A climate change report card for water

Working Technical Paper

1. Changes in groundwater levels, temperature and quality in the UK over the 20th century: an assessment of evidence of impacts from climate change.

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Summary

Groundwater is a significant component of public water supply and water use in the UK, as well as sustaining environmentally important flows in rivers and wetlands. Groundwater is vital to the economy of the UK and has been valued at about £8 billion. Across England and Wales the average annual recharge to the main aquifers is ~7 billion m^3. About 30% of this is abstracted from aquifers at a rate of ~7 million m^3/day, mostly from principal aquifers in southern, eastern and central England. Groundwater temperature varies with depth and is a function of the background geothermal gradient and ambient temperature at the land surface. The average temperature of groundwater in the upper parts of aquifers is around 10-11º C. The natural, or baseline, quality of groundwater is highly variable and reflects the chemistry of the recharge water and the geochemistry of the soils and rocks through which it moves and is stored. The quality of groundwater has been extensively impacted by a wide variety of pollutants throughout the 20th century with nitrate being the most widespread.

There is a consensus that relatively little is known about how groundwater has responded to climate change. Groundwater systems are naturally very variable in their characteristics and are expected to respond to climate change in a complex way. In addition, groundwater systems are sensitive to other environmental factors, such as land use change. Consequently, distinguishing between the impacts of what may be relatively small climate change signals from other environmental changes is very challenging. In the UK, groundwater levels are highly variable and long-term trends may be influenced by a wide range of factors, such as: changes in recharge caused by changes in land-use and agriculture practices; changes in land cover, particularly urbanisation, and changes in groundwater abstraction with time. At groundwater level monitoring points that have been selected to avoid these external influences, there is no evidence of a change in groundwater levels as a result of changing climate. Groundwater level records in the UK are typically less than 20 years long. Consequently, even if climate induced trends in groundwater levels are present the measurement record at the vast majority of monitoring points may be too short to enable climate trends to be seen. In addition, groundwater level data are generally of not good enough quality to enable more subtle changes, such as changes in the timing and length of the recharge season, to be investigated and characterised. This is because the monitoring was not originally designed to monitor for the effects of climate change.

There is some evidence for a rise in average groundwater temperatures. For the period 1990 to 2008 it has been estimated that there may have been an increase in average temperature of groundwater of between 0.01°C/yr and 0.02°C/yr. There have been no systematic investigations of the relationship between groundwater quality and climate change in the UK. However, long-term changes in baseline groundwater quality have been documented as being due to other environmental and societal changes not related to climate change. For example nitrate in groundwater has increased by an average of 0.34mgNO_3/l/yr during the second half of the 20th century, a rise entirely consistent with increases in agricultural application of fertilizer. The effects of these other environmental changes are thought to be far more significant in terms of their impacts on groundwater quality than any direct effects from climate change. The current monitoring of groundwater level, temperature and quality is inadequate for the investigation and quantification of climate change impacts and it is recommended that dedicated monitoring of groundwater is established to enable assessment of future climate change impacts on groundwater.

Introduction

This paper discusses changes in groundwater levels, temperature and quality in the UK over the 20th century and provides an assessment of the evidence for impacts from climate change. The rest of this section consists of a brief overview of groundwater occurrence and use in the UK, and a note on the current international peer-reviewed literature related to empirical evidence for the impact of climate change on groundwater. Following this, controls on groundwater levels are described, the availability and quality of groundwater level data in the UK are noted and the suitability of the data for climate impact assessments is assessed. Changes in groundwater levels in the UK are then briefly discussed in the context of climate change. Changes in groundwater temperature and quality are similarly described and assessed in subsequent sections. Confidence in the current science associated with each of these topics and gaps in current research are highlighted.

Groundwater in the UK

Groundwater is a significant component of public water supply and water use in the UK as well as sustaining environmentally important flows to our rivers and wetlands. Groundwater resources are important to the economy of the UK and have been valued at about £8 billion (Environment Agency, 2005). Across England and Wales the average annual recharge to the main aquifers is ~7 billion m^3. About 30% of this is abstracted from aquifers at a rate of ~7 million m^3/day (Environment Agency, 2005). Most of the groundwater is abstracted in southern, eastern and central England from the principal aquifers: the Chalk; Permo-Triassic sandstone; Jurassic limestone; and Lower Greensand (Allen et al., 1997; Environment Agency, 2011). Locally in the south of England groundwater may provide in excess of 70% of the public water supply. Because of the absence of principal aquifers in Scotland and Northern Ireland only a very small fraction of water that is abstracted for use in these regions comes from groundwater, and much of this is from small private supplies.

