – 5,000	cf. page 264, Allen et al. 1997

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Table 3 T, S and aquifer length (L)[1] values for the Permo-Triassic sandstone aquifer as a whole

Aquifer	Parameter	Geometric mean	Median	Range	Suggested range of appropriate values (m)	Comments
Permo-Triassic Sandstones	T (m^2/d)	189	206	0.9 - 5200	-	Approx. log-normal distribution
	S	10^{-3}	-	-	-	-
	L (m)	-	-	-	-	Cf. page 158, Allen et al. 1997

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Table 4 T, S and aquifer length (L)[1] values for the Chalk on a region-by-region basis

Region	Parameter	Geometric mean	Median	Range	Suggested range of appropriate values (m)	Comments
Hampshire & South Downs	T (m^2/d)	686	1200	0.2 – 20000	-	Data from A MacDonald (pers.com)
	S	-	-	-	-	
	L (m)	-	-	-	-	
Thames Basin	T (m^2/d)	446	585	0.46 - 25000	-	Data from A MacDonald (pers.com)
	S	-	-	-	-	
	L (m)	-	-	-	-	
East Anglia	T (m^2/d)	402	450	0.1 – 30500	-	Data from A MacDonald (pers.com)
	S	-	-	-	-	
	L (m)	-	-	-	-	
Yorkshire, Humberside and Lincolnshire	T (m^2/d)	1292	1800	0.1 – 30500	-	Data from A MacDonald (pers.com)
	S	-	-	-	-	
	L (m)	-	-	-	-	

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Table 5 T, S and aquifer length (L)[1] values for the Chalk on a sub-regional basis (from Allen et al., 1997; MacDonald and Allen, in prep)

Region	Parameter	Geometric mean	Median	Range	Suggested range of appropriate values (m)	Comments
Dorset	T (m^2/d)	383	985	-	-	Hampshire and S Downs region
	S	0.004432	0.005248	-	-	-
	L (m)	-	-	-	-	-
Salisbury Plain	T (m^2/d)	1400	1600	50 – 8200	-	Hampshire and S Downs region
	S	0.0052	0.01	$1x10^{-4}$ - 0.05	-	-
	L (m)	-	-	-	~ 30,000	cf. page 48, Allen et al. 1997
Hampshire	T (m^2/d)	1600	2600	0.55 – 2900	-	Hampshire and S Downs region
	S	0.008	0.009	$7x10^{-5}$ - 0.06	-	-
	L (m)	-	-	-	~ 50,000	cf. page 51, Allen et al. 1997
South Downs	T (m^2/d)	500	440	16 - 9500	-	Hampshire and S Downs region
	S	0.0018	0.0022	$2x10^{-4}$ - 0.032	-	-
	L (m)	-	-	-	10,000 - 15,000	cf. page 56, Allen et al. 1997
Kennet Valley	T (m^2/d)	620	830	5 - 8000	-	Thames Basin Region
	S	0.006	0.0075	$1x10^{-4}$ - 0.071	-	-
	L (m)	-	-	-	~ 25,000	cf. page 61, Allen et al. 1997
Chilterns	T (m^2/d)	820	860	38 - 25000	-	Thames Basin Region
	S	0.0037	0.0029	$6.5x10^{-5}$ - 0.09	-	-
	L (m)	-	-	-	~ 25,000	cf. page 67, Allen et al. 1997
Thames	T (m^2/d)	160	230	1 - 4300	-	Thames Basin Region
	S	0.0016	0.0024	$3.5x10^{-5}$ - 0.05	-	-
	L (m)	-	-	-	~ 50,000	cf. page 73, Allen et al. 1997

