POTENTIAL IMPACTS OF CLIMATE CHANGE ON GROUNDWATER RESOURCES: FROM THE HIGH PLAINS OF THE U.S. TO THE FLATLANDS OF THE U.K.

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ABSTRACT

Global climate change is expected to have negative effects on water resources as a result of increased variability in extreme events such as droughts and floods. Compared with surface water resources, there has been less research into the impacts of climate change on groundwater both in terms of the effects on quantity and quality and also linkages within the hydrological cycle. This paper presents an overview of possible climate change impacts on groundwater using evidence presented at the 1st Symposium of the UNESCO IHP *GRAPHIC* project with examples reported from Asia, North America and Pacific Ocean atolls. A further, more detailed case study is presented that uses a numerical groundwater model to investigate the possible impacts of climate change on saline intrusion in a low-lying coastal area in East Anglia. In this example in north east Norfolk, and compared to the 1970s baseline condition, a rise in sea-level in the 2080s to an elevation of 57 cm and a 60% decrease in annual actual groundwater recharge under a Medium-high gas emissions scenario will potentially cause saline water to advance 1700 m further inland into the coastal sand and gravel aquifer. As a consequence of the shallow depth of saline water in the coastal aquifer, the chloride concentration in coastal drains may increase to about 4000 mg/l in the 2080s. In general, this paper highlights that the impacts of climate change on water resources is specific to geo-climatic regions which only emphasises the future challenges of adapting to climate change. The mitigation and avoidance of these effects is, however, also apparent and include better dissemination of information to water resources managers and local communities and the development of sustainable groundwater abstraction methods.

INTRODUCTION

Groundwater is an important natural resource. Worldwide, more than 2 billion people depend on groundwater for their daily supply (Kemper 2004). A large proportion of the world's agriculture and irrigation is dependent on groundwater, as are a large number of industries. Whether groundwater or surface water is exploited for water supply is largely dependent on the location of aquifers relative to the point of demand. As a result of the growth in the global population, the demand for clean water is rising and the pressures on surface water and groundwater resources is increasing, particularly in semi-arid and arid regions of the world where useable water supplies are scarce. In terms of groundwater, the demand has been poorly managed due to low investment in investigation during the 20th century, at a time when its intensive use for agricultural irrigated crop production has placed groundwater resources under stress. To better manage groundwater resources, the vulnerability of groundwater resources to drought, over-abstraction and quality deterioration must be assessed both now and in the context of climate change, and the natural functions of groundwater for river runoff and ecosystems safeguarded (Struckmeier et al. 2004).

The global climate is changing with instrumental records showing that during the last century the Earth's temperature rose by about 0.6°C (IPCC, 2001). The warming trend for the last 30-year period is roughly three times that for the past 100 years as a whole (Stouffer *et al*.,1994; WMO, 2002) and it is expected that global temperatures will continue to rise by between 1.4 and 5.8°C by 2100 due to the emissions of greenhouse gases (McCarthy *et al*., 2001).

The hydrological cycle is an integral part of the climate system and climate change is expected to have negative effects on water resources such as a shorter precipitation season and an increase in hydrological extremes such as floods and droughts. Relative to surface water resources, the potential consequences of climate change on groundwater have not received as much attention (IPCC, 2001) but can be expected to include variations in groundwater level fluctuation (Chen et al., 2004), effects on soil pore water pressure (Collison et al. 2000), alteration of groundwater flow regimes (Scibek and Allen, 2006) and changes in the volume and quality of groundwater resources (Brouyère et al., 2004; Bloomfield et al. 2006; Ranjan et al. 2006). Several studies have aimed to quantify the likely direct impacts of changing precipitation and temperature patterns on groundwater recharge (Eckhardt and Ulbrich, 2003), while another has extended this analytical approach to include the indirect effects on recharge of alterations in soil and landscape resulting from different socio-economic scenarios under future climate change (Holman, 2006).