Groundwater temperature varies with depth and is a function of the background geothermal gradient and ambient temperature at the land surface (Stuart el al., 2010). In the UK, groundwater temperature in the shallow subsurface, typically down to about 15m bGL, is mainly influenced by the ambient temperature at the land surface, while below this level it is predominantly influenced by the background geothermal gradient modulated by groundwater flow. At a depth of ~15m bGL the temperature is ~10º C.

In the UK, the natural, or baseline, quality of groundwater is highly variable with groundwater chemistry varying as a function of factors such as rainfall chemistry, aquifer lithology, geochemical environment, groundwater flow paths and residence time (Shand et al., 2007). The natural groundwater quality has been extensively impacted by a wide variety of pollutants throughout the 20th century.

Climate change impacts on groundwater – empirical evidence

There is a consensus amongst researchers worldwide that relatively little is known about how groundwater has or will respond to recent man-induced climate change (Holman, 2006; Green et al., 2007; IPPC, 2007; Bovolo et al., 2009; Green et al., 2011). This has been emphasised in a recent state-of-the-art review of groundwater and climate change by Green et al. (2011) who observed that the a lack of necessary data has made it impossible to determine the magnitude and direction of change groundwater levels attributable to climate change. Why should this be so, given that much is known about the intimate and complex relationships between climate, precipitation and evapotranspiration, and groundwater?

Groundwater systems are inherently spatially heterogeneous and respond in a highly non-linear manner to changes in climate forcing. Groundwater systems act as low-pass filters preferentially degrading higher frequency components of climate signals. They are also commonly characterised by their relatively slow response to environmental change compared with surface water because of their large storage capacity (Arnell, 1998; Price, 1998; Alley, 2001).

In addition to these intrinsic characteristics of groundwater systems, the sensitivity of groundwater to multiple environmental change drivers further complicates any assessment of groundwater level response to climate change. For example, changes in land cover, land use and water resource management affect groundwater resource and quality, and these environmental changes may themselves be indirectly related to changes in climate (Holman, 2006). Separating what may be relatively small climate change signals from these other environmental change signals in groundwater systems is proving to be highly challenging (Green et al., 2011).

Groundwater levels and climate impacts

Controls on groundwater levels

Groundwater levels reflect both the intrinsic storage and hydraulic conductivity properties of an aquifer and the dynamic balance of water recharging and discharging an aquifer over a wide range of spatial and temporal scales.

Hydraulic conductivity can vary by orders of magnitude from about $1x10^{-2}$m/sec for shallow unconsolidated gravel aquifers to less than $1x10^{-6}$m/sec for consolidated sandstone aquifers, while aquifer storage depends on both lithology and the degree of aquifer confinement. It can range from $5x10^{-5}$ in confined aquifers to 0.3 in unconfined aquifers (Freeze and Cherry, 1979). Aquifers with high storage and/or low hydraulic conductivity values respond relatively slowly to changes in recharge, conversely low storage and/or high hydraulic conductivity aquifers can show very rapid responses to changes in recharge. Therefore even without significant spatial or temporal variations in recharge, if a catchment consists of a number of aquifers with different properties, or if there are spatial variations in storage and hydraulic conductivity within an aquifer, groundwater levels at observations boreholes will be highly variable.

Groundwater recharge is influenced by a wide range of factors including local soil type and geology, topography, land cover and vegetation, surface water characteristics, land-use activities (such as urbanisation, woodland and cropping practices) and climate (precipitation and temperature) (Green et al., 2011; Stoll et al., 2011). Consequently, groundwater recharge is temporally and spatially highly variable. Groundwater discharge is the loss or removal of groundwater from an aquifer, for example to rivers through baseflow, as spring discharge or through groundwater abstraction. Groundwater depletion occurs when rates of groundwater discharge exceeds rates of recharge.

Research context

There have been a number of studies of historic trends or changes in groundwater levels in the 20th century, although few have been specific investigations into causal links between groundwater levels and climate change. In contrast, there is a rapidly growing body of research that explicitly seeks to link future climate change to changes in groundwater levels using a range of groundwater modelling techniques (this is the subject of a companion paper to this overview - see Jackson et al., 2012). Studies of historic changes in groundwater levels include, for example: regional studies of relationships between climate and groundwater levels (Chen et al., 2004); studies of relationships between ocean-atmosphere teleconnection patterns and historic groundwater levels (Holman et al., 2011; Tremblay et al., 2011); studies relating changes in recharge processes and mechanisms to changes in groundwater levels (Scanlon et al., 2006); and large-scale studies of groundwater depletion due to groundwater pumping and exploitation (Wada et al., 2010; 2012).

