Assessments of the sensitivity to climate change of flow and natural water quality in four major carbonate aquifers of Europe

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Abstract: A numerical modelling approach has been developed to predict the vulnerability of aquifers to future climate change. This approach encompasses changes in recharge regime, dynamics of flow and storage patterns within aquifers, and natural hydrochemical changes. An application of the approach has been made to four hypothetical spring catchments representative of major carbonate aquifers in three European climatic zones. Since prolific carbonate aquifers typically combine a high transmissivity with a low specific yield, they can be expected to be more sensitive than clastic aquifers to changes in recharge patterns. Simulations of the study systems to the middle of the 21st century predict different outcomes in the three different climate zones: (1) in the northern maritime zone (UK) recharge (and therefore discharge) is predicted to increase by as much as 21% in response to anticipated increases in precipitation; (2) in the continental zone (Germany) recharge in winter is predicted to remain approximately the same as at present, but summer recharge will decline dramatically (by as much as 32%), so that a net decrease in aquifer discharge is predicted; and (3) in the Mediterranean zone (Spain) recharge is predicted to decrease by as much as 16% of the present-day values. For all three systems, increases in water hardness in response to rising CO_2 are predicted, but are expected to be negligible in water resources terms.

Europe is highly dependent on its groundwater resources (Crampon *et al.* 1996). Even in countries like Britain and Germany, which are relatively rich in surface water resources, groundwater accounts for more than a third of all public water supply. In the Mediterranean countries of Europe, where surface water resources are limited, groundwater is often the sole source of public supply. Consequently, any major reductions in groundwater availability in such countries can be anticipated to have serious economic implications. Climate change clearly poses a threat to the long-term viability of European water resources (e.g. Arnell 1992; Price 1998). If current global warming prognoses are correct (Wigley *et al.* 1997; Arnell 1999), then serious consideration will need to be given to ways of meeting the supply-demand balance in future. While improvements in water conservation and demand management practices will have a considerable contribution to make, provision of further storage is virtually certain to become increasingly important in decades to come. With surface reservoirs becoming increasingly contentious in many parts of the world, groundwater storage is likely to assume even greater importance than at present in overall water resources management strategies (e.g. Price 1998).

Despite the likely increased importance of

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groundwater resources under the changed climate conditions of the future, few assessments of the water resources implications of climate change have yet considered groundwater explicitly. To date, most assessments have focused on surface water quantity, principally through studies of changes in rainfall run-off behaviour which can be expected under possible future climatic conditions (e.g. Solomon *et al.* 1987; Arnell 1992, 1998). While an early attempt was made to predict possible changes in groundwater dynamics at the global scale in response to global warming (Zekster and Loaiciga 1993), relatively few aquifer-scale assessments have been made. Early studies were largely restricted to evaluations of changes in recharge (e.g. Vaccaro 1992; Cole *et al.* 1994; Sandstrom 1995). The implicit assumption in these studies was that total groundwater discharge would simply equal the total recharge under changed climate conditions (e.g. Bouraoui *et al.* 1999). This is logical enough if one is concerned only with long-term average volumes of discharge. However, where inter-annual or sub-annual variations in groundwater discharge rate are of interest (which is nearly always the case in water resources evaluations), then the degree to which flow and storage within an aquifer transform a recharge time-series into a discharge time-series with different characteristics becomes very important. In other words, groundwater flow and storage processes effectively attenuate discrete incoming parcels of infiltration to produce a relatively smooth, continuous aquifer discharge. Groundwater storage also results in aquifers having much longer residence times than river systems. In some cases the impacts of a given period of extreme rainfall (low or high) on aquifer responses may persist for several years. Hence aquifer responses to climate change might be expected to show a considerable temporal lag which will not be picked up by simply equating total recharge to total discharge.

In recognition of these complications a number of climate change impact studies have included model representations of groundwater flow and storage processes. Most numerous are studies in which aquifer processes are represented in a 'lumped' manner within catchment-scale water balance models (e.g. Gellens 1991; Ferrier *et al.* 1993; Panagoulia & Dimou 1996; Eltahir & Yeh 1999; Kilsby *et al.* 1999; Rosenberg *et al.* 1999; Dehn *et al.* 2000; Limbrick *et al.* 2000). These models have the advantage that they generally demand input data at the same sort of spatial resolution as the outputs generated by atmospheric general circulation models (GCMs). However, spatial resolution is only one consideration when choosing an appropriate model for aquifer responses to climate change. The 'lumped' models listed above differ widely in their internal functioning, varying from simple linear storage models (e.g. Dehn *et al.* 2000) to relatively sophisticated models based on aggregation of physically based response modelling to large scales (e.g. Kilsby *et al.* 1999). Given that it is generally inadvisable to apply empirical input-output response models to conditions that fall outside their calibrated ranges, the physically based aggregation approach is the most defensible for climate change impact assessments (Kilsby *et al.* 1999). Where possible, it would be preferable to use a fully physically based model with spatial resolution on the typical scale of interest for water resources evaluations.

Although physically based, distributed numerical models are very widely used in hydrogeology they have found surprisingly few applications in climate change impact studies to date. Wilkinson & Cooper (1993) and Cooper *et al.* (1995) used finite difference models to examine groundwater–surface water dynamics in hypothetical, idealized systems representative of systems found in southern and central England. More recently, numerical modelling has been used to evaluate the possibility of exacerbated saline intrusion into coastal aquifers in Egypt and India (Sherif & Singh 1999; Bobba *et al.* 2000), although evaluations in that setting are complicated by possible sea-level rises in addition to changes in recharge patterns. A numerical modelling study of the karstic Edwards Aquifer in Texas, USA concluded that resources in the aquifer can be expected to come under severe stress in the next few decades in the likely event that predicted decreases in recharge are realised (Loaiciga *et al.* 2000). While the isolated studies listed above are interesting, the fact that they are restricted to single climate zones limits their utility in gaining an overall impression of the range of possible climate change impacts on public-supply aquifers. A study that applies the same evaluation criteria to a number of aquifers in a range of climate settings is therefore desirable.

There is a further aspect of groundwater–climate interactions that is receiving increasing attention, namely the role of the subsurface as a possible sink (or source) for atmospheric CO_2. Recent studies have illustrated that consumption of CO_2 in weathering reactions worldwide is of sufficient magnitude that it might feasibly influence global warming rates over the medium to long term (Kump *et al.* 2000; Liu & Zhao 2000). What has not yet been considered is whether increased weathering rates in response to rising atmospheric CO_2 have important consequences for groundwater quality.

All studies of aquifer responses to climate change have to overcome problems of coupling climate change prediction results to the small-scale soil–plant–atmosphere dynamics that ultimately govern recharge (e.g. Kilsby *et al.* 1998; Bouraoui *et al.* 1999). There are a number of possible approaches to climate change impact assessments. At their simplest, assessments can be made by simply modifying present-day rainfall totals in proportion to anticipated changes in atmospheric temperature (e.g. Panagoulia & Dimou 1996; Loaiciga *et al.* 2000). Such simple approaches might overlook significant changes in evapotranspiration which are expected to result from any change in climate. Another approach is to assume that the present latitudinal zonation of climate patterns will simply shift north or south, so that future conditions in England can be directly compared with, say, present-day conditions in central France. This approach ignores the important factor of day length, which is determined astronomically and is thus independent of climate.

Overall, the most scientifically defensible approach to climate change impact assessments is to use the output from physically based, process-oriented GCM simulations (Hulme *et al.* 1994; Kilsby *et al.* 1998). GCMs are generally formulated as finite difference (or more rarely, finite element) solutions of large systems of coupled partial differential equations which describe the movement of atmospheric air masses. Despite their pre-eminence in climate impact studies, GCM outputs are difficult to apply to hydrological change studies for at least two reasons (Gleick 1986 1989):

(1) Problems of discretization: the spatial resolution of GCM grids is generally too coarse to provide hydroclimatological information at a scale relevant to catchment or aquifer modelling.
(2) Problems of process representation: while many GCMs include representations of Earth surface hydrology (which represent important feedbacks to the atmosphere), the process representations used in the GCMs are usually very simple and do not provide information of sufficient detail (spatial or temporal) for standard water resources modelling purposes.