THE GRAPHIC PROJECT

In responding to the challenge of managing groundwater resources, the UNESCO International Hydrological Programme (IHP) GRAPHIC (Groundwater Resources Assessment under the Pressures of Humanity and Climate Change) project seeks to improve understanding of how groundwater contributes to the global water cycle and thus how it supports ecosystems and humankind (UNESCO IHP 2006). In addition to the pressures of a growing population, climate change will alter groundwater recharge rates, and rising sea-levels will cause saltwater intrusion and so further decreasing the amount of usable groundwater. The GRAPHIC project advocates a comprehensive understanding of groundwater resources, specifically an evaluation of the changes to groundwater composition, storage and groundwater flux (recharge and discharge rates) from various population pressures and climate change scenarios.

The structure of the GRAPHIC project is divided into three themes: (i) thematic, cross-regional issues; (ii) methodological approaches; and (iii) representative geographical areas, where pilot studies will be carried out. The 1st GRAPHIC Symposium held at the Research Institute for Humanity and Nature, Kyoto, explored these themes and a number of perspectives were presented on the impacts of climate change on groundwater. The purpose of this paper is to summarise a selection of these perspectives from different regions of the world (Asia, North America and Pacific Ocean atolls) and to present a case study of the possible impacts of climate change on saline intrusion in a low-lying coastal area in eastern England.

ASIA

In Mid and Central Asia, output from the MRI-CGCM2.3.2 coupled atmosphere-sea surface global circulation model for the period 2080-2100 shows a rise in temperature of 3.5−4.5^{o}C and a decrease in precipitation. For South Asia, a temperature increase of 2.5−3.5^{o}C and an increase in precipitation are simulated. Changes in the precipitation amount are expected to decrease mean runoff by 1 mm/day in Mid and Central Asia and to increase mean runoff by a similar amount in South Asia. As a consequence of the change in the variability of precipitation, surface water resources are becoming more unreliable creating a shift to the development of groundwater resources, such as has been observed in Taiwan. Contrary to the trend in South Asia, in Sri Lanka, dry season flows linked to groundwater discharge to streams are observed to be decreasing in some areas as a result of deforestation causing more rapid surface runoff and less groundwater recharge.

In northeast Mongolia, the annual precipitation trend from south to north shows a gradient from 50−300 mm. Against this background, precipitation has decreased and temperature has increased in the last 50 years due to climate change. The decrease in the availability of fresh water is in conflict with the demand from the nomadic people for drinking water which is 80% dependent on groundwater abstracted from dug wells in alluvial and sandstone aquifers. Also, over-grazing of livestock is causing land degradation with vegetation patterns changing from steppe to desert grassland, for example in the Kherlan river basin, and so affecting recharge and runoff characteristics.

In the world's mega-cities such as found in South East Asia, increasing urbanisation is warming the ground surface and changing the temperature profile of shallow groundwater bodies. From 42 observation sites in upland and lowland areas of Tokyo, downhole temperature logging has revealed increases in temperature of 3^{o}C in shallow groundwater (to a depth of 20m) in lowland areas with an inversion of the geothermal gradient at a depth of about 100 m. Since monitoring began in 2001, no change in the geothermal gradient has been observed below this inversion depth but the estimated temperature (deduced by projecting the thermal profile to the ground surface) at the surface is warmer than is predicted by air temperature records. These records indicate the additional warming of the ground from the overlying city infrastructure.

HIGH PLAINS AQUIFER, NORTH AMERICA

The High Plains (or "Ogallala") aquifer underlies about 450,700 km^2 in the semi-arid west-central United States (US). The aquifer has profound importance for US and global agriculture, providing water for 27% of the irrigated land in the US and supplying about 30% of the groundwater used for irrigation. Human-induced stresses on groundwater in the form of abstractions of water from the aquifer for irrigation and agrichemical use have resulted in water-table declines greater than 30 m in some areas and widespread elevated nitrate and pesticide concentrations in groundwater. This has raised questions about resource sustainability and health concerns for nearly 2 million people who rely on the aquifer as a source of drinking water.