In the UK, there has only been one systematic unpublished study to investigate changes in historic groundwater levels in the UK as a consequence of changes in climate (Butler et. al., pers. comm.). There have been a number of studies that have looked at the response of groundwater levels to extreme events such as droughts in the historic record (Marsh et al., 2007). In addition, a number of investigations have investigated specific links between groundwater levels and drivers of environmental change. Price (1998) investigated the implications for water resources as a result of regional variations in climate and storage across the UK. Holman (2006) and Herrera-Pantoj and Hiscock (2008) investigated the potential effects of climate change on recharge in the UK. With a team of co-workers, Holman has considered the implications of multiple drivers of change for water resources (Holman et al., 2005; Henriques et al., 2008; Holman et al., 2012), and has also investigated ocean-atmosphere teleconnection patterns and historic groundwater levels in the UK (Holman et al., 2011).

Groundwater level data for the UK

In the UK, long-term monitoring of groundwater levels is primarily undertaken by the environmental regulators (the Environment Agency, EA, in England and Wales, and by the Scottish Environmental Protection Agency, SEPA, in Scotland). A recent review of groundwater level monitoring in England and Wales by the Environment Agency documented just over 6,000 observations boreholes being monitored (Environment Agency, 2008), but noted that about a quarter of these were of questionable value, for example due to problems associated with a lack of essential metadata for the site (e.g. datum levels) , non-uniqueness of borehole location and adverse influences from neighbouring abstractions.

Examination of groundwater level data from the EA monitoring network to assess possible impacts from climate change (Butler et. al., pers. comm.) found fewer sites (~1,000) were potentially suitable for trend analysis if selection criteria included sites with 20 years or more data and with a minimum of 12 measurements a year. Only 40 sites were suitable for trend analysis if only sites with measurement records of greater than 40 years in length were used. Butler et. al. (pers. comm.) noted the generally poor quality of the groundwater level records with many sites having large gaps in the time series and varying frequency of observations. They also noted that at a number of the sites observation boreholes may dry out so that the observational record included biases.

Notwithstanding the often poor quality of groundwater level records, the relatively short nature of the records may cause particular problems with respect to quantifying trends in groundwater level data. Chen and Grasby (2009) have shown that given the predominance of 45-60 year climate cycles typically observed in instrumental records of hydro-meteorological time series, if tests such as the Mann-Kendall and Thiel-Sen tests are used to search for trends in hydroclimatic data, time series records of >60 years should be used. Clearly, the vast majority of groundwater level records in the UK are significantly shorter than this and, at the moment, it may not be possible to use robust statistical techniques to identify trends in data for all but a few sites.

Changes in groundwater levels in the UK

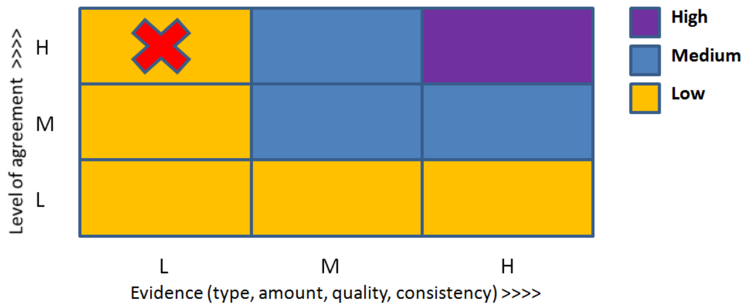
Using normalised groundwater level data from 62 observation boreholes unimpacted by abstraction, Butler et al. (pers. comm.) undertook a graphical analysis of trends in annual minimum groundwater levels by plotting annual groundwater level minima for 10, 15 or 20 year periods against their respective Wiebull plot positions and then fitting a linear regression to the plot for each borehole. They found that for 20 year analysis periods there appeared to be a general decline in annual groundwater level minima for all regions and aquifer types, but that no such trend could be seen when 10 year periods were used in the analysis. A range of concerns with the preliminary data analysis were noted, including: the use of annual groundwater level minima to characterise long-term changes in groundwater levels; the short length of the observational records and; problems with data quality and consistency even at the few sites that were analysed. Consequently, it has been recommended that the findings of this study should be used with caution.

Qualitative studies of groundwater levels in the UK include the analysis of groundwater response to historic droughts (Marsh et al., 2007; Bloomfield, pers. comm.). Based on groundwater levels records from the National Groundwater Level Archive (NGLA, 2012), Marsh et al. (2007) identified six groundwater droughts in the 20th century. All were in response to reduced winter recharge over one, or more (usually two) seasons, and in some cases compounded by hot dry summers. Marsh et al. (2007) found no evidence to suggest that groundwater droughts in the UK have changed in their intensity or frequency over the 20th century. As a precursor to a more qualitative analysis of extreme groundwater levels, and using groundwater level data from the same NGLA, Bloomfield (pers. comm.) has developed a standardised Groundwater Level Index (GLI) based on the Standardised Precipitation Index (SPI). Semi-quantitative analysis of groundwater droughts using the GLI for 40 sites in England and Wales gives results consistent with the findings of Marsh et al (2007).