The down-scaling of GCM output for water resources management studies is an area of active research with a rapidly changing orthodoxy (see, for instance, Kilsby *et al.* 1998; Mavromatis & Jones 1998, 1999; Wilby *et al.* 1998). For this reason, specific climate impact predictions tend to have an extremely short 'shelf-life'.

This paper addresses a number of the issues identified above. In particular, we describe: (1) the use of a purpose-written, physically based numerical modelling code to simulate the responses of carbonate aquifers to climate change, in terms of both quantity and quality (primarily hardness) of water; and (2) a technique for using GCM output in aquifer studies, which has then been applied across a range of systems representative of the main climate zones of western Europe.

The work reported here was undertaken under the aegis of an European Commission research project entitled 'GRACE' (Groundwater Resources and Climate Change Effects). Full details of the GRACE project are available elsewhere (Clemens *et al.* 1996, 1997; Sauter *et al.* 1997; Younger *et al.* 1997; Elliot *et al.* 1998; Manzano *et al.* 1998; Sauter & Liedl 1998); this paper brings together key findings to provide an overview of possible climate change impacts on carbonate aquifers throughout western Europe.

Carbonate aquifers and climate change

Sensitivity of carbonate aquifers to climate change

As the first full analysis of its kind, GRACE focused on the 'worst-case scenario' represented by carbonate aquifers. Carbonate aquifers may be regarded as a 'worst case' for the following reasons:

(1) Those aquifers most responsive to changes in recharge will be those with low specific yields and (at least locally) high transmissivities; carbonate aquifers, being generally fracture-flow systems, generally fall into this category.
(2) Carbonate aquifers might be expected to show exacerbated lowering of the water table in the longer term if changes in atmospheric carbon dioxide concentration induce dissolutional enlargement of fracture apertures (and thus an increase in permeability).
(3) If dissolution of carbonate rocks becomes more vigorous over time, then the hardness of the groundwater can be expected to increase, possibly resulting in unacceptable water quality.

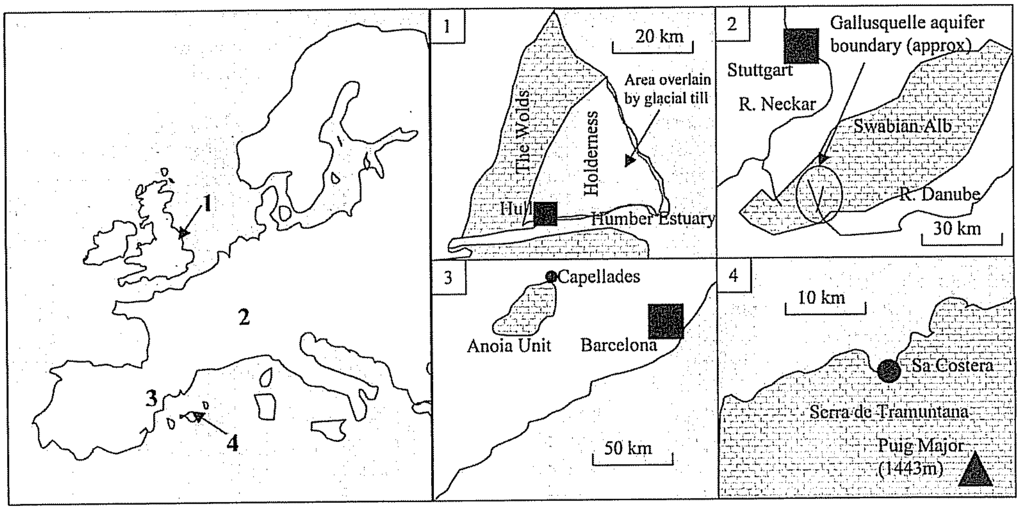


Fig. 1. Sketch map showing the locations of the four European carbonate aquifer systems discussed in the text. (Note that the right-hand edge of each box is oriented approximately north-south).

The first of these postulates is illustrated to some degree by the results obtained for the Edwards aquifer in Texas by Loaiciga *et al.* (2000), although their future climate scenarios were not rigorously based on GCM results. In this paper we provide inter-comparable, GCM-derived evaluations for four aquifers in three climatic settings. The latter two issues listed above have not been examined previously, and are therefore also considered in this study.

Carbonate aquifers in three European climatic zones were selected for detailed analysis (Fig. 1):

(1) The Yorkshire Chalk (UK; northern maritime climatic zone);
(2) The Gallusquelle aquifer (Germany; temperate continental climatic zone); and
(3) The Anoia Unit (Catalunya) and the Serra de Tramuntana (Mallorca) (Spain; Mediterranean climatic zone).

Comprehensive accounts of the hydrogeology of these aquifers are given elsewhere (Sauter 1992; Cardoso da Silva 1997; Younger *et al.* 1997; Lambán Jiménez 1998); hence only brief summaries are given below.

Yorkshire Chalk aquifer (UK) – northern maritime climate zone

The Yorkshire Chalk aquifer underlies an area of some 1800 km^2 north of the Humber Estuary in eastern England (study area 1 in Fig. 1). The hydrogeology of the aquifer has been described in detail (e.g. Foster & Milton 1974, 1976; Institute of Geological Sciences/Yorkshire Water Authority 1980; Elliot *et al.* 1998, 2001). Essentially the Yorkshire Chalk comprises two hydrogeological zones:

(1) A western zone of unconfined Chalk, in and adjoining the recharge area in the hills of the Yorkshire Wolds. Transmissivities in this zone vary from around 10^1 m^2 d^{-1} beneath interfluves to as much as 10^4 m^2 d^{-1} in the axes of the wider valleys. Unconfined storativities rarely exceed 0.02. Many natural springs drain this unconfined zone. Large well abstractions are also long-established. While some large conduits (diameters ≤ 0.5 m) have been observed in the Yorkshire Chalk at outcrop, these are rarely continuous over distances of more than a few metres. Hence, despite possessing some of the classical attributes of a karst system (such as a dense network of dry valleys), the Yorkshire Chalk is probably best regarded as proto-karstic.
(2) An eastern zone of confined Chalk, beneath the Holderness Plain, where the Chalk is overlain by Quaternary glacial sediments (predominantly low-permeability tills). Transmissivities in this area tend to fall in the range 10^1–10^2 m^2 d^{-1}, and confined storativities are usually in the range 10^{-5}–

10^{-7}. There are few natural discharges from this zone of the aquifer, though there are several significant well abstractions.

Although the total stratigraphic thickness of the Yorkshire Chalk exceeds 420 m, structural dip and weathering history have resulted in significant transmissivity development being restricted to the uppermost 80–100 m of the Chalk rock mass at any one point. Hydrochemical patterns in the aquifer coincide to some degree with the eastern and western hydrogeological zones (Pitman 1986). Elliot *et al.* (2001) have argued that hydrochemical patterns can be explained in terms of palaeohydrogeological events, the nature of which shed light on the sensitivity of the aquifer to climate change, inasmuch as the presence of bodies of saline water in parts of the aquifer are actually the result of previous changes in recharge regime and sea level rather than responses to artificial abstractions. The Yorkshire Chalk aquifer is an important source of public supply to the City of Hull and environs, both directly via well abstractions, and indirectly by providing most of the baseflow in the River Hull, from which water is also drawn for public supply. Within the last 5 years water levels in the Yorkshire Chalk have fallen to all-time low levels during a succession of dry summers, prompting fears that the aquifer may be a less reliable water resource than it had previously been considered (Elliot *et al.* 1998).

