A climate change report card for water

Working Technical Paper

4. Changes in groundwater levels in the UK over the 21st 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 to our rivers and wetlands. 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 $m^3 day^{-1}$. Most of the groundwater is abstracted from the principal aquifers in southern, eastern and central England.

The role of groundwater in the management of water resources is likely to become more important because it can be used to support public water supply and ecosystem services during more severe drought periods projected under climate change. However, the understanding of how groundwater will respond to changes in coupled climate and human stresses is limited and insufficient research has been undertaken.

Groundwater *recharge* generally refers to the downward vertical flux of water at the water table. *Potential recharge* refers to drainage from the base of the soil, which depends on the rainfall, runoff, interflow and evaporation balance of the soil, as well as soil and vegetation characteristics. Most potential recharge occurs during the winter months when soils are wet and potential evaporation rates are lower.

Ten separate studies have been reported which project potential recharge rates in the UK over the 21st century. These studies cover 12 sites and predominantly focus on the Chalk aquifer in south-east England, although other studies have investigated the Permo-Triassic sandstone in the Midlands and the Devonian and Carboniferous limestone in Scotland.

Overall, there is some consensus about changes in mean annual potential recharge in the UK. Most studies simulate a decrease by the 2050s but projections are in the range ~ -30 –+21%. There is most agreement for Chalk catchments in southern England, where the length of the recharge season is likely to shorten. There is less agreement about the impact of climate change on recharge to the Chalk aquifer in East Anglia. There is some agreement over future changes in recharge to Permo-Triassic sandstone aquifers, although the small number of studies means that there is limited evidence to support the findings. Overall it seems that recharge rates will decrease by the 2080s over most aquifers. However, there is significant uncertainty about the magnitude of changes due to a cascade of uncertainty from and about greenhouse gas emissions scenarios, climate model uncertainty, and the effect of socio-economic change on land-use planning and water demand.

Knowledge of potential future changes in groundwater levels is important, not only because they are indicative of the total amount of water stored in an aquifer, but also because they affect the degree to which an aquifer can be exploited. Potential changes in the spatial and temporal distribution of groundwater levels in the future will also affect groundwater flood risk.

Whilst there is some agreement as to how groundwater levels will change in the future, an insufficient number of studies have been undertaken. There are significant differences in current projections, again due to multiple sources of uncertainty.

There is a clear need to undertake more research, particularly at the national scale, which adopt consistent approaches, explore the full range of uncertainties and are spatially coherent.

Introduction

This paper discusses changes in groundwater levels in the UK over the 21st century and provides an assessment of the evidence for the potential impacts of climate change. It is structured as follows. First, a brief overview of groundwater occurrence and use in the UK is given. This is followed by a summary of current research drivers within the context of UK groundwater resources. Current projections of the UK's climate over the 21st century are then summarised before the various methods that are used to apply these projections in catchment, or aquifer specific, assessments are described. Evidence for potential future changes in groundwater recharge and groundwater levels is then presented. An assessment of the confidence in the science is given for each of these variables. Finally, gaps in the research are discussed before a summary of currently ongoing research studies.

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 $m^3 day^{-1}$ (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, 2011a). 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.

Research drivers

In recent years a significant amount of research has been undertaken to examine the range of possible impacts of climate change on surface water resources. The number of studies investigating the effects on groundwater has increased over the last decade but remains inadequate (Bates et al., 2008). Groundwater resources may be relatively robust in response to changes in the driving climate variables under climate change compared with surface water, due to the buffering effect of groundwater storage (Dragoni and Sukhija, 2008). However, as discussed by Green et al. (In press), the understanding of how groundwater will respond to changes in coupled climate and human stresses is limited. This is particularly relevant to the groundwater resources of the UK because many of the countries groundwater bodies have been assessed as being *over-licensed* or *over-abstracted* (Environment Agency, 2008). The role of groundwater in the management of water resources is likely to become more important because groundwater can be used to support public water supply and ecosystem services during the more severe drought periods projected under climate change scenarios for southern UK (Murphy et al., 2009). Whether this is possible will depend on changes in intra-annual recharge rates as well as the projected potential shortening of the winter recharge season. Consequently, there is a need to investigate the potential impacts of changes in climatic variability, in addition to changes in annual average conditions; research is not only required to support improved drought management planning but also to understand potential changes in groundwater flood risk (Hughes et al., 2011).

Climate change projections

Warming of the global climate system is unequivocal and evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC, 2007). In line with the warming of the global climate over the past 150 years, the climate of the UK has changed and average temperatures have risen. Evidence for this is provided by the instrumental record of temperature for central England (Parker et al., 1992; Parker and Horton, 2005): 16 of the 30 warmest years between 1659 and 2011 have occurred after 1980.

Projections of changes in the climate of the UK can be obtained from a number of global climate modelling centres (see www.ipcc-data.org). Whilst global climate models (GCMs) are the most sophisticated tools for simulating current and future climate, there remains considerable variability between the results of different models. This uncertainty in the future projections, and the limited skill with which climate models reproduce some historic observations, has led to the question of whether impact studies based on climate model projections are fit for the purpose of managing or adapting to the future (Beven, 2011).

Uncertainty in climate model projections is discussed by Rowell (2006) who presents estimates of changes in temperature and precipitation for the UK for the 2080s from an ensemble of regional and global climate model integrations: changes in seasonal temperature are in the range ~1 – 5°C and changes in seasonal precipitation in the range ~ ±40%. A more recent set of probabilistic estimates of changes for the UK, the UKCP09 projections, has been produced by the Met Office's Hadley Centre (Murphy et al., 2009). This ensemble of projections gives central estimates of increases in summer mean temperatures by the 2080s, relative to the 1961–1990 baseline, of up to 4.2°C for parts of southern England. 10^{th} and 90^{th} percentile probabilities are 2.2 and 6.8°C, respectively, for the same region. Projections for UK precipitation include both negative and positive changes.