Against this background, there is increasing recognition that inter-annual to inter-decadal natural climatic variability can augment or diminish human-induced stresses on groundwater availability and quality. The interaction between these climate cycles produces a cumulative effect that can, for example, affect the distribution of precipitation and, in turn, affect water requirements for irrigation, recharge and agrichemical flux to groundwater. Groundwater can respond dramatically when climate variability from different cycles is coincident in a positive (wet) or negative (dry) phase of variability. Spectral time-series analysis shows the effect of overlapping climatic cycles on precipitation, temperature, streamflow, spring flow, groundwater levels and abstraction, and selected water-quality parameters throughout the High Plains aquifer region. Preliminary analysis indicates that cyclical changes occur in all the evaluated time series. In particular, cycles that are partially coincident with the El Niño Southern Oscillation (ENSO, every 2-6 years), North American Monsoon System (NAMS, every 6-10 years) and the Pacific Decadal Oscillation (PDO, every 10-25 years) occur in the hydrologic and water-quality time series for the High Plains aquifer. Statistically, the rainfall patterns are 84% explained by the PDO and NAMS and 16% by ENSO, and the PDO is found to correlate with changes in the thicker zones of the saturated aquifer. In particular, cyclic variability similar to known climate cycles occurs in specific conductance, temperature and chloride concentrations for selected stream reaches and wells and further understanding of these variations should help guide water-resource management policies, such as the establishment of thresholds for total maximum daily loads in streamflow that are aligned with climate variability (Gurdak and Hanson, 2005; Gurdak, 2006).

PACIFIC OCEAN ATOLLS

Water resources in atolls are under critical pressure from urbanisation and rising sea-level. Atolls only contain small volumes of fresh water as a narrow lens (5-15 m thick) which discharges to the coastline. At most, only 20 litres of water are available per person per day. The influence of the El Niño and La Niña creates fluctuation in rainfall with coefficients of variability of 40-60%. For example, Tarawa Atoll in the central Pacific Ocean experiences variation in annual rainfall of 300 to over 4000 mm. During drought periods, people drink fluid in coconuts or are forced to leave the atoll due to the shortage of fresh water. Desalination plants fail after 2-3 years due to technical difficulties. Climate change is a serous challenge for atolls given that rising sea-levels are likely to severely reduce fresh water resources (by analogy, during El Niño events, the depth of a fresh water lens can be depleted by 0.5 m). Furthermore, the uncontrolled pollution in urban districts, which includes petroleum products, fertilisers and E. coli from cattle, are compounding the problem of contamination by salinisation. Irrigation of coconut trees (which each need 170 litres of water per day) competes with drinking water needs. Given the combined pressures on groundwater resources, mitigation strategies include the use of skimmer pumps to abstract fresh water more sustainably but must be supported by information and accurate assessments of the available resource and water supply demands.

EAST ANGLIA, EASTERN ENGLAND

The climate of the United Kingdom has changed: the central England temperature rose by 1^{o}C during the twentieth century and the 1990s was the warmest decade since temperature records began in the 1660s (Hulme *et al*., 2002). Summers have been getting drier, with notable droughts between 1988 and 2006, especially in southern England. Although patterns in precipitation are less apparent, there is a tendency towards an increase in winter precipitation and in the frequency of extreme events, particularly in Scotland and western Britain (Osborn *et al*., 2000). By the end of this century it is expected that the mean annual temperature in the UK may rise by between 2°C and 3.5°C. Hotter and drier summers and warmer and wetter winters are expected to become more frequent in the south and east of the UK (Houghton *et al*., 1990, 1992) with East Anglia expected to experience an increase in temperature between 0.9°C and 2.3°C by the 2050s, compared to the period between 1961 and 1990 (Hulme *et al*., 2002).

The increase in temperature will cause an expansion of the volume of near-surface ocean water and global sea-level is predicted to rise by 9 to 88 cm by 2100 (IPCC, 2001). For East Anglia, a rise in future net sea-level of between 8 to 77 cm is predicted. Table 1 shows the updated net sea-level change for eastern England relative to 1961-1990 (UKCIP, 2005).