Holman et al (2011) used wavelet coherence techniques to investigate links between three long-term groundwater level records in the UK (Dalton Holm, New Red Lion and Ampney Crucis) and three atmospheric circulation pattern indices (the North Atlantic Oscillation, the East Atlantic Pattern and the Scandinavian Pattern). They observed multi-annual to decadal periods where there was a significant coherence between groundwater levels and atmospheric signals and other periods of similar duration where there was no significant correlation with the teleconnection indices. Although the aim of the study was not to investigate trends in the driving variables (or at least surrogates for driving climate data) and groundwater levels, the study serves to illustrate the complex and dynamic relationship between climate and groundwater levels in the UK.

In summary, groundwater levels are temporally and spatially highly variable and their long-term trends may be influenced by a wide range of factors, such as: changes in the nature of recharge through changes in land-use and agriculture practices; changes in land cover, particularly urbanisation; and, changes in the abstraction regime with time. At observation boreholes where these influences are thought to be negligible, there is no convincing evidence for climate change effects on groundwater level trends. Even if climate induced trends are present, the measurement record at the vast majority of observation boreholes may be too short to enable them to be characterised. In addition, the data is at present of inadequate quality to enable more subtle but potentially important indications of climate change, such as changes in the timing and length of the recharge season, to be characterised.

Confidence in the science



There is a high level of agreement that the evidence for, and understanding of, climate change impacts on groundwater levels based on the observational record, both internationally and in the UK, is poor.

Gaps in research

There is a need for a bespoke groundwater level monitoring network dedicated to characterising long-term changes in groundwater levels in the UK. This network needs to be capable of characterising long term trends in groundwater level, quantifying changes in the length and timing of groundwater recharge season, and characterising extreme events. Relatively high frequency (better than daily) groundwater level measurements are required at each of the network sites and each site needs to unaffected by other change factors. Ideally this climate change network should be developed in conjunction with monitoring of groundwater temperature and quality, as well as other catchment hydrometric parameters such as soil moisture, river stage and hydro-ecological observations.

There is a need to improve existing historic groundwater level data by systematically infilling gaps, removing spurious data points and establishing a reference dataset of the best observations for future climate impact studies. For the few boreholes where there is a relatively long record of observations, eg. Chilgrove House and Dalton Holme, spectral analysis and or wavelet techniques should be used to characterise periodicities in groundwater levels in order to: i.) assess the limitations of applying robust trend analysis techniques to groundwater level data (Chen and Grasby, 2009), and, if appropriate, undertake those analyses, and ii.) investigate any changes in seasonality of groundwater levels. In both cases, any observed trends or changes in seasonality should be analysed in the context of appropriate climate data.

Groundwater temperature and climate impacts

Controls on groundwater temperature

Groundwater temperature varies with depth and is a function of two main factors: the background geothermal gradient and ambient temperature at the land surface (Stuart et al., 2010). In the absence of groundwater flow, the subsurface temperature normally follows the geothermal gradient, typically an increase of 1°C per 20 to 40 m of depth (Anderson, 2005). Within the geothermal zone the temperature profile is not subject to seasonal variations and typically increases linearly with depth except where perturbed by groundwater flow or changes in thermal conductivity of the matrix. Groundwater flow perturbs the geothermal gradient by infiltration of cooler water into recharge areas and upward flow of warmer water in discharge areas.

Within the near surface zone temperature is influenced by seasonal heating and cooling of the land surface. Shallow groundwater temperature is generally 1-2°C higher than the mean annual surface temperature (Busby et al., 2009), where mean annual air temperature at sea level in the UK varies from 8°C in the north to 12°C in the south. In northern temperate climate regions diurnal variations are not generally seen below 1.5 m depth whereas seasonal temperature cycles penetrate the ground to depths of the order of 10 to 15 m at a rate dependent on the thermal diffusivity of the ground (Busby et al., 2009; Taylor and Stefan, 2009). Below about 15 m thermal gradients are the dominant control on groundwater temperature.

Research context

Small perturbations in borehole temperature profiles induced by seasonal and annual changes in temperature at the ground surface have been correlated with atmospheric circulation patterns such as the Arctic Oscillation (Figuera et al., 2011). They have also been used extensively by many workers to reconstruct ground surface temperature (GST). GST histories have been interpreted as providing good estimates of surface air temperature (SAT) and hence have been used to investigate climate change (Beltrami et al., 1995; Bodri and Cermák, 1995; Bodri and Cermák, 1997; Harris and Chapman, 1997; Pollack et al., 1998; Huang et al., 2000; Pollack and Huang, 2000; Harris and Chapman, 2001; Mann and Schmidt, 2003).