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Region	**Parameter**	**Geometric mean**	**Median**	**Range**	**Suggested range of appropriate values (m)**	**Comments**
North Downs	T (m^2/d)	720	670	52 - 7400	-	Thames Basin Region
	S	0.0031	0.0036	$1x10^{-5}$ - 0.06	-	-
	L (m)	-	-	-	~ 30,000	cf. page 76, Allen et al. 1997
Hertfordshire	T (m^2/d)	326	580	26 - 1407	-	East Anglian Region
	S	0.0047	0.004	-	-	-
	L (m)	-	-	-	-	-
Cambridgeshire	T (m^2/d)	670	800	10 - 7000	-	East Anglian Region
	S	0.0043	0.0058	-	-	-
	L (m)	-	-	-	-	-
West Suffolk	T (m^2/d)	680	780	1 - 10000	-	East Anglian Region
	S	0.0037	0.0035	$1.4x10^{-4}$ - 0.1	-	-
	L (m)	-	-	-	-	-
West Norfolk	T (m^2/d)	500	1000	2 - 9500	-	East Anglian Region
	S	0.0059	0.004	$2.7x10^{-4}$ - 0.1	-	-
	L (m)	-	-	-	-	-
East Norfolk	T (m^2/d)	277	250	1 - 10000	-	East Anglian Region
	S	0.0022	0.0022	$5x10^{-7}$ - 0.1	-	-
	L (m)	-	-	-	-	-
East Suffolk	T (m^2/d)	255	315	-	-	East Anglian Region
	S	0.0032	0.0025	-	-	-
	L (m)	-	-	-	-	-

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Region	Parameter	Geometric mean	Median	Range	Suggested range of appropriate values (m)	Comments
North Essex	T (m^2/d)	370	400	1 - 7000	-	East Anglian Region
	S	0.0016	0.00125	$7x10^{-5}$ - 0.1	-	-
	L (m)	-	-	-	-	-
Yorkshire	T (m^2/d)	1258	1250	1 - 10000	-	Yorkshire, Humberside and Lincolnshire Region
	S	0.002	0.005	$1.5x10^{-4}$ - $1x10^{-1}$	-	
	L (m)	-	-	-	-	
Lincolnshire	T (m^2/d)	1607	1637	60 - 1000	-	Yorkshire, Humberside and Lincolnshire Region
	S	0.00016	0.00023	$2x10^{-6}$ - 0.056	-	
	L (m)	-	-	-	-	

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Table 6 T, S and aquifer length (L)[1] values for the Lincolnshire Limestone aquifer

Aquifer	**Parameter**	**Geometric mean**	**Median**	**Range**	**Suggested range of appropriate values (m)**	**Comments**
Lincolnshire Limestone	T (m^2/d)	665	-	<100 - ~10,000	-	
	S	~ 10^{-4} (?)	~ 10^{-4} (?)	$2x10^{-7}$ - 0.58	-	Modelled value in range 0.001 - 0.01 (unconfined) and $2.5x10^{-4}$ (confined)
	L (m)	-	-	-	5,000 - 10,000	cf. Page 136, Allen et al. 1997

[1] Aquifer length refers to the distance between the groundwater divide and a river which acts as the single point of groundwater discharge in an idealised aquifer (Wilkinson and Cooper, 1993)

Appendix 2 Hydrological and climatic datasets available at CEH

SPATIAL DATASETS

Precipitation Data

DATASET	DATA TYPE
Rainfall for individual months (1961-present)	1km grid
1961-90 annual average rainfall	1km grid
SAAR (1941-70 annual average rainfall)	1km grid and vector
M52D (5 yr return period 2 day rainfall)	1km grid and vector
RJEN (5 yr return period 1 hour rainfall as a % of M52D)	1km grid and vector
5 yr return period 25 day rainfall as % of SAAR	1km grid and vector
Estimated maximum 2 hour rainfall	1km grid and vector
Estimated maximum 24 hour rainfall	1km grid and vector
2 year return period maximum snow depth	1km grid and vector

Climatic Data (excluding precipitation)

DATASET	DATA TYPE
Potential evaporation (for grass)	1km grid and vector

Drainage Data

DATASET	DATA TYPE
1:50,000 rivers	Vector
Catchment boundaries (existing digitised boundaries to river flow gauging stations)	Vector
Hydrometric area boundaries	Vector
Northern Ireland primary and secondary drainage basins	Vector
Runoff	1km grid