Estimating impacts and uncertainties

The simulation of the effects of climate change on hydrological variables, such as groundwater recharge and groundwater levels, necessitates the use of a model of some type – perhaps based on relatively simplified mathematical concepts (Wilby et al., 2006), statistical analyses of data (Chen et al., 2002) or complex representations of physical processes (Ferguson and Maxwell, 2010). These hydrological models are typically at a much higher resolution, and smaller spatial and temporal scales than climate models. Consequently, climate projections are generally downscaled for application in catchment hydrological or groundwater models. This can be performed by constructing plausible scenarios that are informed by the results of climate models (Eckhardt and Ulbrich, 2003; Woldeamlak et al., 2007), which for example, incorporate different percentage changes in annual or seasonal precipitation (e.g. Malcolm and Soulsby, 2000) or by transferring GCM output to the catchment scale through the use of statistical downscaling methods (Li et al., 2010; Scibek and Allen, 2006) or weather generators (Herrera-Pantoja and Hiscock, 2008).

Whichever downscaling method is applied, the results of a climate change impact study should be described within the context of the range of uncertainties within the modelling process. A number of sources of uncertainty should be considered, relating to the representation and modelling of the catchment or groundwater system, to the projection of the future climate and to future socio-economic change at the local or catchment scale (Holman, et al., 2012). In groundwater modelling, uncertainties are associated with the conceptual model of the aquifer (Bredehoeft, 2005; Poeter and Anderson, 2005), the structure and parameterisation of the numerical model (Refsgaard et al., 2006; Wilby, 2005) and the observations on which it is based. Furthermore, process responses may not be stationary over time. For example, it is not possible to know a-priori whether the relationship between temperature, precipitation and recharge will remain the same under a changing climate (Younger et al., 2002). As previously discussed, there are also a number of sources of uncertainty associated with the projections of climate change: (i) the formulation and accuracy of climate models, (ii) the magnitude of anthropogenic emissions, (iii) the temporal and spatial effect of natural variations internal to the climate system and (iv) the method of downscaling climate model information to the regional or catchment scale (Rowell, 2006).

No studies have assessed the full cascade of uncertainty from climate model projection, through climate downscaling and groundwater modelling to simulated impact.

Groundwater recharge impacts

To undertake an assessment of potential changes in groundwater levels and aquifer storage, it is necessary to quantify changes in groundwater recharge. Aquifers can be replenished by both *diffuse recharge* across the land surface and *focussed recharge* via leakage from, for example, rivers, lakes, agricultural irrigation schemes and, sewerage systems and pressurised water mains. Most studies that have investigated potential future changes in groundwater resources in temperate climates such as the UK, have considered only changes in diffuse groundwater recharge (Green et al., In press). This has been because diffuse recharge is generally the major input to the groundwater balance but also partly because the consideration of changes in other sources of recharge, such agricultural irrigation, necessitates an analysis of socio-economic change and a multi-disciplinary approach; most of the existing studies of the impact of climate change on groundwater recharge impact have been undertaken by researchers working within the hydrological sciences discipline.

When considering diffuse groundwater recharge there is a need to differentiate between *recharge*, which is generally considered to be the downward vertical flux at the water table, and *potential recharge*, or drainage from the base of the soil zone. Rates of potential recharge at a location and point in time differ from recharge rates at the water table due to the buffering effect of the unsaturated zone (Ireson et al., 2006; Ireson and Butler, 2011).

Controls on groundwater recharge

Potential groundwater recharge is one component of a mass balance of the soil zone, the others being precipitation, surface runoff, interflow, and evaporation. Evaporation includes interception and transpiration losses from vegetation, and direct evaporation from the land surface. Consequently, rates of potential recharge depend on a number of non-climatic factors (Green et al., In press): soil physical properties and thickness, local geology, topography, vegetation, and land-use activities (e.g. crop rotation or soil compaction by livestock). Most potential recharge occurs during the winter months when soils are wet and potential evaporation rates are low.

Variations in potential recharge rates do not correlate directly with vertical inflows to the saturated groundwater store because of the effect of the unsaturated zone. Exactly how potential recharge rates are modified between the soil zone and the water table depends on the physical properties of the unsaturated zone, its thickness, its saturation state (i.e. the proportion of its pore space that is filled with water), and antecedent potential recharge rates.

A consideration of the role of the unsaturated zone is important when investigating any of the major aquifers in the UK but particularly so when quantifying the groundwater resources of the Chalk. The Chalk consists of an unsaturated zone with a high storage-low hydraulic conductivity porous matrix intersected by a low storage-high hydraulic conductivity fracture network. Thick (up to ~150 m) unsaturated zones, which stay close to saturation (85 – 90%) throughout the year, mean that a significant volume of water is held above the water table. Slow drainage of this water to the water table can cause groundwater heads to be maintained at higher levels than might be expected during drought periods. This is also why rivers on chalk aquifers keep flowing during even very dry summers (Lewis et al., 1993).

Research context

The construction of projections of future recharge rates across an area has necessitated the use of numerical models. The validation of these models against observations is difficult and consequently they have generally been calibrated through the application of groundwater flow models that can be tested against observed groundwater levels and river flows (e.g. Heathcote et al., 2004; Jackson et al., 2011). However, simulated recharge rates are in most cases uncertain because of the parameterisation of models is based on a land surface that exhibits highly heterogeneous coverage of soil, geology, vegetation types, and land-use practice (Holman, 2006). Understanding of the controls on groundwater recharge within the UK has improved during the last decade (Ireson, et al., 2006; Roberts and Rosier, 2006; Ireson and Butler 2011), through research programmes such as the NERC funded LOCAR programme (Wheater et al., 2006), but knowledge remains limited (Green et al., In press).