Any increases in air temperature associated with climate change will lead to increases in groundwater temperature due to the close coupling of groundwater, GST and SAT. The long-term impacts of increasing groundwater temperature are likely to impact directly on water quality and indirectly on groundwater receptors such as groundwater dependent aquatic and terrestrial ecosystems. For example, elevated temperature typically decreases the levels of dissolved oxygen in water while leading to rises in the rate of photosynthesis by algae and aquatic plants. It can increase metabolic rate of aquatic animals leading to adverse cellular biology and ecological affects. Bloomfield et al. (2006) and Stuart et al. (2011) have also suggested that climate change induced increases in groundwater temperature may affect the fate and behaviour of pesticides and nitrate in groundwater.

In the UK there has only been one systematic study of groundwater temperature profiles and time series (Stuart et al., 2010). The following is a summary of the findings of that study.

Trends in groundwater temperature in the UK

Stuart et al. (2010) analysed groundwater temperature data collected by the EA from about 3700 monitoring sites. The dataset comprised of about 216,000 individual temperature measurements. The first record in the dataset is from 1975, however there are few observations until the mid-1980s. Most of the measurements are from the Chalk and Permo-Triassic sandstone aquifers and consequently, most of the observations are from southern and central England. Borehole depths follow an approximately normal distribution with a median depth of 91m although the sample depth within boreholes is typically unspecified. Using the entire dataset, annual trends were characterised and compared with trends in the Central England Temperature (CET) time-series. In addition, where there were more than 50 temperature measurements at a given borehole, more detailed characterisation of annual and seasonal trends was undertaken.

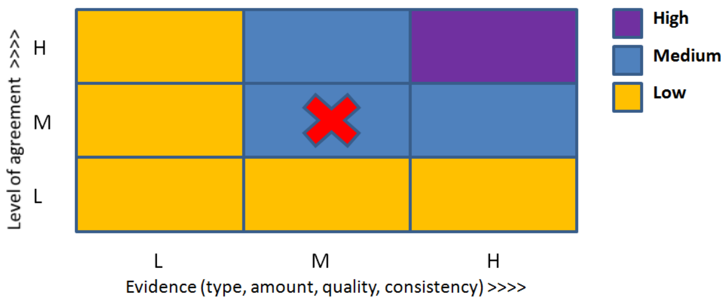
Based on the full dataset, the mean groundwater temperature was 11.35°C with a standard deviation of 1.76°C and for the period 1990 to 2008 an increasing trend in groundwater temperature of 0.023°C/yr was found. However, Stuart et al. (2010) question the reliability of some of the data and inferred that a significant number of the measurements “do not represent true groundwater temperatures and have most probably adjusted to ambient air temperature during sampling”. Consequently, Stuart et al. (2010) also estimate trends only using groundwater temperature data from sites that they assess are reliable and only include data from sites where there is a minimum of 25 observations. Using this data they found an increasing trend in groundwater temperature of 0.035°C/yr. These trends compare with a trend of 0.032°C/yr for the CET series for the similar period.

In addition to analysis of the full dataset, individual temperature time series from 495 sites were analysed to obtain site specific trends using ordinary least squares, robust line and non parametric (Kendal tau and Sen slope) methods. The mean temperature for this sub-set of groundwater temperature data was 11.3°C, consistent with the full dataset. However, the median trend was 0.0102°C/yr with a standard deviation of 0.058°C/yr, significantly less than the trends for the full data. There were no clear correlations in trend with aquifer type, borehole depth or geographical location. A simple test for seasonality was carried out on the sub-set of the temperature data. Groundwater temperature was shown to be seasonal in all but 27 of the sites, the range in seasonal variation was inversely proportional to borehole depth and the median seasonal variation in groundwater temperature was 2.18°C. In addition, Stuart et al. (2010) noted that some time series showed an apparent reduction in amplitude of the seasonal variation with time, but that the relatively short length of most time series makes this observation “difficult to characterise ... more fully”.

The strongly seasonal behaviour was unexpected and Stuart et al. (2010) suggested a number of possible explanations for the apparent phenomena: an artefact of the sampling procedure (temperature of groundwater is modified by temperature of headworks); groundwater temperature is affected by borehole abstraction and localised shallow groundwater flow paths in vicinity of the monitoring point, and; groundwater temperature is modified as it passes through pumps during abstraction. Stuart et al. (2010) did not investigate any of these further.

