Water in a changing climate: past changes and future prospects for the UK

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ABSTRACT

A changing climate is anticipated to alter hydroclimatological and hydroecological processes across the UK and around the world. This paper builds on a series of reports commissioned in 2012 (WCCRC 2012) that interpreted and synthesised the relevant, peer-reviewed scientific literature on climate change impacts on the water environment in the UK. It aims to provide reliable, clear information about the potential impacts of climate change on hydrology and the water environment in the UK so that this is not a barrier to climate change adaptation. We review new evidence (since 2012) for historical and potential future changes in precipitation and evapotranspiration, followed by river flows and groundwater levels, then river and groundwater temperature and quality and finally in aquatic ecosystems. Some new evidence exists for change in most components reviewed and is typically in support of spatial and temporal changes reported in WCCRC 2012. However, it remains the case that more research has been conducted on rainfall and river flows than evapotranspiration, groundwater levels, river and groundwater temperature, water quality and freshwater ecosystems. Consequently, there remains a clear disparity of robust evidence for historical and potential future change between the ‘top’ and ‘bottom’ of the hydroclimatological-hydroecological process chain. As was the case in WCCRC 2012, this is a significant barrier to informed climate change adaptation in these components of the water environment.

Key words: Climate change, climate change impacts, water, water environment, hydrology, hydroclimatology, hydroecology, adaptation

1. INTRODUCTION

The availability of reliable, clear information about the potential impacts of climate change on hydrology and the water environment remains a barrier to climate change adaptation in the United Kingdom, and worldwide (Watts et al., 2015a). To address this stumbling block, a series of reports were commissioned in 2012 (WCCRC 2012 herein) that interpreted and synthesised the relevant, peer-reviewed scientific literature on climate change impacts on the water environment in the UK. This paper aims to update the findings of those reports by reviewing the relevant literature published since 2012. Specific objectives are as follows: (1) to synthesise the evidence of ***historical changes*** to UK hydrology and the water environment (section 2), (2) to summarise ***projected changes for the 21st century*** (section 3), and (3) to identify the ***outstanding research needs*** to improve understanding of the water-related impacts of climate change (section 4).

As for WCCRC 2012, we review the evidence for changes along the hydroclimatological process chain and into the hydroecological process chain. Specifically, we review new evidence for historical and potential future changes in precipitation and evapotranspiration, followed by river flows and groundwater levels, then river and groundwater temperature and quality. Finally, we review new evidence for change in aquatic ecosystems. The paper is focused primarily on observed and projected change in components of the water environment that are modified by anthropogenic climate change. There are multiple, often interlinked, confounding factors that may have influenced any detected changes; therefore, unless all other possible causes can be excluded then changes are not, and indeed should not be, attributed to human modified climate change.

2. HISTORICAL CHANGES

In this section, scientific evidence of historical changes to the UK water cycle published since 2012 is reviewed.

2.1 Precipitation and evapotranspiration

WCCRC 2012 reported small, but significant, increases in winter rainfall intensity and duration and increased intensity of long-duration summer rainfall; however, there was no evidence to suggest that these trends were driven by anthropogenic climate change (Watts et al., 2015b). Since 2012, studies have focussed on specific regions (e.g. Afzal et al., 2015; Kosanic et al., 2014), used new datasets (Kosanic et al., 2014; Simpson and Jones, 2014) and/or methods (e.g. Jones et al., 2014; Prosdocimi et al., 2014) to analyse historical change at annual and seasonal timescales.

At the annual timescale, significant positive trends have been detected in rainfall totals within Scotland (Afzal et al., 2015, period 1961-2000) and also in the magnitude of extreme rainfall events (i.e. maxima) in the north, especially Scotland, (e.g. Prosdocimi et al., 2014, period 1961-2010; Jones et al., 2014, period 1961-2010) and west (Jones et al., 2014) of the UK. Significant decreases are observed in the magnitude (Jones et al., 2014) and intensity (Kosanic et al., 2014, period 1975-2010) of extreme precipitation events in southern regions. However, no significant positive or negative trend is observed in annual extreme events across the majority of the UK (Prosdocimi et al., 2014).

Seasonally, average rainfall and rainfall intensity have increased significantly in winter months (December, January and February) throughout the UK, with the greatest changes observed in Scotland (Simpson and Jones, 2014, period 1932-2010; Wilby and Quinn, 2013, period 1871-2011). Winter rainfall maxima have increased in the north of England and Scotland, and summer maxima have decreased in the south of England (Prosdocimi et al., 2014). Afzal et al. (2014), Kosanic et al. (2014) and Simpson and Jones (2014) propose that the trends they detected may be linked to natural periodicities associated with the North Atlantic Oscillation (NAO). The NAO may have been enhanced by a changed climate (Simpson and Jones, 2014); however, this hypothesis has not been tested systematically. There remains insufficient evidence to propose a link between anthropogenic climate change and these reported changes in precipitation. This is unsurprising, since it has been suggested that a link may not become evident until the 2050s (Fowler and Wilby, 2010).