The Gallusquelle aquifer (Germany) – temperate continental climate zone

The Gallusquelle aquifer (study area 2 in Fig. 1) forms part of a regional-scale karstic mountain range, the Swabian Alb, in south-west Germany. The aquifer comprises limestones of Jurassic (Oxfordian and Kimmeridgian) age. (Note that these quintessentially English chronostratigraphic terms are also used in Germany.) The main aquifer units are the upper Kimmeridgian limestones. Within the catchment area, the whole limestone sequence dips south-east at about 1–2°. As in the Yorkshire Chalk, the effective aquifer base is not stratigraphically determined; rather it cuts discordantly across lithostratigraphic horizons according to the local degree of development of porosity and permeability (Sauter 1992). This discordance is a result of the genetic history of the aquifer and the petrography of the limestone rocks. Like the Yorkshire Chalk, the Gallusquelle aquifer has transmissivities in the range 10^1 to 10^4 m^2 d^{-1}, but in this case the higher values are associated with well-developed systems of dendritic, phreatic caves (Sauter 1992).

Most water resources in the Swabian Alb are exploited via natural springs; abstraction wells are rare, partly because of the difficulties of access in the mountainous terrain, and partly because the chances of hitting highly transmissive zones are rather slim. The Swabian Alb karst springs are also of immense ecological and emblematic importance, since they form the headwaters of the Danube, arguably Europe's greatest river.

The Anoia Unit, Catalunya (Spain) – Mediterranean climatic zone

The Anoia Unit (study area 3 in Fig. 1) is a tectonically complex hydrogeological system that lies in the Catalan Prelitoral Range, a range of mountains running south-west to north-east and rising to between 400 and 700 m asl some 60 km W of Barcelona. A recent comprehensive hydrogeological study of the area has been made by Lambán Jiménez (1998), from which the following summary has been compiled. The Anoia Unit underlies 160 km^2 and constitutes a multi-layered carbonate aquifer system of Triassic and Eocene age. The unit is surrounded on all sides by a variety of Caenozoic and Palaeozoic strata of relatively low permeability. Within the Anoia Unit are three carbonate aquifer horizons (Lower Muschelkalk, Upper Muschelkalk and Lower Eocene) which are fissured and lightly karstified. These are inter-bedded with two units which are generally presumed to be of lower permeability: a silty and clayey sand (Middle Muschelkalk) and a marly gypsiferous sequence (Keuper). Nevertheless, local karstification of the marls and gypsum results in the Keuper being highly permeable. The Lower Eocene aquifer is up to 60 m thick, while the Upper and Lower Muschelkalk aquifers are each about 100 m. However, folding produces greater apparent thicknesses. The whole Anoia Unit is smoothly folded, with the axes in a south-west to north-east disposition, and with all axes plunging to the north-east. Consequently, the older formations cropout to the south of the unit while the younger ones cropout in the north. These structural patterns control the hydraulic behaviour of the unit, with the degree of confinement of the aquifer layers varying over short distances.

Large areas of unsaturated limestone which overlie low permeability formations at altitude serve to conduct recharge to the lower-lying saturated areas. Discharge takes place mainly through three major spring zones (the largest being at Capellades; see Fig. 1), though there are also a number of public supply wells. Piezometric records over the last 23 years show a declining trend attributable to the onset of well abstractions in 1978. Data on the transmissivity of the aquifer system come from some pump tests carried out in the 1970s, from qualitative field observations, and from point dilution tracer tests performed in the 1970s and 1990s. In general, transmissivity values are higher in (or close to) fractured zones, ranging from 2000 to 3000 $m^2 d^{-1}$. Outside of the fracture zones values range from low (probably less than 10 $m^2 d^{-1}$) to medium transmissivity (Lambán Jiménez 1998).

Serra de Tramuntana, Mallorca (Spain) – Mediterranean climatic zone

The island of Mallorca lies approximately 160 km E of the Spanish mainland (Fig. 1), and has a total area of 3626 km^2. The island is subdivided into three geomorphological regions that coincide with the main hydrogeological systems: the high and abrupt mountain range called Serra de Tramuntana, which rises to 1400 m and effectively forms a 80 km long 'rampart' along the north-western coast of the island; the Central Plain, of relatively low relief; and the range called Serra de Llevant, in the south-east of the island.

The climate of the island is of Mediterranean type, with mean annual temperature around 17°C and mean annual rainfall quite variable due to orographic effects (ranging from 400 mm in low-lying zones of the island up to 1500 mm in the Tramuntana Range). Also, there is a wide variation in rainfall between dry and wet years, and between winter and summer in each year. Localized intense rainstorms are quite common.

The Serra de Tramuntana receives the highest rainfall of any area of Mallorca, which makes the aquifers of the area attractive as water resources, despite the difficulties inherent in groundwater development in mountainous terrain. The north-eastern and central sectors of the Serra de Tramuntana are predominantly composed of carbonate rocks of Liassic (Jurassic) and Raethian (Triassic) age, with limestones, dolomites and breccias predominating. These carbonates form aquifers that drain to three major springs, the most prolific of which is the Sa Costera Spring (study area 4 on Fig. 1). The catchment of Sa Costera includes the Puig Major, which is the highest peak in Mallorca. The Sa Costera spring is the largest single discharge of natural freshwater in Mallorca, and is therefore of considerable interest as a potential water resource. Unfortunately, the natural drainage of the Sa Costera is straight into the sea from a very remote cliff line (Fig. 1), and major investment is required to divert the waters by submarine pipeline to the major demand centres around the island's capital, Palma. The susceptibility of the Sa Costera to climate change is therefore a material consideration in the cost-benefit balance for its exploitation.

Recent geological and hydrogeological field investigations (Cardoso da Silva 1997) confirm that the catchment of the Sa Costera is structurally complex, with imbricate thrust sheets giving rise to a 'multi-reservoir' aquifer system underlying a total area of some 10 to 17 km^2. Definition of the aquifer hydrodynamics is not an easy task, and it is made no easier by a shortage of reliable data. The range of discharge rates of the spring is subject to considerable uncertainty, with two earlier unpublished studies giving alternative ranges of $4.9–22.7 \times 10^6 m^3 a^{-1}$ (average of $10.4 \times 10^6 m^3 a^{-1}$) and $2.6–26.3 \times 10^6 m^3 a^{-1}$ (average of $8.2 \times 10^6 m^3 a^{-1}$). New gauging facilities were installed at the start of the GRACE project to address these discrepancies. Data obtained to date reveal the Sa Costera to have a rather steady baseflow in the order of 17 Ml d^{-1}, with peak flows reaching 170 Ml d^{-1} in wet winter periods. These figures suggest that the smaller of the two annual flow ranges quoted above is probably the more reasonable.

Climate change assessment methodology

Aquifer simulation methods

Two groundwater modelling codes were developed within the GRACE project to support the climate change assessments: CAVE (*C*arbonate *A*quifer *V*oid *E*volution), and BALDOS.

CAVE simulates coupled flow and non-equilibrium carbonate dissolution in dual-porosity carbonate aquifer systems. CAVE is based upon the well-known USGS MODFLOW code (McDonald & Harbaugh 1984). MODFLOW has previously been adapted to simulate two-domain (= dual porosity) groundwater flow in carbonate aquifers by means of setting up two standard MODFLOW grids in parallel, with water being exchanged between them according to the heads in the corresponding cells of the two grids (Teutsch & Sauter 1991). In other words, the diffuse domain and the conduit domain within a carbonate aquifer are each represented by separate, but inter-communicating, equivalent porous media. This approach gives good results where only quantities of water are of interest (Sauter 1992). However, where carbonate dissolution needs to be considered, it is necessary to define geometrically the surface on which the dissolution takes place. In significantly fractured carbonate aquifers, recharge waters which are under-saturated with respect to calcite will penetrate the aquifer primarily in the conduit flow system. It therefore makes sense to define the geometry of the dissolving surface as being the walls of the conduit system. To achieve this goal, CAVE was configured so that the conduit domain is represented by a pipe network model of readily defined geometry, rather than by an equivalent porous medium as in previous studies. The algorithmic approach necessary to attain this model representation is documented in detail by Younger *et al.* (1997), and has also been published in summary form by Clemens *et al.* (1996, 1997) and Sauter *et al.* (1997). It should be noted here that the GRACE project only considered 2-D regional flow, using a single MODFLOW layer for the diffuse domain. Further generalization of the approach to three dimensions, and to the case where the diffuse domain is unsaturated, have recently been described by Adams & Younger (2001). Within the GRACE project, the CAVE code was used to simulate the German and UK study systems. The Spanish study systems had insufficient data to support the use of fully distributed modelling using CAVE. For these systems BALDOS was developed and applied.