Less than a decade ago very little research had been undertaken into potential changes in groundwater resources generally, and even less into groundwater recharge specifically (Jackson et al., 2006). Those climate change and water resource impact studies that had been performed predominantly examined surface water systems. Since then the number of studies investigating future groundwater resources has increased each year (Green et al., In press). These have focussed on both the global scale (Döll and Fielder, 2008; Döll, 2009) and the catchment scale (e.g. Younger et al., 2002; Holman, 2006; Herrera-Pantoja and Hiscock, 2008; Jackson et al., 2011).

Projections of changes in groundwater recharge

Using a global hydrological model on a 0.5˚ resolution with a daily time-step Döll (2009) estimates the vulnerability of global scale water resources to climate change. This involves the simulation of changes in groundwater recharge rates using two global climate models and both a medium (B2) and high (A2) greenhouse gas emissions scenario (IPCC, 2000). The results are at a reasonably coarse scale but suggest that changes in mean groundwater recharge by the 2050s (2041-2070) compared to a 1961-1990 baseline would be in the range $\pm$30%.

Ten separate studies (Figure 1 and Table 1) have been reported which project recharge rates in the UK over the 21st century. These studies cover 12 sites and predominantly focus on the Chalk aquifer in south-east England, although other studies have investigated the Permo-Triassic sandstone in the Midlands and the Devonian and Carboniferous limestone in Scotland.

Almost all the studies reviewed applied models that simulate recharge using conceptual soil moisture accounting (SMA) methods based on the original Penman-Grindley model (Penman, 1948; Grindley, 1967). Importantly, these models do not incorporate complexities such as the attenuating effect of the unsaturated zone (Green et al., In press) and therefore consider only potential groundwater recharge. An exception is the study undertaken by Younger et al. (2002) which estimated future recharge rates from temperature and precipitation projections using site-specific transfer functions. However, these transfer functions were themselves calibrated based on recharge datasets derived from an SMA approach, and therefore must also be considered as potential recharge projections.

Projections are typically made for at least one of three time-slices in the 21st century. These can be generalized as the 'early' (2020s and 2030s), 'middle' (2040s and 2050s) and 'late' (2080s) 21st century. The recharge models are driven using perturbed climate data derived from GCMs for a given time-slice and under a certain emission scenario. These are then downscaled to represent the local climate at the site of interest. Typically this is achieved by using the GCM data to generate change factors which are used to perturb an observed historical climate record. Generally, for UK projections, the GCM of choice is one of the Met Office Hadley Centre's coupled models (e.g. HADCM2 and HADCM3; Gordon et al., 2000).

CHALK IN SOUTHERN ENGLAND

There is high agreement in the literature that potential recharge to the Chalk aquifer in the south of England will decrease during the 21st century. However, the magnitude of this reduction is uncertain according to current projections. Cooper et al. (1995) were the first to provide empirical evidence of this by constructing an idealized aquifer/river model of the Lambourn catchment in Berkshire coupled with a SMA model. Regardless of the emission scenario used, they simulated decreases in annual potential recharge to the Chalk aquifer of as much as 21% by 2050. However, these results should be treated with caution, firstly because the emission scenarios were derived from the now dated Climate Change Impacts Review Group (CCIRG, 1991) and were assumed to have no effect on precipitation, only potential evaporation. Secondly, the model used simplistic boundary conditions and aquifer properties, and therefore cannot be assumed to be entirely indicative of the Lambourn catchment.

Later, a study undertaken by Limbrick et al. (2000) used a semi-distributed rainfall-runoff model with climate inputs from three GCMs developed by the Hadley Centre in 1996 to model the River Kennet. Similar reductions in annual recharge were projected as well as significant changes to the recharge season whereby the winter recharge period could be reduced from six months to four months by 2050. They attributed this change to a combination of longer periods of little or no rainfall in the summer, and increased evaporation rates resulting in greater and more persistent soil moisture deficits.

Using a 'high' emissions scenario climate change projection generated by the HadCM3 model in conjunction with the CRU weather generator (Watts et al., 2004), Herrera-Pantoja and Hiscock (2008) investigated the most extreme consequences of a changing climate on recharge over the Chalk of southern England. An analysis of monthly climate projections indicated that precipitation would increase during the wet season

(October – March) and a decrease during the dry season (April – September). The magnitude of these changes increased between 2011 and 2100 resulting in a net reduction of potential recharge by 15, 23 and 39% in the early, mid and late 21st century, respectively.

As part of a study for the Environment Agency, Entec (2008) estimated groundwater recharge during the 2020s using the 4R recharge model (Heathcote et al., 2004) driven by the UKCIP02 (Hulme et al., 2002) medium-high emissions scenario climate projection for the Chalk aquifer of the Test and Itchen catchments. This study projected that by 2020, mean annual recharge to the Chalk could reduce by more than 6%.

Jackson et al. (2011) provide the most recent investigation of Chalk groundwater resources in southern England. Furthermore, they quantify the uncertainty in the projections due to the choice of GCM. Thirteen different GCMs are used to simulate potential recharge over the Malborough and Berkshire Downs and south-west Chilterns. The ensemble average suggested there will be a ~5% reduction in annual potential recharge across the aquifer, although this is not statistically significant at the 95% confidence level. The results for simulated changes in annual potential groundwater recharge ranged from a 26% decrease to a 31% increase by the 2080s, with ten predicting a decrease and three an increase. On average the multi-model results suggested that seasonality will be enhanced with more potential recharge occuring during the winter but for a shorter period of time. Significant changes were simulated to occur during April and October. The ensemble average suggested that potential recharge across the Kennet catchment will decrease from 0.4 to 0.28 mm day^{-1} during April and from 0.62 to 0.29 mm day^{-1} during October.