In summary, Stuart et al. (2010) found that the groundwater temperature data set held by the EA appeared to contain a significant number of observations that were probably ‘adjusted to ambient air temperature during sampling’. The full dataset was temporally limited with the earliest observations being in 1975 and few observations until the mid-1980s. For the period 1990 to 2008 the data show an increase of 0.023°C/yr, but the rate of increase in temperature for a sub-set of sites where good time-series data are available is significantly less with a median increase of 0.0102°C/yr. These compare with a trend of 0.032°C/yr for the CET series for the similar period. The vast majority of sites with a good temperature time-series show strong seasonal changes in temperature which were unexpected on the basis of hydrogeological considerations and are currently unexplained.

Confidence in the science



Internationally there is some evidence that climate change has modified groundwater temperatures. In the UK the current observational record is too poor to assess unambiguously the impact of climate change on groundwater temperatures in the 20th century. However, there is some evidence for a general rise in groundwater level temperature of the order of 0.0102°C/yr to 0.023°C/yr.

Gaps in research

Based on the work of Stuart et al. (2010), it is clear that the evidence base for changes in groundwater temperature in the UK is inadequate and is almost certainly compromised by unreliable sampling. There is currently no co-ordinated monitoring of groundwater temperatures to assess the impacts of climate change. Consequently, there is a need to develop bespoke monitoring of groundwater temperature, ideally in conjunction with a dedicated monitoring network of hydrogeologically representative sites across the UK (see previous comments related to groundwater level monitoring). At each site there would be a requirement to understand the temperature profile with depth, and the groundwater flow regime in the vicinity of the borehole. Groundwater temperature monitoring should be co-ordinated with other groundwater environmental impact studies, particularly focussing on areas where there are groundwater dependent terrestrial ecosystems or surface flows with a significant groundwater (high baseflow) contribution.

Groundwater quality and climate impacts

There have been relatively few studies of the effects of climate change on groundwater quality. Most of these studies have focussed on the implications for groundwater quality due to potential climate induced change in groundwater recharge and discharge processes and changes in storage characteristics (Green et al., 2011). For example, studies of the impact of climate change on groundwater quality include implications of changes in recharge for the input of salts and dissolved solids to aquifers and the mobilisation of salts and contaminants in the unsaturated zone. Other studies have considered the impact of climate change on groundwater salinization, particularly in coastal regions (see Green et al., 2011 for an overview). Bloomfield et al. (2006) and Stuart et al (2011) have noted potential implications of climate change for the transport and fate of pesticides and nutrients in groundwater.

Groundwater quality is a complex function of the physio-chemical and biotic controls on aquifers and changes in climate are just one of many change drivers that have affected groundwater quality. Over the 20th century other drivers such as the intensification of agriculture and associated contamination from diffuse pollution, urbanisation and the development of mega-cites, and the increased abstraction of groundwater for irrigation, industry and potable water have all modified groundwater quality significantly. Consequently, identifying climate change effects on groundwater quality is extremely challenging (Green et al., 2011) and it is recognised that long-term monitoring efforts are required to understand climate-related spatiotemporal trends in groundwater quality (Dragoni and Sukhija, 2008).

In the UK there have been no systematic investigations to characterise large-scale trends in groundwater quality as a consequence of climate change.

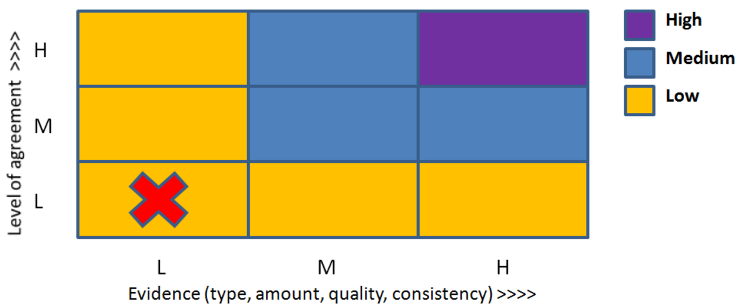
Changes in groundwater quality in the UK in the 20th century

In their review of baseline groundwater quality in the UK, Shand et al (2007) note that urbanisation and industrialisation were important factors affecting groundwater quality in the early 20th century. The most significant factor affecting groundwater quality in the second half of the 20th century has been the intensification of agriculture and the consequent impact on groundwater quality from diffuse agricultural pollution, in particular from nitrate. The effects of these environmental and societal changes not related to climate change are considered to be far more significant in terms of their impacts on groundwater quality than any direct effects from climate change (Bloomfield et al., 2006; Stuart et al., 2011).

For example, Stuart et al. (2007) quantified increases in nitrate concentration in the groundwater of England and Wales. They used EA groundwater monitoring data for 191 sites and found an average increase in nitrate of 0.34mgNO_3/l/yr. Wang et al. (2012) have subsequently constructed a national nitrate input function based on historic agricultural nitrate loading that is consistent with the observed rise in nitrate in groundwater across England and Wales.