BALDOS is a semi-distributed recharge-routing model that simulates both direct and indirect groundwater recharge (*sensu* Lerner *et al.* 1990). BALDOS was developed from a pre-existing code (BALAN), which calculates classic Penman-Grindley based infiltration and closes the water balance with measured aquifer discharges by the use of empirical time-lag coefficients (Samper & García-Vera 1992). As at least some of the recharge in carbonate terrains is indirect (for instance via dolines), the original BALAN code was updated to include process representations for recharge via dolines, either directly from surface run-off or via drainage in the epikarstic zone. As for CAVE, full algorithmic details for BALDOS are given by Younger *et al.* (1997). BALDOS was applied to the Anoia Unit and the Serra de Tramuntana aquifers (Spain).

Both CAVE and BALDOS were thoroughly tested for their ability to reproduce observed flow and carbonate chemistry patterns in the study aquifer systems (Younger *et al.* 1997). This engendered confidence in their applicability for the simulations of possible future climate change scenarios. Nevertheless, it must always be borne in mind that the use groundwater models to predict circumstances which necessarily fall outside of the range of observed conditions is fraught with uncertainties. To avoid giving the misleading impression that definitive predictions of the future had been made, rather than the tentative numerical experiments which the authors consider the simulations to constitute, all climate change impact assessments were undertaken for 'fictitious' catchments, which closely resembled real catchments but were not explicitly identified with them. Thus the models reported here may be termed 'scoping models' inasmuch as the predictions that they yield are meant to be indicative of the possible ranges of aquifer responses that might be encountered, providing a basis for further discussion rather than for site-specific management interventions.

Using GCM outputs to define recharge scenarios

The problems of spatial resolution and inadequate process representation which beset the application of GCM models in hydrological impact studies (Gleick 1986, 1989; Mavromatis & Jones 1998; Wilby *et al.* 1998) have been discussed above. To overcome problems of spatial resolution an approach developed by Viner & Hulme (1994) was adopted and modified. In this approach mesoscale (or even more localized) climatic patterns are related to the appropriate GCM values, which are regarded as grid-averaged values (Skelly & Henderson-Sellers 1996). With respect to problems of process representation, the starting point for the GRACE simulations was to recognize that GCM predictions of changes in primary climatological variables (e.g. temperature and precipitation) are generally regarded as being better than their predictions of secondary (derived) parameters such as evapotranspiration and surface run-off (e.g. Reed 1986; Gregory & Mitchell 1995; Kilsby *et al.* 1998). Recharge was therefore calculated using GCM predictions of temperature and precipitation (in lieu of any credible alternatives), utilizing well-known formulae to calculate potential evapotranspiration [e.g. Thornthwaite and/or Blaney-Criddle; see Palutikof *et al.* (1994) for a discussion of their applicability in climate impact studies], and standard (Penman-Grindley type) soil–water budgeting methods. To this end, GCM grid-point estimates for mean surface air temperature

(T) and mean precipitation (P) for the GRACE study areas were obtained from the UK Climate Impacts-Link project (coordinated by the University of East Anglia, UK).

GCM modelling is a rapidly developing field of research. Until the mid-1990s, GCM-based simulations of possible future climate scenarios were necessarily based on the use of so-called 'equilibrium models', in which the dynamics of the atmosphere with a fixed CO_2 concentration were simulated. Concentrations are normally expressed as '$1 \times CO_2$' for 'pre-warming' atmospheric CO_2 concentrations (323 ppm by volume, representing conditions in about 1968), and thus for various increments up to the predicted eventual doubling of pre-industrial CO_2 (to 646 ppm by volume) which is designated '$2 \times CO_2$'. Intermediate states are definable only by interpolation between the predictions of 'dynamic equilibrium' conditions represented by each of the models. By the mid-1990s a new generation of GCM models, termed 'transient GCMs', was becoming available (Viner *et al.* 1994). Transient GCMs simulate progressive changes in atmospheric circulation over simulation periods of many years in response to gradually rising atmospheric CO_2. Clearly this is conceptually more realistic than assuming that atmospheric circulation reaches a quasi-equilibrium at all stages of the increase in CO_2 concentration. However, transient GCMs suffer from the same problems of 'cold start' which bedevil transient groundwater flow models, in that initial conditions prescribed *a priori* by the modeller may not be consistent with the internal parameterization of the model at the start of the simulations. At the time of the GRACE study, serious 'cold start' problems with transient GCMs were still being tackled, and only a limited range of greenhouse gas emission scenarios had been incorporated into transient GCM runs (Viner & Hulme 1994). Consequently, the GRACE predictions were developed by an interpolation method based on equilibrium GCM output which was considered the most robust data available at the time.

The equilibrium GCM output used in GRACE originated in an equilibrium experiment named 'UKHI' (Viner & Hulme 1993*a*), which was obtained using a second-generation GCM code, configured to run with 10 min time steps, with radiation updated every 3 h, and assuming the oceanic heat reservoir to be a 50 m single mixed-layer 'slab-ocean'. Simulations were then obtained for 'Control' ($1 \times CO_2$) and 'Perturbed' ($2 \times CO_2$) cases. For each case, the simulations were performed until the climate had reached a quasi-equilibrium state. Thereafter, 10 years of data were obtained for each scenario. The output of these simulations provides spatial fields of the climate parameters of interest with cell-average values provided at grid-centre points. The resultant model spatial temperature change field at each GCM grid-point i as generated in these equilibrium experiments can then be expressed as grid-point changes in T per °C of global warming, i.e. the standardized change for a grid-point i value ($\Delta T_i{}^*$) from a GCM experiment:

$$\Delta T_i{}^* = (T_i(2 \times CO_2) - T_i\ (1 \times CO_2))/(\Delta T_{2x}) \quad (1)$$

where $T_i(2 \times CO_2)$ and $T_i(1 \times CO_2)$ are the 10-year monthly average temperature values at GCM grid-point i for the Perturbed and Control experiment fields respectively; and ΔT_{2X} is the GCM model climate sensitivity, which is defined as the global annual equilibrium temperature change for a doubling of CO_2 concentration (within the scenario represented by the particular GCM experiment) (e.g. Cess & Potter 1988). The UKHI experiment gives a ΔT_{2X} of 3.5°C, and this value is used to standardize the parameter change fields. (Ten-year monthly average values at a grid-point were used to define climatically relevant change values in GRACE.)

For precipitation, standardized changes between Control and Perturbed runs were defined in a similar manner, save that changes could here be expressed as percentages:

$$\Delta P_i{}^* = 100\ \{(P_i(2 \times CO_2) - P_i\ (1 \times CO_2))/(P_i\ (1 \times CO_2))\} \quad (2)$$

where $P_i(2 \times CO_2)$ and $P_i\ (1 \times CO_2)$ are the 10-year monthly average precipitation values at GCM grid-point i for the Perturbed and Control experiment fields respectively, and $\Delta P_i{}^*$ is the percentage change in the precipitation value at grid-point i for the climate perturbation experiment.

An assessment of percentage changes is used in equation (2) because precipitation is highly variable from month to month and place to place, and absolute values are difficult to interpret due to discrepancies between control climate data and direct observations.