CHALK IN EAST ANGLIA

There is less agreement about the impact of climate change on recharge to the Chalk aquifer in East Anglia. In an early study Yusoff et al. (2002) estimated these impacts using a SMA model coupled with a two-layer transient groundwater model. Using climate projections based on medium-low and medium-high emissions scenarios, they simulated longer and drier summers for Norfolk with maximum decreases in seasonal potential recharge of up to 35% and 26%, respectively by 2050. These reductions in summer are offset by increased recharge during winter making annual changes less clear (10.4% decrease for medium-low scenario and 1.4% increase for medium-high). Interestingly, they conclude that the 2020s are likely to be wetter with higher annual recharge volumes followed by a decrease in recharge for the 2050s. Herrera-Pantoja and Hiscock (2008) reached a similar conclusion under the most extreme high emission scenario, suggesting that recharge could increase by 14% in the 2020s due to twice the number of wet periods, but then progressively fall by 20% of present rates by 2080. A later study by Herrera-Pantoja et al. (2011), which investigated the impact of climate change on groundwater fed wetlands in Norfolk, supported these findings. In this study recharge was simulated to increase by 15% in the 2020s and to decrease by the 2050s with a 29% reduction in the number of wet events.

Holman et al. (2009) highlight two major complexities surrounding recharge projections under climate change in Norfolk, which can also be considered important across the UK. Firstly, they drive a SMA model using climate change factors derived from 100 different climate datasets output by the CRU weather generator in an attempt to represent the uncertainty distribution of future climate. By doing so, they showed that the choice of downscaling method produced more uncertainty in the projections than the climate scenario. Secondly, they found that the soil type has a significant effect on change in recharge under climate change. In particular, sandy soils were simulated to be less susceptible to change than loamy soils in the Coltishall catchment. Furthermore, they found, contrary to the findings of the previous studies, that the median of the 100 simulations projected a decline of recharge by up to 18% at Coltishall in Norfolk by 2020 and a decline by as much as 37% by 2050.

Permo-Triassic Sandstone in the Midlands

Only three studies have investigated the Permo-Triassic sandstone in the UK, all of which are situated in the Midlands. There is some agreement over future changes, although the small number of studies means that there is limited evidence to support the findings. Cooper et al. (1995) undertook one of the first studies to project changes in recharge over the Permo-Triassic sandstone. Their findings suggested that future recharge in the Teme catchment is highly dependent on the climate change scenario applied. Assuming a low emission scenario, recharge was simulated to increase by 2%. Conversely, a high emissions scenario resulted in a reduction in recharge of 13% by the middle of the 21st century.

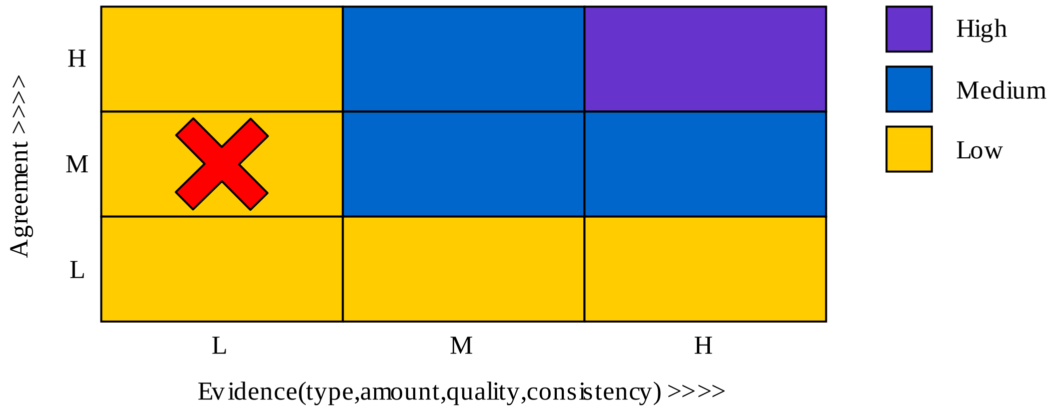
Lewis et al. (2004) and Entec (2008) however, draw more definite conclusions. Both used variations of the Penman-Grindley SMA model driven by UKCIP02 change factors and concluded that annual recharge volumes will reduce by between 8 and 9% by 2020. Lewis et al. (2004) calculated that by 2050, recharge will decrease by between 5 and 21%. However, the lack of other studies in this area means that there is limited confidence surrounding this result.

Devonian and Carboniferous Limestone (DCL)

Herrera-Pantoja and Hiscock (2008) present the only available study on future changes in recharge within a DCL catchment near Paisley, Scotland. They projected that annual recharge will fall by 7% by the end of the century, with the largest reductions (85%) seen in the summer months compared to 2% decreases in winter.

Confidence in the science

Overall, there is medium agreement about changes in mean annual recharge in the UK. There is most agreement for Chalk catchments in southern England, where the length of the recharge season is likely to shorten. However, the studies in other regions provide inconclusive evidence. There are still large regions of the UK where no climate change impact studies on recharge have been undertaken. Even the areas covered so far have few results to compare, and therefore the level of evidence can be described as being limited. The overall confidence in the scientific literature to date for projections of groundwater change in recharge is low.



Groundwater level 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 1×10^{-2} m sec^{-1} for shallow unconsolidated gravel aquifers to less than 1×10^{-6} m sec^{-1} for consolidated sandstone aquifers, while aquifer storage depends on both lithology and the degree of aquifer confinement. It can range from 5×10^{-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.