Ward and Seymour (pers. comm.) reviewed the risk of saline intrusion to costal aquifers in the UK from climate change induced sea level rise. They didn't undertake an assessment of recent trends in salinity in the coastal aquifers, but they did note that regionally the risk of increase in salinity due to climate change induced sea-level rise was low, although there were potentially local risks associated with inundation and changes in abstraction regimes.

Confidence in the science



Internationally there are some case studies that have linked climate change to changes in processes that control groundwater quality, however, the process understanding is relatively immature and there are very limited supporting observational records. In the UK there have been no systematic investigations to characterise large-scale trends in groundwater quality as a consequence of climate change.

Gaps in research

The indirect effects of climate change on nutrient transport and fate requires more research in particularly sensitive catchments and hydrogeological settings (Bloomfield et al., 2006; Stuart et al., 2011). Locally where saline intrusion is significant, the indirect impact of changes in sea level and or changes in demand and abstraction regimes may require research in the future (Ward and Seymour, pers. comm.). Groundwater quality in shallow aquifers may be affected by changes in groundwater temperature, so additional monitoring of aspects of groundwater quality in these aquifers, particularly where there are groundwater dependent ecosystems, may be required and should ideally form part of an enhanced national monitoring network (see comments related to groundwater level and temperature research gaps).

References

Allen DJ, Brewerton LJ, Coleby LM, Gibb BR, Lewis MA, MacDonald AM, Wagstaff SJ and Williams AT. 1997. The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report, WD/97/34. British Geological Survey, Keyworth, Nottingham.

Alley WM. 2001. Ground water and climate. Ground Water, 39, 161

Anderson MP. 2005. Heat as a groundwater tracer. Ground Water, 43, 951-968

Arnell NW. 1998. Climate change and water resources in Britain. Climatic Change, 39, 83-110

Beltrami H, Chapman DS, Achambault S and Bergone Y. 1995. Reconstruction of high resolution ground temperature histories combining dendrochronological and geothermal data. Earth and Planetary Science Letters, 136, 437-445

Bloomfield JP. (pers. comm.) Identification and characterisation of regional groundwater droughts in the UK.

Bloomfield JP, Williams RJ, Gooddy DC, Cape JN and Guha P. 2006. Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater – A UK perspective. Science of the Total Environment, 369, 163-177

Bodri L and Cermák V. 1995. Climate changes of the last millennium inferred from borehole temperatures: Results from the Czech Republic - Part 1. Global and Planetary Change, 11, 111-115

Bodri L and Cermák V. 1997. Climate changes of the last millennium inferred from borehole temperatures: Results from the Czech Republic - Part 2. Global and Planetary Change, 14, 163-173

Bovolo CI, Parkin G and Sophocleous M. 2009. Groundwater resources, climate and vulnerability. Environ. Res. Lett., 4, 035001

Busby J, Lewis M, Reeves H and Lawley R. 2009. Initial geological considerations before installing ground source heat pump systems. Quarterly Journal of Engineering Geology and Hydrogeology, 42, 295-306

Butler A. (pers. comm.). Climate change indicators from Environment Agency groundwater level data.

Chen Z and Grasby SE. 2009. Impact of decadal and century-scale oscillations on hydroclimate trend anlaysis. Journal of Hydrology, 365, 122-133

Chen Z, Grasby SE and Osadetz KG. 2004. Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. Journal of Hydrology, 290, 43-62

Dragoni W and Sukhija BS. 2008. Climate change and groundwater: A short review. Geological Society Special Publications, 1-12

Environment Agency. 2005. Underground, under threat. The state of groundwater in England and Wales. Environment Agency, Bristol.

Environment Agency. 2008. Review of the national groundwater level monitoring network. Environment Agency Internal Report, Bristol.