Equations (1) and (2) do not directly provide for assessment of temporal changes in climate. Without resort to transient GCM output, this is best achieved by linking equilibrium GCM output to estimates of the effect of transient emissions of greenhouse gases on global temperature rise, assuming that changes in the T and

P variables directly follow this trend (e.g. Viner & Hulme 1993*b*). A climate model named 'MAGICC' (Model for the Assessment of Greenhouse gas Induced Climate Change; Hulme *et al.* 1995) has been used for this purpose. MAGICC provides mutually consistent estimates of global-mean CO_2 concentration and temperature change at yearly intervals over the future period 1990 to 2100, as functions of a range of user-selected scenarios of anthropogenic emissions of carbon dioxide, methane, nitrous oxide and halocarbons. MAGICC is conveniently implemented within the software package SPECTRE (Barrow *et al.* 1994). Although there are a number of uncertain parameters in MAGICC, by far the most important is the climate sensitivity (ΔT_{2X}). The Inter-Governmental Panel on Climate Change (IPCC) best estimate of ΔT_{2X} is 2.5°C, with a range of 1.5 to 4.5°C. In the SPECTRE software, MAGICC has been run for eight prescribed greenhouse gas emissions scenarios for each of these three values, generating a range of uncertainty for the resulting estimates of global mean temperature rise from each scenario (termed LOW, MID and HIGH estimates respectively). The above protocol allows scaling of the GCM climate variables (T, P) change scenario at any grid-point both in time (following defined transient emissions scenarios for greenhouse gases), and also with respect to different GCM model climate sensitivities.

From the plethora of alternative greenhouse gas emission scenarios available in MAGICC, three were selected for detailed aquifer response simulations using CAVE and BALDOS (Fig. 2). At the optimistic end of the spectrum is the 'fossil-fuel free energy future' (FFEF) scenario (sometimes called the 'Greenpeace scenario'), assuming a low climate sensitivity ($\Delta T_{2X} = 1.5°C$). This scenario is referred to hereafter as 'FFEF LOW'. The mid-range and upper-bound estimates of likely climate change are both derived from the 1992 IPCC Scenario A (Houghton *et al.* 1992), hereafter referred to as IS92a, which basically assumes that 'business-as-usual' prevails (i.e. CO_2 controls, limitations on deforestation and other important controls on global warming do not become significantly more efficient than at present). The mid-range scenario is obtained by coupling the IS92a emissions scenario to the median estimate of climate sensitivity ($\Delta T_{2X} = 2.5°C$), producing the 'IS92a MID' scenario. The upper-bound ('worst-case') scenario ('IS92a HIGH') couples the IS92a emissions prognosis with the maximum climate sensitivity value ($\Delta T_{2X} = 4.5°C$). The long-term global temperature rises predicted for each of these three scenarios are shown in Figure 2. The implications of the three scenarios for the study aquifers (over 50 years from 1996 to 2045) can now be examined.

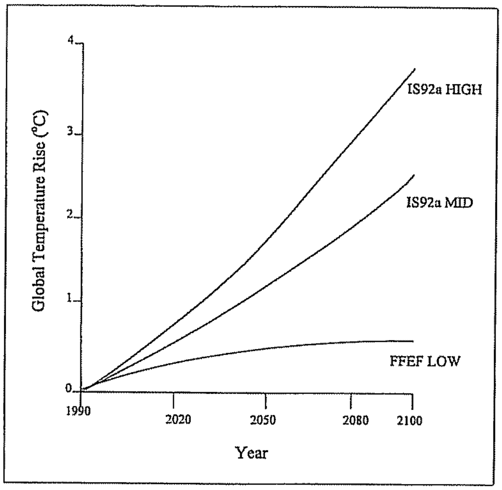


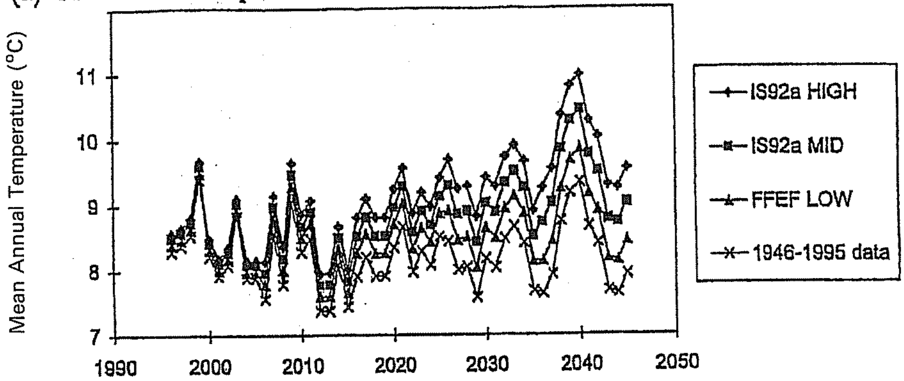
Fig 2. Global average temperature changes for the three scenarios selected for the climate change impact simulations.

Climate change predictions to 2045 AD.

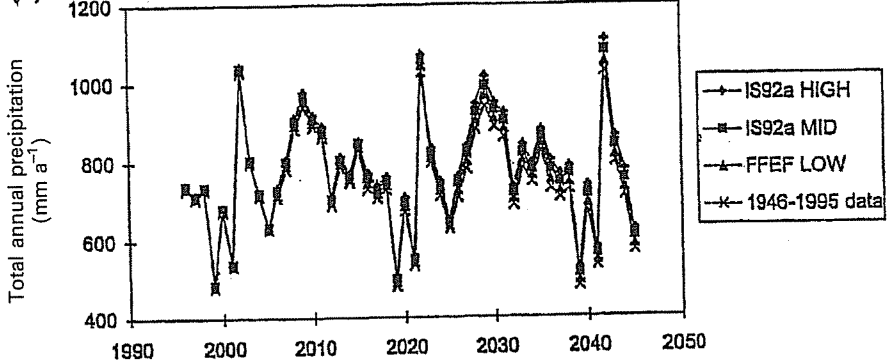
Timescale for predictions

Figure 2 illustrates that under the entire range of future climate scenarios, global temperatures are predicted to rise more or less steeply over the next century (and, by implication, beyond). A number of factors (which were not included in the climate models upon which Figure 2 is based) may in the event serve to slow down the temperature rise, such as the possibility of algal blooms in the world's oceans acting as a major sink for atmospheric CO_2, a process which appears to have contributed to the abrupt halt in global warming during earlier periods of the Earth's history (e.g. Bains *et al.* 2000). Nevertheless, the current consensus is that global warming is a reality, which will certainly give rise to real problems over the coming decades. As water resources managers are rarely able to justify discounting cost-benefit analyses over time-scales in excess of 50 years, predictions using the methodology outlined above have been restricted to the 50-year interval 1996–2045. Nevertheless, when examining the predictions presented below, it should be borne in mind that

(a) Mean annual temperature



(b) Annual mean precipitation



(c) Derived recharge (Blaney-Criddle method)

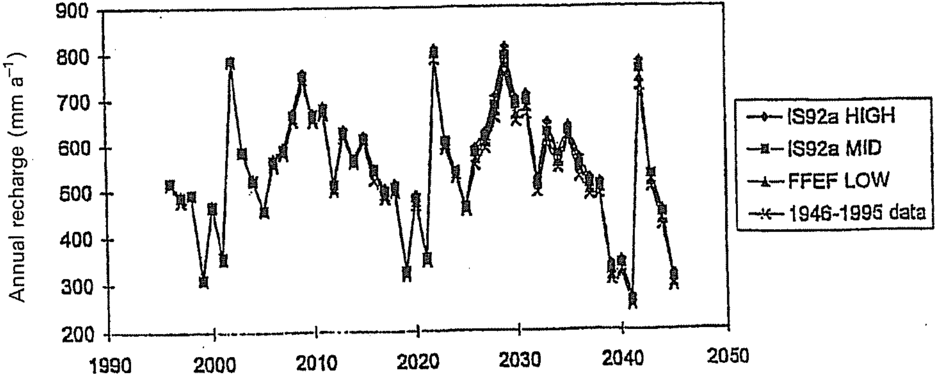


Fig. 3. Temperature (**a**), precipitation (**b**) and recharge (**c**) predictions for the 50 years to 2045 AD, for the Yorkshire Chalk study system.

the current consensus is that global temperature rises are likely to continue beyond 2045 AD (Hadley Centre 2000). Hence, even where predictions of changes to 2045 AD are relatively benign (as in the case of the Yorkshire Chalk), there is no guarantee that more negative water resources impacts will not ensue after 2045 AD.