Research context

Knowledge of potential future changes in groundwater levels is important, not only because they are indicative of the total amount of water stored in an aquifer, but also because they affect the degree to which an aquifer can be exploited. The majority of water that is removed from UK aquifers for human usage is pumped from abstraction boreholes. The maximum amount of water that can be pumped from a borehole is a function of the water level in the borehole, which depends on groundwater levels in the wider aquifer; during drought conditions the drawdown of the water level within a borehole may become excessive, requiring the pumping rate to be reduced. Within the UK the amount of water that can be operationally abstracted from a borehole under different aquifer storage conditions has been assessed using the concept of *deployable output* (Beeson, 2000; Misstear and Beeson, 2000). Deployable output (DO) describes the reliable output of a source, as constrained by aquifer properties and characteristics of the borehole, in addition to constraints imposed by, for example, the environment, licence conditions, water quality and the capacity of the pumping plant, treatment and transfer or output main. Water Companies have a duty, under the Water Act 2003, to report DO estimates for their sources, and to assess how they could potentially change under future climates, as part of the 5-year water resources management planning cycle (Environment Agency, 2011b).

Because of the control that groundwater levels have on the exploitation of the resource, much of the research assessing the impacts of climate change on UK groundwater levels has been funded by the water industry through their research organisation UKWIR. Consequently, the research has generally been applied in nature with the objective of providing practical tools and methodologies that water companies can use to undertake climate impact assessments (UKWIR 2003, 2007). Water companies have undertaken a number of studies of the potential impacts of climate change on their groundwater sources but these are all unpublished.

Potential changes in the spatial and temporal distribution of groundwater levels in the future will also affect groundwater flood risk. Groundwater flooding in the UK occurs predominantly when the water table rises above the land-surface causing groundwater to discharge to normally dry valleys. The most recent series of severe groundwater floods occurred during winter 2000-2001 across the Chalk of southern England (Hughes et al., 2011).

Changes in groundwater levels will result in related impacts on the hydrological cycle such as changes in discharge to baseflow dominated rivers or to groundwater dependent wetlands. Few studies have assessed the impact that future changes in groundwater levels will have on groundwater discharge to surface water but notable exceptions are Herrera-Pantoja et al. (2011) and Jackson et al. (2011). Changes in groundwater levels may also impact saline intrusion into coastal aquifers. Very few studies have examined this potential impact within the UK.

Projections of changes in groundwater levels

Projections of changes in groundwater levels are reviewed first for the Chalk aquifer and then for the Permo-Triassic sandstone. Potential impacts of a change in sea level on groundwater levels are then discussed.

CHALK

Entec (2008) used the 4R recharge model (Heathcote et al., 2004) and a MODFLOW (McDonald and Harbaugh, 1988) groundwater model to investigate groundwater levels under climate change in the Test and Itchen Chalk catchments in Hampshire. They projected a 0.3 m fall in groundwater levels by the 2020s, but used only a single medium-high emissions scenario, and therefore did not consider greenhouse gas emissions uncertainty. However, they did address the issue of potential land use change and found that by introducing a land use change scenario, the groundwater level fell by a further 0.3 m. Jackson et al. (2011) found similar sensitivities in an investigation of changes in groundwater levels across the Malborough and Berkshire Downs and south-west Chilterns. Specifically, they simulated future recharge rates to be lower beneath an area covered by deciduous woodland than less vegetated areas, resulting in year-round reductions in groundwater levels by the 2080s. This highlights the potential significant effect of land cover on the results of impact modelling studies.

Bloomfield et al. (2003) conducted an alternative statistical approach to simulating groundwater levels by finding a multiple linear relationship between monthly rainfall values and annual minimum groundwater levels for a Chalk groundwater catchment in Kent. The model was only able to explain about 50% of the variance in the data. Furthermore, their findings contrast with the other studies in this region and project that annual minimum groundwater levels will increase in the 2020s, followed by a reduction in the 2050s and 2080s to below the present day mean annual minimum level.

Yusoff et al. (2002) provided more evidence of the uncertainty in groundwater level projections under climate change in the Chalk. Their study of the Norfolk Chalk concluded it was not possible to tell whether groundwater levels will rise or fall by the 2020s or 2050s as it depended on the climate scenario chosen. Under a medium-low scenario they calculated that groundwater levels could fall by as much as 4.5 m by 2050 in the winter months, but conversely could rise by as much as 1.6 m in the spring months under a medium-high emissions scenario. Herrera-Pantoja et al. (2011) supported this conclusion after finding that a 25% change in annual recharge would change the groundwater level by as much as 2.7 m in the Chalk near Coltishall, Norfolk.

Permo-Triassic Sandstone

Due to higher specific yields and lower transmissivities, Permo-Triassic sandstones are considered to be less susceptible to changes in groundwater level than Chalk aquifers. Cooper et al. (1995) constructed an idealized, homogeneous model of a sandstone aquifer in central England. Using this simple model, they simulated that aquifer storage could reduce by up to 12% by 2050 under the most extreme climate change scenario. Studies by Lewis et al. (2004) and Entec (2008) support this finding using transient 3D groundwater models in the same region and projected that levels could reduce by as much as 3 m and 1.2 m, respectively by 2050.

Bloomfield et al. (2003) used their statistical approach to project drought frequency in a sandstone catchment in Devon. They suggested that this region will see an increase in annual minimum groundwater levels of 4% by 2080. This contradicts the previous results, possibly because of spatial variations in changes of meteorological variables as well as the modelling method employed.