Table 1 Future net sea-level change (cm) in eastern England (UKCIP, 2005) under future low and high gas emissions scenarios

Low Emissions			High Emissions		
2020s	2050s	2080s	2020s	2050s	2080s
8	13	17	18	42	77

Groundwater in low-lying coastal areas is considered to be very sensitive to climate change and this is the case in north east Norfolk, an area of agricultural land within the Broads. In this internationally renowned area, a network of shallow lakes and drainage channels discharges to the North Sea. Much of the area lies at or below sea-level and is protected from the sea by an extensive belt of sand dunes. Pumped land drainage for agricultural purposes over the past centuries has lowered the groundwater in the underlying Pleistocene sand and gravel (Crag) aquifer, with consequent saline intrusion into the coastal portion of the aquifer (Holman and Hiscock, 1998). The ecological impact of increased salinity in the Broads is episodic algal blooms of Prymnesium parvum which can be fatal to fish and some gill breathing invertebrates (Holdway et al., 1978).

To explore the impact of climate change on this environmentally sensitive area, a simplified groundwater model of the Crag aquifer was constructed (Tanaka, 2006) in which the recharge input and sea-level boundary for a range of future scenarios was tested to simulate the change in salinity distribution in the Crag and the main drainage network. The first step was to calculate the groundwater recharge for the historic period (1961-1990) and the future scenarios (2020s, 2050s and 2080s) and this was achieved with the use a stochastic daily weather generator (Jones and Salmon, 1995) driven by precipitation inputs derived for Hemsby in north Norfolk (co-ordinates 52°68' N, 1°68'E). The climatic data were obtained from the BETWIXT project (Built Environment: Weather Scenarios for investigation of Impacts and Extremes; http://www.cru.uea.ac.uk/cru/projects/betwixt/) available at the Climatic Research Unit at the University of East Anglia. The amount of actual recharge to the underlying aquifer was then calculated using a soil moisture balance approach using the Food and Agriculture Organization (FAO) method as modified by the Environment Agency (EA) (Hulme *et al*., 2002).

CLIMATE CHANGE IMPACTS ON ACTUAL GROUNDWATER RECHARGE

Values of mean actual groundwater recharge calculated by the FAO-EA spreadsheet for the '1970s' and each of the '2080s' gas emissions scenarios is summarised in Table 2. The least extreme decrease in future actual recharge occurs under the 2080's Low emissions scenario which experiences the highest annual precipitation of the four scenarios presented. The most extreme decrease in actual recharge occurs under the 2080's Medium-high gas emissions scenario.

Table 2 Calculated mean annual and seasonal actual groundwater recharge (mm) for Hemsby for the 1970's baseline and 2080's gas emissions scenarios

Time period	1970s	2080s			
Scenario	Baseline	Low	Medium-low	Medium-high	High
Annual	106.7	62.2	44.6	42.3	48.6
Summer (JJA)	4.9	0.4	0	0	0
Winter (DJF)	48.9	50.7	41.7	33.9	38.1

Relative to the 1970's, mean annual actual recharge decreases by around 40-60 % in the 2080's emissions scenarios (Table 3). Seasonally, as expected, actual recharge is greater in winter than in summer. For the 1970s baseline, the actual recharge in winter is around 46% of the annual actual recharge, changing to about 80% in the 2080s.

Table 3 Percentage change in mean actual groundwater recharge for the 2080's gas emissions scenarios relative to the 1970's baseline

	2080s Low	2080s Medium-low	2080s Medium-high	2080s High
Annual	-41.7	-58.2	-60.4	-54.5
Summer (JJA)	-92.4	-100.0	-100.0	-100.0
Winter (DJF)	+3.8	-14.6	-30.7	-22.1