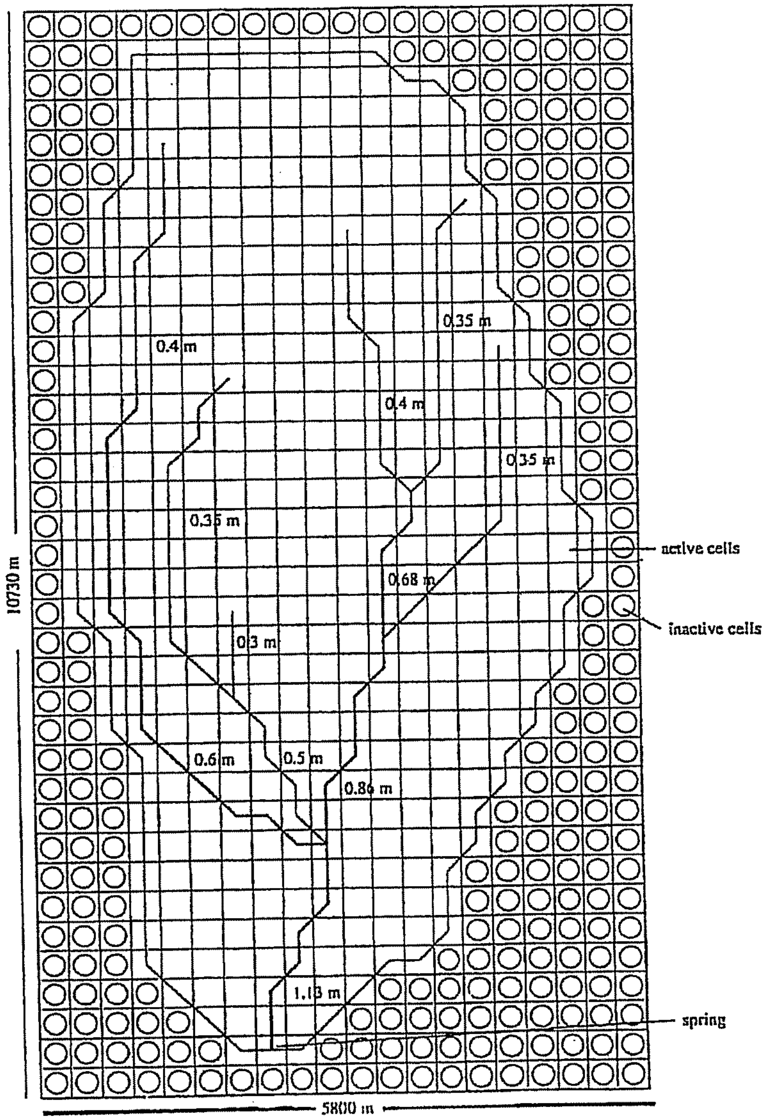


Fig. 4. Model grid for the hypothetical catchment representative of the Gallusquelle Aquifer study system in Germany.

Experimental approach

To facilitate comparisons between the four study systems in three quite different climate zones, it is necessary to ensure that we are comparing like with like. To this end, all of the simulations reported below were developed in accordance with the following experimental plan:

(1) All predictions are based on the temperature and precipitation estimates for future climate scenarios FFEF LOW, IS92a MID and IS92a HIGH (as described above) specific to GCM grids corresponding to each of the study systems. The temperature and precipitation data were used to derive

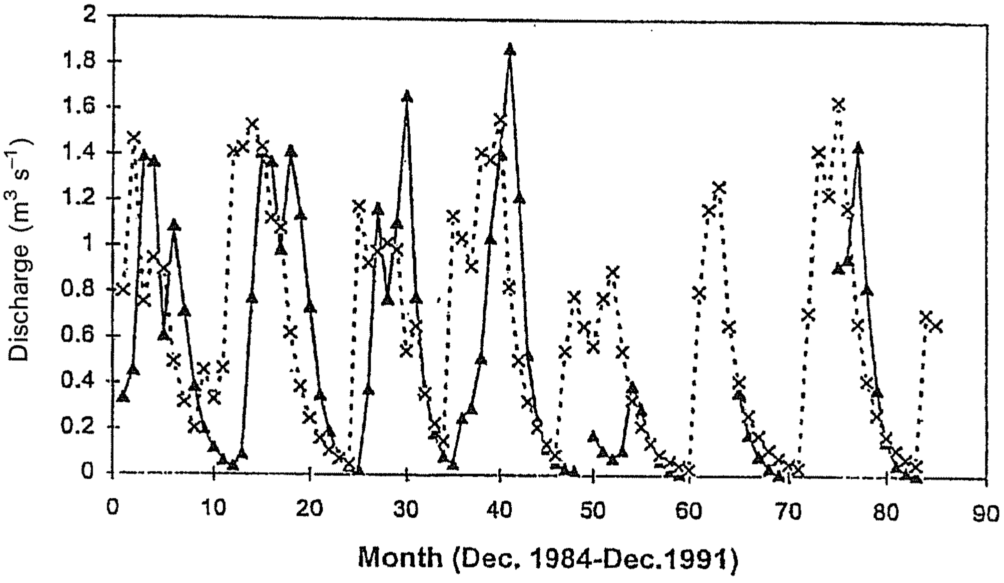


Fig. 5. A comparison between modelled (dashed line) flow patterns for the hypothetical catchment in the Yorkshire Chalk, and observed (solid lines) flow patterns in the real Tibthorpe spring catchment, obtained without site-specific calibration, illustrating that the magnitudes and general durations of periods of high flow and baseflow are captured in the hypothetical catchment model.

50-year time series of estimates of future recharge rates, using site-specific 'transfer functions' (such as a locally calibrated version of the well-known Blaney-Criddle formula; e.g. Palutikof *et al.* 1994). These transfer functions were developed by relating observed mean monthly values of temperature and precipitation to accepted actual recharge figures (obtained for present day conditions using Penman or similar methods, and checked by incorporation in regional groundwater flow models). An example of the temperature, precipitation and recharge predictions for the 50 years to 2045 AD is shown in Figure 3 for the Yorkshire Chalk study system. Sauter and Liedl (1998) and Manzano *et al.* (1998) have published the analogous predictions for the German and Spanish study systems respectively.

Adoption of this approach necessarily assumes that the functional relationship between temperature, precipitation and actual recharge will remain stationary as climate changes. While this is arguably a bold assumption, there is no practical alternative given the current state-of-the-art in predicting soil and vegetation changes in response to global warming.

(2) A 'hypothetical catchment' was developed as the basis for climate change experiments for each study area. The properties of the hypothetical catchments were defined in accordance with the generalized hydrogeological properties of the study aquifers identified during the individual regional investigations. Each hypothetical catchment was established to have the following properties:

(a) it will be a well-defined catchment area feeding a spring, to avoid the need to arbitrarily define well pumping regimes etc.
(b) it will be bounded for the most part by no-flow boundaries, except where fixed heads are needed to avoid singularities. This will ensure that the response is dominated by changes in recharge dynamics, without allowing arbitrary boundary inflows to compensate for reductions in recharge. Figure 4 shows the model grid for the hypothetical catchment representative of the Gallusquelle study system in Germany. (In this particular catchment the conduit system is based on well-characterized dendritic cave systems in the region, which have

been the subject of underground exploration and tracer testing (Sauter 1992). The equivalent grid for the Yorkshire case lacks this interesting feature.)