Coastal Aquifers

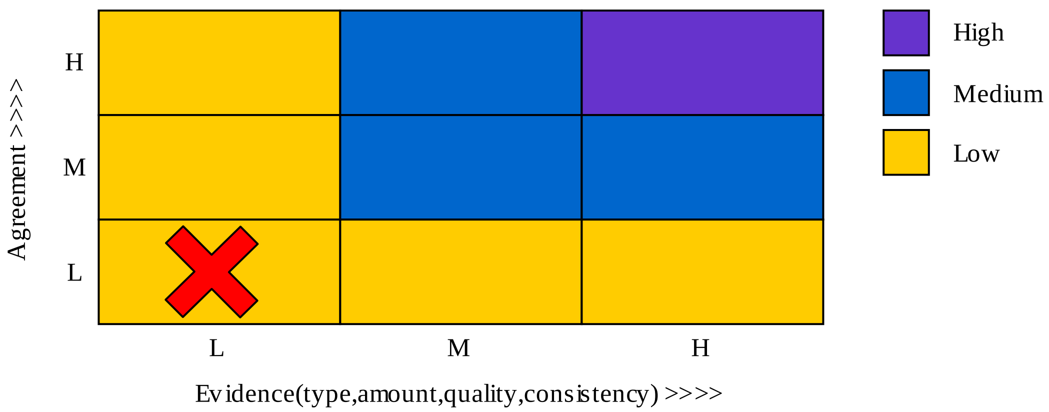
As well as changes in meteorological inputs, it is estimated that the sea level could rise by between 11 and 76 cm under different emissions scenarios by 2100 (Lowe et al., 2010). This could potentially impact on groundwater levels in coastal aquifers by modifying the hydraulic gradient. Cole et al. (1994) conducted one of the first investigations into the effect of sea level rise on groundwater levels and quality by constructing a finite element model coupled to a Ghyben-Herzberg approximation (Bear and Verruijt, 1987) of saline intrusion for three coastal aquifers (Lincolnshire Chalk, Otter Valley sandstone and Brighton Chalk). At all three locations sea level rise was projected to reduce the sustainable yield of the aquifer by 1.5%. However, these results should be interpreted with caution due to the simplistic representation of saline intrusion in coastal aquifers.

Potentially more vulnerable are small shallow coastal aquifers such as the dune slacks in Ainsdale, Merseyside. Clarke and Santiwong Na Ayutthaya (2010) constructed a simple water balance model of these sand dunes to determine groundwater flow. They drove the model with the UKCIP02 medium-high scenario, downscaled using the stochastic CRU weather generator and ran the model from 2005 to 2100. By doing so, they found that sea level rise increased the groundwater level by 0.2 m at a distance of 750 m away from the coast and by 0.08 m one kilometre from the coast. However, the model results were heavily dependent on the stochastic sequencing of the rainfall data generated by the CRU weather generator. More specifically, by generating 500 random sequences of rainfall, the 90% confidence bounds of groundwater level change were between a 0.5 m and 3 m reduction, highlighting another potential source of uncertainty associated with the downscaling of GCM data.

Even without sea level rise, shallow coastal aquifers are still potentially at risk from climate change. Malcolm and Soulsby (2000) investigated the impact of climate change on a groundwater fed wetland coastal dune system in St. Fergus, north-east Scotland. Here, isostatic rebound essentially cancels out any sea level rise projected to occur by 2100. They derived change factors from a number of sources to generate ten climate change scenarios. Although they did not report on groundwater levels, their results implied that changes in meteorological variables alone will have negligible effect on flood frequency of the wetlands.

Confidence in the science

Whilst there is some agreement as to how groundwater levels will change in the future, there are significant differences in current projections due to uncertainty in greenhouse gas emissions scenarios, land use change, vegetation evolution, climate models and downscaling techniques (Yusoff et al., 2002; Herrera-Pantoja et al., 2011; Jackson et al., 2011). An insufficient number of studies have been undertaken. Of those that have been reported few have investigated the effect of multiple sources of uncertainty on the resulting projections. There is low agreement about how groundwater levels will change across the UK, and limited evidence to validate the projections that have been made to date. The overall confidence in the scientific literature for projections of change in groundwater levels is low.



Gaps in the research

The evidence for the impacts of climate change on UK groundwater recharge, resources and levels is limited. The number of studies that have been undertaken is small and different approaches have been adopted to quantify impacts. Furthermore, these studies have generally been focussed on relatively small regions and reported local findings. Consequently, it is difficult to compare between different locations and hard to identify appropriate adaptation responses.

There is a clear need to undertake more research, particularly at the national scale, which adopt consistent approaches, explore the full range of uncertainties and are spatially coherent. This conclusion is supported by the recent comprehensive review of the science relating to the impacts of climate change on groundwater undertaken by Green et al. (In press).

Uncertainty is large in climate change impact modelling. Past groundwater studies have addressed particular sources of uncertainty but none have undertaken a comprehensive assessment of the full range of uncertainty. This is discussed by Holman et al. (2011) who propose best practice guidance for quantifying future changes in groundwater. They propose the following:

i. Use climate projections from multiple climate models.
ii. Use multiple greenhouse gas emissions scenarios.
iii. Consider the implications of the choice of climate downscaling methodology.
iv. Assess model structural error and model parameter uncertainty.
v. Consider the limitations of models in representing changes in plant response to climate change.
vi. Evaluate model performance across a wide range of historic groundwater levels and climate conditions.
vii. Consider socio-economic change, in particular its effect of land-use change and water demand.
viii. Consider potential adaptation measures in response to changes in water resource states.

Aquifers are large stores of water, and with careful management provide the potential to ameliorate the impacts of potentially more severe droughts on both surface water and groundwater supply. The role of aquifers as buffers to impacts needs to be explored through the wider use of regional groundwater models. Many more hydrological models have been used than groundwater models in impact studies but these do not adequately represent delays in the transfer of water from the soil, through both the unsaturated zone and saturated zone, to surface waters and abstraction boreholes.

Estimates of future regional resources need to be linked to the security of groundwater supply. This requires linkages to be made between observations of groundwater level at observation boreholes and the performance, or yield, of an abstraction borehole. This needs to considered within a holistic framework that considers the conjunctive use of both surface water and groundwater resources.

Further research is required not only assess changes in water resources but also to assess potential changes in hazards such as groundwater flooding, or soil moisture controlled land-slides (Collison et al., 2000). This will require improved understanding of changes in climate variability, groundwater flow processes and catchment responses.

Current research

A number of studies investigating the effects of climate change on the UK's groundwater resources are currently ongoing.