Environment Agency. 2011. The case for change – current and future water availability. Environment Agency, Bristol.
Figuera S, Livingstone DM, Hoehn E and Kipfer R. 2011 Regime shift in groundwater temperature triggered by Arctic Oscillation. Geophysical Research Letters, 38, L23401
Freeze RA and Cherry JA. 1979. Groundwater. Prentice Hall, New Jersey, USA
Green TR, Taniguchi M, and Kooi H. 2007. Potential impacts of climate change and human activity on subsurface water resources. Vadose Zone J., 6, 531-532
Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM , Treidel H and Aureli A. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. Journal of Hydrology, 405, 532-560
Harris RN and Chapman DS. 1997. Borehole temperatures and a baseline for 20th century global warming estimates. Science, 275, 1618-1621
Harris RN and Chapman DS. 2001. Mid-latitude climatic warming inferred by combining borehole temperatures with surface air temperatures. Geophysical Research Letters, 28, 747-750
Henriques C, Holman IP, Audsley E and Pearn K. 2008. An interactive multi-scale integrated assessment of future regional water availability for agricultural irrigation in East Anglia and North West England. Climatic Change, 90m 89-111
Herrera-Pantoja M and Hiscock KM. 2008. The effects of climate change on potential groundwater recharge in Great Britain. Hydrological Processes, 22, 73-86
Holman IP, Rounsevell MDA, Shacklet S, Harrison PA, Nicholls RJ, Berry PM and Audsley E. 2005. A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change. Climatic Change, 71, 9-41.
Holman IP. 2006. Climate change impacts on groundwater recharge-uncertainty, shortcomings , and a way forward? Hydrogeology Journal, 14, 637-647
Holman IP, Rivas-Casado M, Bloomfield J and Gurdak J. 2011. Identifying non-stationary groundwater level responses to North Atlantic ocean-atmosphere teleconnection patterns using wavelet analysis. Hydrogeology Journal, 19, 1269-1278
Holman IP, Allen DM, Cuthbert MA and Goderniaux P. 2012. Towards best practice for assessing the impacts of climate change on groundwater. Hydrogeology Journal, 21, 1-4
Huang S, Pollack HN and Shen P-Y. 2000. Temperature trends over the past five centuries reconstructed from borehole temperatures. Nature, 403, 756-758
IPPC. 2007. Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, UK and New York, USA.
Jackson CR, Mackay JD and Bloomfield JP. 2012. Changes in groundwater levels in the UK over the 21st century: an assessment of evidence of impacts from climate change. LWEC Report Card
Mann ME and Schmidt GA. 2003. Ground vs. air temperature trends: Implications for borehole surface air temperature reconstructions. Geophysical Research Letters, 30, 1607
Marsh TJ, Cole G and Wilby R. 2007. Major droughts in England and Wales. 1800-2006. Weather, 62, 87-93
NGLA. 2012. National Groundwater Level Archive. http://www.bgs.ac.uk/data/waterwatch.html
Pollack HN, Huang S and Shen P-Y. 1998. Climate change record in subsurface temperatures: a global perspective. Science, 2833, 279-281
Pollack HN and Huang S. 2000. Climate reconstruction from subsurface temperatures. Annual Review of Earth and Planetary Sciences, 28, 339-365
Price M. 1998. Water storage and climate change in Great Britain – the role of groundwater. Proceedings of the Institute of Civil engineers Water, maritime and Energy, 130, 42-50
Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM and Simmers I. 2006. Global synthesis of groundwater recharge in semi-arid and arid regions. Hydrological Processes, 20, 3355-3370

Shand P, Edmunds WM, Lawrence AR, Smedley PL and Burke S. 2007. The natural (baseline) quality of groundwater in England and Wales. British Geological Survey Research Report RR/07/06

Stoll S, Hendricks Franssen HJ, Barthel R and Kinzelbach W. 2011. What can we learn from long-term groundwater data to improve climate impact studies. Hydrol. Earth Sys. Sci., 15, 3861-3875

Stuart ME, Chilton PJ, Kinniburgh DC and Cooper DM. 2007. Screening for long-term trends in groundwater nitrate monitoring data. Quarterly Journal of Engineering Geology and Hydrology, 40, 361-376

Stuart ME, Gooddy DC, Williams AT and Bloomfield JP. 2011. The impact of climate change in future nitrate concentrations in groundwater: a case study from the UK. Science of the Total Environment, 409, 2859-2873

Stuart ME, Jackson CR and Bloomfield JP. 2010. Preliminary analysis of trends in UK groundwater temperature measurements from England and Wales. British Geological Survey Internal Report IR/10/033

Taylor CA and Stefan HG. 2009. Shallow groundwater temperature response to climate change and urbanisation. Journal of Hydrology, 375, 601-612

Tremblay L , Larocque M, Anctil F and Rivard C. 2011. Teleconnections and interannual variability in Canadian groundwater levels. Journal of Hydrology, 410, 178-188

Wada Y, van Beek LPH and Bierkens MFP. 2012. Global depletion of groundwater resources. Geophysical research Letters, 37, L20402

Wada Y, van Beek LPH and Bierkens MFP. 2012. Nonsustainable groundwater irrigation: A global assessment. Water Resources Research, 48, W00L06

Wang L, Stuart ME, Bloomfield JP, Butcher AS, Gooddy DC, MsKenzie AA, Lewsi MA and Williams AT. Prediction of the arrival of peak nitrate concentrations at the water table at the regional scale in Great Britain. Hydrological Processes, 26, 226-239

Ward R and Seymour K (pers. comm.). Risk of saline intrusion of coastal aquifers from climate change induced sea level rise. Environment Agency internal report.