(c) for modern values of recharge, the catchment will exhibit an areally normalized flow distribution (e.g. flows expressed in terms of $m^3 s^{-1} km^{-2}$ of catchment area) which resembles that of a similar real system in the study area. Acceptable resemblance will be to order-of-magnitude precision and will be assessed in terms of the objective functions listed under point 4 below. A comparison between modelled and observed flow patterns obtained during model development for the hypothetical catchment in the Yorkshire Chalk is shown in Figure 5.

(3) Unless there were compelling reasons to the contrary (which proved to be the case for the Spanish catchments; Manzano *et al.* 1998), all simulations were performed using the CAVE software with the carbonate dissolution mode enabled. The maximum time-step for flow modelling purposes was monthly.

(4) The overall objective function for the flow simulations is the distribution of spring discharge rates. Because monthly time-steps were used, it is not feasible to use flow distribution descriptors which are most appropriately derived from daily data (such as Q_{95} etc.). It was therefore decided that the following descriptors would be logged throughout the prediction periods: total annual flow; minimum, maximum and mean flows for January and June; the maximum and minimum flow in each year; and the percentage deviation of the above from the 10-year average values for a simulation using modern temperature and precipitation values.

(5) The moving average of the calcium content ($mg\ l^{-1}$) of the spring discharge water was calculated throughout the 50-year simulation period, to allow evaluation of whether an increase (or indeed a decrease) in the total hardness of water supplies might be anticipated under changing climate conditions. Changes in conduit diameter at no less than two user-selected positions within the catchment were also logged at yearly intervals throughout the 50-year simulation period, to enable an evaluation of the possibility that enhanced dissolution rates serve to increase aquifer permeability.

Simulation results - flows

Tables 1–3 summarize the principal findings of the study for each of the four study areas. The tables compare the 10-year average behaviour at the end of the 50-year simulation period (i.e. the modelled results for 2036–2045) with the observed values for the 10-year period which preceded the modelled period (i.e. 1986–1995).

In assessing the predicted changes in groundwater recharge and discharge, the best way to proceed is to compare the magnitude of predicted changes with the magnitude of inter-annual variability (e.g. Hulme *et al.* 1999). Using this sort of approach, any change of less than about 10% is unlikely to be considered significant in water resources terms. Using a threshold of this magnitude, the results presented in Tables 1–3 do predict significant reductions (i.e. negative percentage values > 10) in one or more of the indicator variables for the hypothetical catchments in Germany and Mallorca. By contrast, the magnitudes of predicted changes in flow rates in the Anoia Unit and the Yorkshire Chalk catchments are unlikely to exceed the magnitude of inter-annual variability. Nevertheless, the predicted trend in the Anoia Unit is towards decreasing groundwater recharge and discharge. In the case of the Yorkshire Chalk, the IS92a MID and HIGH scenarios (Tables 2 and 3 respectively) suggest that year-round increases in flow are likely. Only under the FFEF LOW scenario (Table 1) are any reductions in flow predicted for the Yorkshire Chalk, and even in that case the total annual flow is still predicted to rise slightly. On the face of it, therefore, global warming potentially represents local 'good news' for users of the Yorkshire Chalk aquifer. However, there is little scope for complacency as the global temperature trends shown in Figure 2, taken together with the latest predictions of climate change (Hadley Centre 2000), strongly suggest that extrapolation of predictions beyond 2045 might well lead to increases in evapotranspiration exceeding increases in rainfall, so that recharge will eventually decline later in the 21st century.

Turning to the results obtained for the Gallusquelle catchment in Germany, although rises are consistently predicted for the mean and maximum January flows (which coincide with periods of generally low demand), all other flows are predicted to be significantly in deficit compared with pre-1995 conditions (Tables 1–3). Nevertheless, as Sauter and Liedl (1998) have pointed out, the amplitude of inter-annual

Table 1. - *Summary of 'best-case' climate change impact predictions for the four GRACE study systems.*

Study System	δQ_{total} Annual	δQ_{min} Annual	δQ_{max} Annual	δQ_{min} January	δQ_{mean} January	δQ_{max} January	δQ_{mean} June	δQ_{min} June	δQ_{max} June
Yorkshire Chalk, United Kingdom	+5	–1	–0.5	–1	–0.1	–0.5	–0.1	–0.1	–0.5
Gallusquelle Aquifer, Germany	–12	–16	–10	–12	+10	+23	–31	–25	–26
Anoia Unit, Catlunya, Spain	–1	–3	+2	–1	+1	+2	–2	–1	–0.5
Serra de Tramuntana, Mallorca, Spain	–4	–6	–2	–	–	–	–	–	–

Results generated using GCM output for the optimistic scenario 'FFEF LOW', as described in the text. All values are in percentages, as the changes in the 10-year mean values between the periods 1986–1995 and 2036–2045.

δQ_{total} Annual, % change in the average total annual flow; δQ_{min} Annual and δQ_{max} Annual, % changes in the minimum and maximum annual flows respectively; δQ_{min} January, dQ_{mean} January, δQ_{max} January, and δQ_{min} June, δQ_{mean} June, δQ_{max} June are the corresponding % changes in minimum, mean and maximum flows in January and June as appropriate.

Table 2. *Summary of 'best-estimate' climate change impact predictions for the four GRACE study systems*

Study System Annual	δQ_{total} Annual	δQ_{min} Annual	δQ_{max} January	δQ_{min} January	δQ_{mean} January	δQ_{max} June	δQ_{min} June	δQ_{mean} June	δQ_{max}
Yorkshire Chalk, United Kingdom	+9	+1	+2	+1	+0.2	+1	+0.1	+0.1	+0.5
Gallusquelle Aquifer, Germany	−13	−17	−8	−10	+9	+21	−32	−27	−27
Anoia Unit, Catlunya, Spain	−3	−6	+2	−2	+1	+3	−4.5	−2	−1
Serra de Tramuntana, Mallorca, Spain	−7	−11	−5	–	–	–	–	–	–

Results generated using GCM output for the mid-range scenario 'IS92a MID', as described in the text. All values are in percentages, as the changes in the 10-year mean values between the periods 1986–1995 and 2036–2045.

δQ_{total} Annual, % change in the average total annual flow; δQ_{min} Annual and δQ_{max} Annual, % changes in the minimum and maximum annual flows respectively; δQ_{min} January, δQ_{mean} January, δQ_{max} January, and δQ_{min} June, δQ_{mean} June, δQ_{max} June, are the corresponding % changes in minimum, mean and maximum flows in January and June as appropriate.

Table 3. *Summary of 'worst-case' climate change impact predictions for the four GRACE study systems.*

Study System	δQ_{total} Annual	δQ_{min} Annual	δQ_{max} Annual	δQ_{min} January	δQ_{mean} January	δQ_{max} January	δQ_{min} June	δQ_{mean} June	δQ_{max} June
Yorkshire Chalk, United Kingdom	+21	+2	+4	+1.5	+0.5	+2	+0.1	+0.5	+1
Gallusquelle Aquifer, Germany	–13	–17	–8	–10	+8	+20	–32	–28	–27
Anoia Unit, Catalunya, Spain	–3	–8.5	+2	–2.5	+0.5	+3	–7	–2	–1.5
Serra de Tramuntana, Mallorca, Spain	–11	–16	–7	–	–	–	–	–	–

Results generated using GCM output for the optimistic scenario "IS92a HIGH", as described in the text. All values are in percentages, as the changes in the 10-year mean values between the periods 1986–1995 and 2036–2045.