The Future Flows and Groundwater Levels project aims to produce a unified national-scale assessment of the effects of climate change on both river flows and groundwater levels across Great Britain using the climate projections from UKCP09 (Murphy et al., 2009). This project has been funded by the Environment Agency, Defra, UKWIR, the Centre for Ecology and Hydrology (CEH), the British Geological Survey (BGS) and Wallingford HydroSolutions (WHS). BGS has applied climate projections to (i) lumped catchment groundwater models of groundwater level time-series at 24 observation boreholes across Britain in the different major aquifers, and (ii) a regional groundwater model of the Chalk of the Marlborough and Berkshire Downs and south-west Chilterns. Projections for changes in groundwater level have been generated based on (i) an 11-member ensemble of transient (1951-2099) climate projection form the Met Office HadRM3 regional climate model and (ii) the UKCP09 ensemble of 10,000 climate change factors for three greenhouse gas emissions scenario and 30-year time slice combinations:

i. 2050s under a medium (A1B) emissions scenario
ii. 2080s under a medium (A1B) emissions scenario
iii. 2050s under a high (A1FI) emissions scenario

The projections for groundwater will be made available through the project web site during April 2012.

The NERC Changing Water Cycle research programme (www.nerc.ac.uk/research/ programmes/cwc) is currently funding one project that is specifically examining changes in groundwater resources under future climate. This project entitled "Hydrological extremes and feedbacks in the changing water cycle (HydEF)" is a collaboration between Imperial College, the University of Reading and the British Geological Survey and is focusing on possible changes in groundwater extreme events: droughts and floods. One of the objectives of the project is to deliver new methods of representing climate extremes and non-stationarity in hydrological models. This involves the identification of hydrologically-relevant climate indices that can be used to improve climate model-to-catchment downscaling techniques for the simulation of extremes. The project is focusing on the Carboniferous limestone and Permo-Triassic sandstone aquifer of the Eden Valley, Cumbria, the Cotswolds Jurassic limestone aquifer and the Chalk of the Thames catchment. A specific objective of the project is to incorporate a representation of groundwater within the JULES land-surface model (Best et al., 2011), to facilitate the simulation of potential feedbacks between groundwater and the climate.

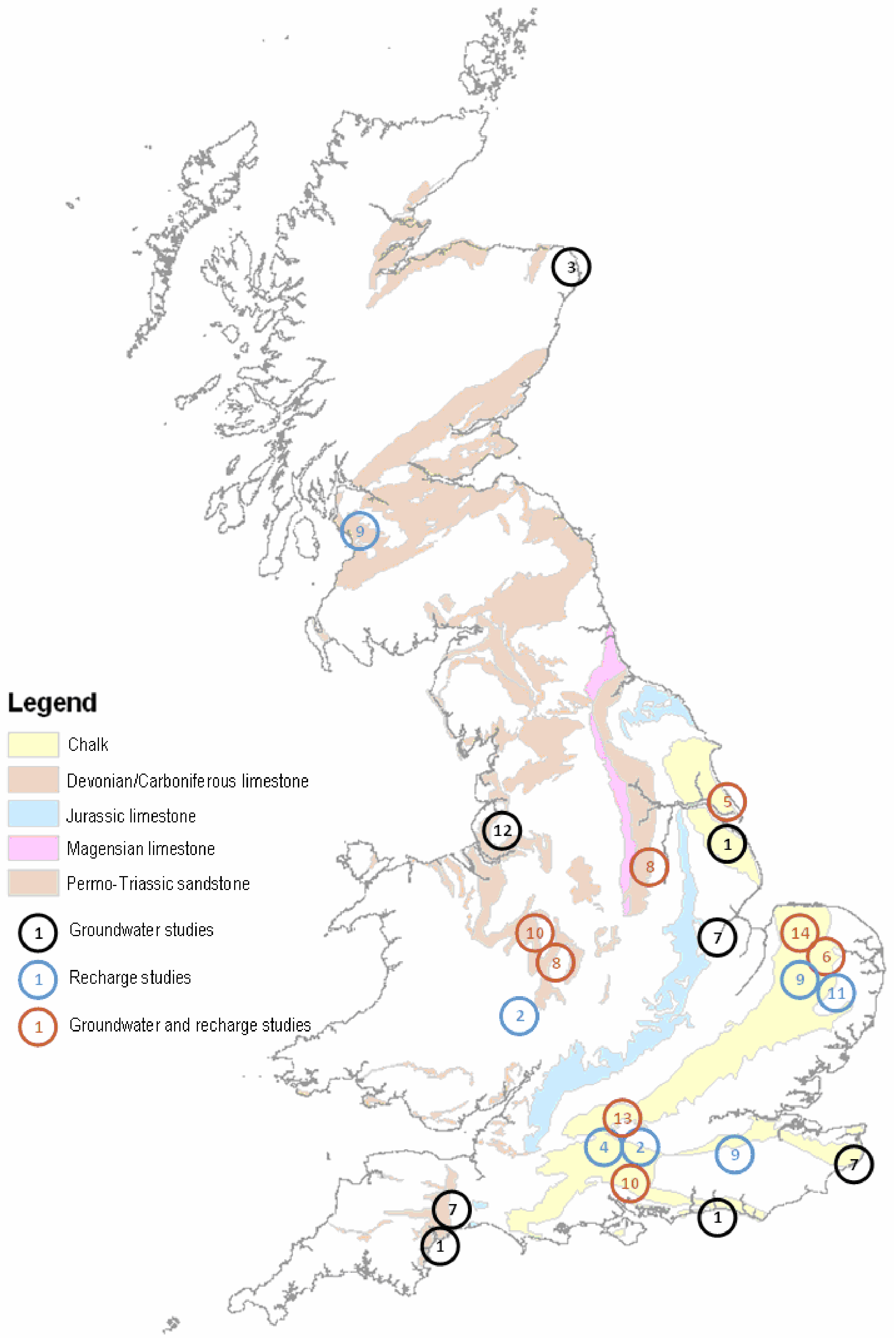


Figure 1 Location of published UK groundwater and climate change impact studies (Numbers refer to Table 1)