Institute of Hydrology Digital Terrain Model

DATASET	DATA TYPE
Elevation	50m grid
Surface type	50m grid
Drainage direction	50m grid
Inflow direction	50m grid
Catchment area	50m grid

Landcover Data

DATASET	DATA TYPE
Built-up areas	50m grid

Soils Data

DATASET	DATA TYPE
WRAP (Winter Rainfall Acceptance Potential)	100m grid .
HOST (Hydrology Of Soil Types classification)	1km grid

TIME SERIES DATA

Code	Dataset	Data type
TDF	Table of daily mean gauged (or naturalised) discharges	Includes monthly and annual summary statistics. Flows in cubic metres per second.
TMF	Table of monthly mean gauged (or naturalised) discharges	Includes monthly and annual summary statistics. Flows in cubic metres per second.
TME	Table of monthly extreme flows	The lowest and highest daily mean flows, together with the highest instantaneous flow and date of occurrence (where available). Flows in cubic metres per second. Includes summary statistics.
TMR	Table of catchment monthly areal rainfall and runoff	Rainfall totals in millimetres and as a percentage of the 1941-70 catchment average (percentages based on the 1961-90 Standard Period will soon be available). Includes summary statistics.
TRR	Table of catchment monthly areal rainfall and runoff	Runoff is normally derived from the monthly mean gauged flow. An additional listing is provided for catchments with naturalised flow records. Includes summary statistics. Rainfall and runoff totals are in millimetres.
YBM	Yearbook data tabulation (monthly)	Monthly river flow and catchment rainfall data for a specified year together with comparative statistics derived from the historical record. Naturalised flows (where available) - and the corresponding runoff - may also be included.
HDF	Hydrographs of daily mean flows	Choices of scale, units, truncation level and overlay grid pattern are available. The period of record maximum and minimum flows, or the mean flow, may be included. The plots may be based on single or n-day means, or on n-day running mean flows.
HMF	Hydrographs of monthly mean flows	Choices of scale, units and overlay grid pattern are available. The period of record maximum and minimum flows may be included.
YBD	Yearbook data tabulation (daily)	River flow and catchment rainfall data for a specified year with basic gauging station and catchment details and flow statistics derived from the historical record.
FDS	Flow duration statistics	Tabulation of the 1-99 percentile flows with optional plot of the flow duration curve. The percentiles may be derived from daily flows or n-day averages and the analysis may be restricted to nominated periods within the year, e.g. April-September only. Choices of scales, grid marking and units are available and the percentiles may be expressed as a percentage of the average flow or of a nominated flow.

THS	Table of hydrometric statistics	Provides a comparison between summary statistics for a selected year, or a group of years, and the corresponding statistics for a nominated period of record (as featured in the Hydrometric Register and Statistics 1986-90).
SCD	Gauging station summary sheet	Includes a daily flow hydrograph (with period of record extreme values) and flow duration curve together with summary relating to river flow, catchment runoff and catchment rainfall. A description of the gauging station and catchment s also provided together with selected catchment characteristics and a concise summary of the archived data.
GSR	Table of gauging station reference information	Tabulation of selected gauging station details and catchment characteristics for nominated gauging stations.
A4S	Gauging station and catchment description	A brief summary of the gauging station, its history and major influences on the flow regime, together with catchment details. .

Appendix 3 Relevant hydrogeological and geological datasets available at BGS

GROUNDWATER LEVEL OBSERVATIONS

The National Groundwater Level Archive maintains an observation network of boreholes in aquifers across the UK. The majority of observation boreholes are measured manually either weekly or monthly. Some observation boreholes are equipped with continuous water level recorders.

HYDROGEOLOGICAL PROPERTIES

The Aquifer Properties Database holds information on:

- Transmissivity
- Storage coefficient
- Q/s
- Porosity
- Hydraulic conductivity

Transmissivity, storage coefficient and Q/s values are available for sites where a pumping test has been carried out. Average matrix values of porosity and hydraulic conductivity are available for sites where geological core has been collected and analysed.