CLIMATE CHANGE IMPACTS ON SALINE WATER INTRUSION

The groundwater flow model Visual MODFLOW version 3.1 with the transport code MT3D was used to simulate groundwater flow and saline intrusion in north east Norfolk by applying current and future actual recharge and sea-level conditions. Models were constructed for the 1970s baseline (1961-1990) and the 2080s (2071-2100) under Low, Medium-low, Medium-high and High gas emissions scenarios. To simplify the complex hydrology and hydrogeology of the drained marshes, a single-layer model was designed to investigate the unconfined Crag aquifer with an assumed depth of 60 m. The east (constant head) boundary of the model represented the North Sea with an elevation of 20 cm above sea-level and two drain cells, located 1500 m and 2500 m west of the coastal boundary, were used to simulate coastal and inland drainage ditches (Fig. 1), respectively. The coastal drain cell was set at an elevation of 58.14 m (1.86 m below sea-level) and the inland drain cell at an elevation of 59.53 m (0.47 m below sea-level) based on field data (Brooks, 2005). Both drains were considered to be in hydraulic continuity with the aquifer. The model contained 50 rows, 50 columns and 10 layer divisions. In the horizontal plane, the model domain was discretised into grid cell dimensions of 60 x 60 m and in the vertical section by 6 m. Hence, the two lines of drain cells occupy the top layer division with a depth of 6 m (Fig. 1). Actual groundwater recharge was also applied to this same top layer.

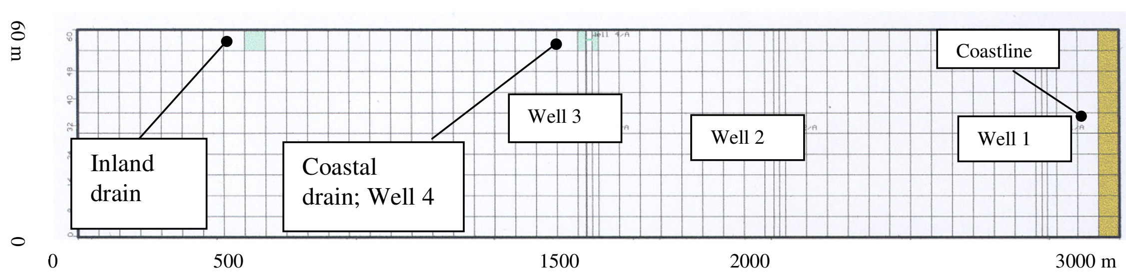


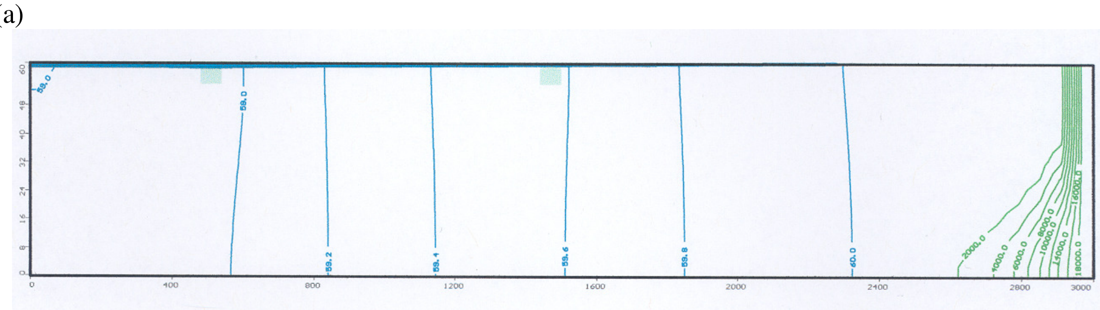
Figure 1 Vertical section of the groundwater model showing the position of four concentration observation wells. The model datum is the base of the aquifer at 0 m, or 60 m below sea-level.

As shown in Fig. 1, four concentration observation wells were applied to compare changes in chloride concentration between the baseline model and future scenarios. The wells are identified as Wells 1, 2 and 3 and were applied at distances of 2800 m, 2000 m, and 1500 m from the western boundary, respectively. The chloride concentration was recorded at a depth of 30 m in these wells. Well 4 was situated in the coastal drain in order to observe concentration changes in the centre of the drain. As input to the transport model, a chloride concentration of 19,000 mg/l was attached to the constant head boundary at the coastline to simulate the influx of seawater.