Table 1 Summary of published UK groundwater and climate change impact studies

No.	Paper	Region	Aquifer	Emission Scenarios	Projections
1	Cole et al. (1994)	1.South-east (Brighton) 2.South-west (Otter Valley) 3.North-east (Grimsby)	Chalk PT Sandstone Chalk	0.6 m sea level rise	For all aquifers a shift in mean sea level will have a minimal effect with only a 1.5% reduction in sustainable yields.
2	Cooper et al. (1995)	1.South (R. Lambourn) 2. West Midlands (R. Teme)	Chalk PT Sandstone	CCIRG (1991) 1.Low 2.High	Groundwater recharge will reduce by the mid 21st century by between 2% (low scenario) and 21% (high scenario). Under a low emission scenario, recharge will increase by 2% by 2050. Under a high scenario, recharge will decrease by 13% in the same time frame.
3	Malcolm and Soulsby (2000)	East Scotland (St. Fergus)	Coastal sand dunes	10 scenarios from various sources	Climate change will have no negligible effect on flood frequency of groundwater fed wetlands.
4	Limbrick et al. (2000)	South (R. Kennet)	Chalk	HadCM1 and HadCM2	Total annual SMD increases for all years and scenarios resulting in reduced recharge period from 6 to 4 months.
5	Younger et al. (2002)	North East (Humber Estuary)	Chalk		Recharge is predicted to rise by up to 21%.
6	Yusoff et al. (2002)	Anglian (R. Ely)	Chalk	HadCM2 1.Medium-high 2.Medium-low	Overall effect of climate change on recharge and groundwater levels is uncertain and dependent on climate change scenario. Winter and spring recharge will rise in the early 21st century, but then fall by 2050. Under the medium-low scenario groundwater levels could fall by 4.5m by 2050 in the winter months, but may rise by 1.6m in the spring months under a medium-high emissions scenario.
7	Bloomfield et al. (2003)	1.South-west (Exeter) 2.Anglian (Lincolnshire) 3.South-east (Kent)	PT Sandstone Jurassic Limestone Chalk	UKCIP98 1.Medium-high	Annual minimum groundwater levels increase by 4% by 2080 resulting in reduced drought frequency. Annual minimum groundwater levels increase by 12% by 2080 resulting in reduced drought frequency. In the early 21st century drought frequency will reduce. From 2050 to 2080 annual minimum groundwater levels will fall resulting in increased drought frequency.
8	Lewis et al.(2004)	1.East Midlands (Doncaster) 2.West Midlands (Kidderminster-Worfe)	PT Sandstone PT Sandstone	UKCIP02	8% reduction in annual recharge by 2020 and 15-20% reduction by 2050. Groundwater levels will fall by 0.5-1.5m by 2020 and 2-3m by 2050.

9	Herrera-Pantoja and Hiscock (2008)	1.South (Gatwick) 2.Anglian (Coltishall) 3.West Scotland (Paisley)	Chalk Chalk D/C Limestone	HadCM3 + CRU 1.High	Reduced recharge throughout the year (50% reduction in summer and 38% reduction in winter by 2080). Increased recharge in the 2020s throughout the year, but then steadily declines to minimum in 2080s with total annual recharge reduction of 20%. Overall annual reductions in recharge of 10.4%, 10.7% and 7.5% for 2020s, 2050s and 2080s respectively. Increase in winter recharge projected for 2080s.
10	Entec (2008)	1.South (R. Test/R. Itchen) 2.West Midlands (Kidderminster-Worfe)	Chalk PT Sandstone	UKCIP02 1.Medium-high	Annual reduction in recharge of 6% and annual reduction in mean groundwater head of up to 0.6m by 2020s. Annual reduction in recharge of 9% and annual reduction in mean groundwater head of up to 1.2m by 2020s.
11	Holman et al. (2009)	Anglian (Coltishall)	Chalk	UKCIP02 + CRU 1.Low 2.High	100 simulations run using the CRU stochastic generator. Soil shown to effect recharge rates. Over loamy soil, median projected recharge reduction of ~30% by 2050. Over sandy soil, median projected recharge reduction of ~23%.
12	Clarke and Santiwong Na Ayutthaya (2010)	North-west (Ainsdale)	Coastal sand dunes	0.6m sea level rise UKCIP02 + CRU 1.Medium-high	Sea level rise results in 0.2m rise in groundwater level 750m from coastline and 0.08m rise 1km from coastline. 500 random sequences of rainfall data generated gave 90% confidence bounds of groundwater level change between a 0.5m and 3m reduction.
13	Jackson et al. (2011)	South (Malborough and Berkshire Downs and south-west Chilterns)	Chalk	13 GCMs 1.Medium-high	Future recharge will reduce at an 84% confidence level by 2080. 95% bounds span from a 26% reduction in recharge to a 31% increase, with a mean of 4.9% reduction. Groundwater level projections are sensitive to overlying vegetation. Over wooded area, groundwater level projections range from a 0.64m increase in spring and a -3.83m decrease in Autumn. Over open area, groundwater level projections range from a 1.19m increase in spring and a -0.52m decrease in Autumn.
14	Herrera-Pantoja et al. (2011)	Anglian (Coltishall)	Chalk	UKCIP02 1.High	Recharge predicted to increase by 15% over 2020s, then decrease for the 2050s and 2080s. The number of wet events will decrease by 29% in the 2050s. Annual mean groundwater levels will increase by 0.32m in the 2020s, by 0.05m in the 2050s and then decrease by 0.9m in the 2080s.

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