δQ_{total} Annual, % change in the average total annual flow;. δQ_{min} Annual and δQ_{max} Annual, % changes in the minimum and maximum annual flows respectively; δQ_{min} January, δQ_{mean} January, δQ_{max} January, and δQ_{min} June, δQ_{mean} June, δQ_{max} June, corresponding % changes in minimum, mean and maximum flows in January and June as appropriate.

variability exceeds the magnitudes of the declines in flow up to 2045. Similar results have been reported in other climate change studies (e.g. Hulme *et al.* 1999). Consequently, unambiguous proof of any systematic decline in flows is only likely to be demonstrable in the second half of the 21st century. One remarkable aspect of the Gallusquelle predictions is that the results for all three scenarios are tightly clustered, with no statistically significant difference between FFEF LOW (Table 1) on the one hand and IS92a HIGH (Table 3) on the other. This somewhat surprising result prompts one to question whether the GCM output for the grid point relevant to Gallusquelle is subject to some mathematical singularity related to GCM configuration. For instance, the proximity of this GCM grid point to those which correspond to the Alps might be responsible for local instability in model performance. This possibility cannot be resolved using the data available to the GRACE team, but may well be worthy of re-examination using the next generation of GCM output.

The results for the Anoia Unit reveal patterns that are similar to, but less extreme than, those obtained for Gallusquelle, with consistent increases in mean and maximum January flows, but decreases in virtually all other indicators. The maximum decrease in recharge that can be expected in the region of the Anoia Unit over the next 50 years or so amounts to about 8% of the total present-day recharge, while the average decrease is about 3%. As the average present-day recharge rate for the period 1942–1991 was estimated to be some 80×10^6 m^3 a^{-1} (over a recharge area of 156 km^2; Lambán Jiménez 1998), the predicted decrease does not represent a particularly dramatic reduction of groundwater reserves. However, when the high inter-annual variability of recharge in the area is taken into account (with an estimated minimum in the past 50 years of 40×10^6 m^3 a^{-1}) the predicted decline in recharge suggests that droughts in the area may become somewhat more severe. Towards the end of the simulated period, recharge becomes increasingly more irregular and variable from year to year, even producing discrete recharge values higher than those of the present day (Younger *et al.* 1997; Manzano *et al.* 1998). This highlights the concern that increases in inter-annual variability may be a more serious general result of global warming than decreases in total effective rainfall (C. Kilsby, University of Newcastle, pers. comm., 1999).

Given the shortage of pre-1995 data for the Sa Costera system, it proved possible to calculate only a few of the indicators in Tables 1–3 to sufficient precision to warrant their inclusion. The figures given suggest that the Sa Costera catchment is the most vulnerable of all four systems studied, with a maximum decrease in recharge (relative to pre-1995 patterns) of as much as 16%. Simulated time series (Manzano *et al.* 1998) suggest an accelerated rate of decline in recharge towards the end of the simulated period. As for the Anoia Unit, the inter-annual variability of recharge increases during the latter part of the 50-year period. However, unlike the Anoia Unit, at no point does the predicted recharge exceed pre-1995 values.

The contrasting predictions for the four study systems clearly demonstrate the general sensitivity of these carbonate aquifers to climatic change. Where maritime climatic influences are strong (as in the UK), increased oceanic evaporation induced by global warming may well result in overall increases in available resources. Even in the continental climatic zone (e.g. southern Germany), atmospheric moisture derived from increased oceanic evaporation may sustain winter rains at their present level, but declines in summer rainfall (coupled with more intense evapotranspiration in a warmer climate), can be expected to result in an overall decrease in available groundwater resources. The inter-annual variability of rainfall in the Mediterranean climatic zone is well known (though its meteorological causes are complex). If this variability is exacerbated as a consequence of global warming (as we predict), then the need for major investment in storage systems (surface reservoirs or – to minimize evaporation losses – the use of artificial groundwater recharge) will become ever more pressing.

It must here be re-emphasized that global warming impacts are expected to accelerate beyond the 50-year investigation horizon of these simulations (Hadley Centre 2000), which is likely to have important implications for recharge variability. In particular, further work is necessary to evaluate whether the predicted rise in recharge in the Yorkshire Chalk system might prove to be followed by a decline in recharge in the decades beyond 2045 AD.

Simulation results – water quality (hardness)

Predictions of increases in the hardness of the groundwaters were obtained for the UK and German systems only, since the CAVE code was not applied to the Spanish systems. Figure 6 shows the predicted increases in dissolved calcium in the Gallusquelle aquifer over the 50-

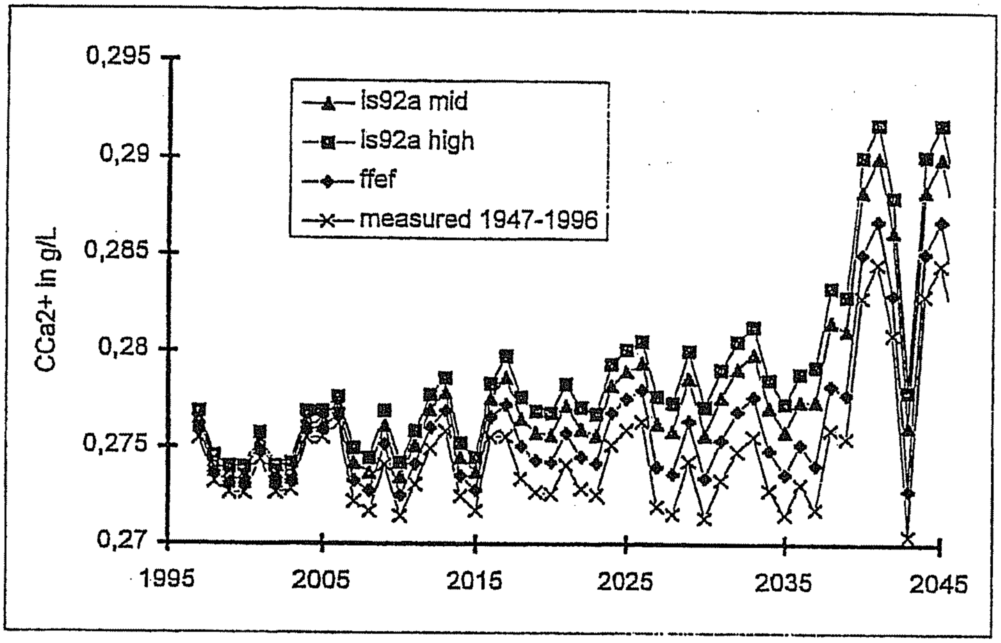


Fig. 6. Predicted climate change impacts on natural water quality: dissolved calcium concentrations('CCa^{2+}') in water flowing from the hypothetical catchment representing the Gallusquelle aquifer, Germany, compared with measured values.

year simulation period to 2045 AD. The overall rising trend in response to increases in atmospheric CO_2 concentrations is clearly evident for all three climate change scenarios. The noticeable peaks in the final decade of the simulations are simply results of a lack of dilution, since they correspond precisely to two episodes of low winter recharge rates. Despite the clear increases in dissolved calcium shown in Figure 6, it is important to examine the *y*-axis labels for the maximum increase in dissolved calcium in the Gallusquelle to 2045 AD amounts to no more than 8 mg l^{-1} (Sauter & Liedl 1998). The results obtained for the Yorkshire Chalk aquifer are very similar, with a maximum increase in dissolved calcium ≤ 10 mg l^{-1}. These increases are negligible in water resources terms, and therefore have little more than curiosity value. Nevertheless, steady increases in hardness in the world's carbonate aquifers represent a significant sink for atmospheric CO_2, which may make a non-negligible contribution to slowing global warming over long time-scales (cf. Kump *et al.* 2000; Liu & Zhao 2000).

Conclusions

Taken at face value, the flow predictions reported here suggest that considerable cause for concern exists in relation to the long-term viability of a number of carbonate aquifers currently used for public supply in central and southern Europe, even when predictions are made using the most optimistic of all future climate scenarios (FFEF LOW). Needless to say, these results are surrounded by sufficient uncertainty that they cannot be used as definitive predictions of future aquifer behaviour at particular points in time and space. A more probabilistic approach to the simulations might have resulted in formal confidence limits on these predictions, but would have been unlikely to change the fundamental conclusion that significant reductions in available resources can be expected in low- and mid-latitude carbonate aquifers in Europe by the middle of the present century.

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