The groundwater flow model was run under a steady-state condition with the transport model allowed to simulate advective flux of solute for periods of 10, 20, 30, 50 and 100 years until equilibium conditions for the solute mass balance were achieved. In total, twenty-two model runs were simulated for different combinations of gas emissions scenarios, drain level conditions and sea-level elevation. In this paper, two of these runs are presented for illustration of the possible effects of climate change on saline intrusion in north east Norfolk assuming the adverse case of the inland drain level being at a lower level than the coastal drain.

The first model run (Fig. 2a) represents the 1970s baseline condition. After 100 years, the saline interface is simulated to move 500 m from the coastline with the interface at a depth of about 30 m below the ground surface. The chloride concentration observed in Well 1 at the end of the simulation period is about 700 mg/l. The second model run (Fig. 2b) simulates the 2080s Medium-high gas emissions scenario with a constant head elevation of 57 cm above sea-level on the coastal boundary. The inland drain level was again set at a lower level than the coastal drain and the same elevation values applied as for the first model run. After a simulation period of 100 years, and with a higher sea-level condition and reduced fresh groundwater recharge, the saline interface now reaches the coastal drain with a chloride concentration of 4000 mg/l. In this scenario, the leading edge of the saline front has reached around 2200 m from the coastline and the final concentrations in Wells 2, 3 and 4 are 16,000, 10,000, and 4000 mg/l, respectively.

(a)



(b)

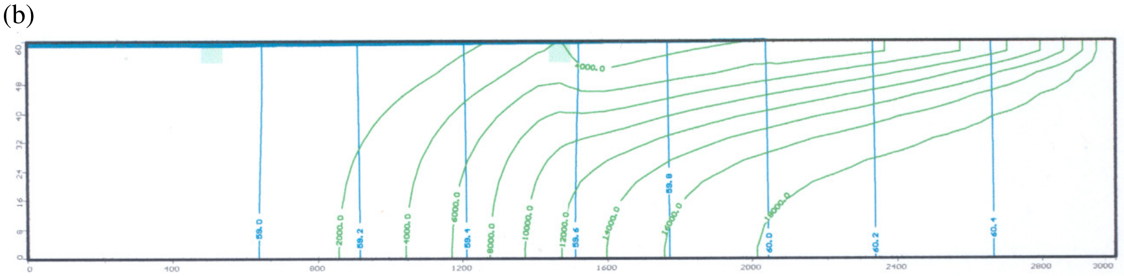


Figure 2 Simulation of saline intrusion in the Crag aquifer of north east Norfolk for (a) the 1970s baseline and (b) the 2080s Medium-high gas emissions scenario for a simulation period of 100 years.

MITIGATION STRATEGY

It is important to plan mitigation strategies for the Broads in north east Norfolk. A possible mitigation plan for lowering the risk of saline intrusion and protecting fresh water is to maintain the coastal drain water level at an elevation lower than the inland drain elevation. This would have the benefit of restricting saline intrusion, although by the 2080s the saltwater interface is predicted to reach the coastal drain and therefore threatening both the coastal and inland drainage areas. It should be noted that the model simulations presented here do not include any future socio-economic simulation for north east Norfolk with respect to changes in the groundwater abstraction regime which could affect the volume and levels of fresh groundwater in the aquifer and drainage network.

CONCLUSIONS

This paper has presented a range of perspectives on the pressures on groundwater resources from climate change, demonstrating a variety of problems specific to geo-climatic regions which only emphasise the future challenge of adapting to climate change and the growing water management crisis. The mitigation and avoidance of these effects is, however, also apparent and include better database management and dissemination of information for water resources managers, the engagement of local communities in solving local problems and the development of sustainable groundwater abstraction methods. Many of these inter-linked issues are acutely highlighted by the degradation of fresh water resources on atolls and low-lying coastal areas and are a stark reminder that international efforts are required to avoid the loss of communities and ecosystems.

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Further details of the GRAPHIC project can be found at:
www.chikyu.ac.jp/USE/GRAPHIC/GRAPHIC.htm.

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