WCCRC 2012 reported only one study (for a single site) of historical changes in evapotranspiration (evaporation to the atmosphere from soil and water surfaces, and vegetation; Kay et al., 2013) in the UK, which demonstrated an increase in potential evaporation (PE, the amount of moisture lost to atmosphere if there are no limits on water-supply; Federer et al., 1996) and a decrease in actual evaporation (AE, loss of moisture limited by soil wetness; Kay et al., 2013). In 2012 there was no evidence to suggest a link between anthropogenic climate change and changes in evapotranspiration. There remains no published study with national coverage of historical changes (Kay et al., 2013). However, Clark (2013) reports on changes in AE and PE at a site in the upper Brue catchment, Somerset. No consistent trend was observed in PE over the period 1986-2010; PE increased by ~50 mm between 1986 and 1996 but declined thereafter, by ~30 mm. AE decreased by ~15% between 1996 and 2008, which is consistent with observations made using the global FLUXNET dataset (see Jung et al., 2010). Consequently the decrease in AE may be representative of a wider area (Clark, 2013), although this hypothesis was not tested. Changes in AE and PE were significantly correlated with air temperature and precipitation respectively, but not linked to anthropogenic climate change.

2.2 River flows and groundwater levels

The 2012 report card synthesised numerous spatially and temporally extensive studies of large-scale changes in river flow throughout the UK. There have been no further studies of change in annual, seasonal or monthly average river flow regimes or low flows/ droughts. However, further studies have used new statistical methods (e.g. Prosdocimi et al., 2014) or used long-term qualitative datasets (e.g. Stevens et al., 2014) to provide further evidence of change and/or variability in high river flows and floods. Prosdocimi et al. (2014) agree broadly with evidence first presented by Hannaford and Marsh (2008) of increased annual maxima in northern England, northern Scotland, and south Wales, and increased winter maxima in northwest England. As of 2012, studies had not observed a clear pattern of change in summer flows; however, Prosdocimi et al. (2014) observed downward trends in south and southeast England and upward trends in Northern Ireland, north and west Great Britain. There remains (after Watts et al., 2015b) little compelling evidence for any long-term increase in flood frequency. Muchan et al. (2015) suggest that flood magnitude (defined as the water year [October-September] maximum flow) decreased in the River Thames between the 1880s and 2014. Stevens et al. (2014) observed an increase in reported flood events during the late 20th and 21st century and significant inter-decadal variation in ‘flood-rich’ and ‘flood -poor’ periods (such periods were also observed by Wilby and Quinn, 2013). However, no long-term trend was evident once the datasets were normalised by population size and number of dwellings (to account for bias in a dataset that relied on public reports of flooding) (Stevens et al., 2014).

No studies existed in 2012 of historical changes in groundwater level within the UK, and consequently no links with anthropogenic climate change could be made. Since WCCRC 2012, groundwater level data from seven boreholes located on the Chalk aquifer were analysed by Jackson et al. (2015). Each record was > 40 years long and part of the UK’s long-term observation borehole network. Groundwater levels declined significantly at four sites, including at two sites with the longest records. Climate change was postulated as a driver for the observed declines, but could not be attributed definitively to an anthropogenically modified climate (Jackson et al., 2015). Indeed, Lavers et al. (2015) demonstrate that groundwater levels are linked strongly to meteorological variability (i.e. sequences of atmospheric patterns, water vapour transport and, in turn, precipitation). Furthermore, Jackson et al. (2015) state that the groundwater systems they studied could have been influenced by changes in abstraction and/ or resource management practices.

To summarise, there remains little evidence of change in groundwater levels and low flows across the UK. However, studies published since 2012 broadly corroborate evidence of change presented in WCCRC 2012 (i.e. high flows have increased, particularly in the north and west but there is no evidence of change in flood frequency). Furthermore, previously undetected changes in summer maxima demonstrate increases in Northern Ireland, the north and west of the UK but decreases in south and south east England. However, none of the observed changes have been attributed to anthropogenic climate change.

2.3 River and groundwater temperature, quality and freshwater ecosystems

There remains (after Watts et al., 2015b) scarce information on historical changes in groundwater temperature in the UK and no investigation of links to anthropogenic climate change; no new studies have been published since 2012. Studies of historical changes in river water temperature are also scarce but generally report increases (Watts et al., 2015b; Hannah and Garner, 2015). Orr et al. (2015) applied sophisticated trend detection methods to a subset (2,773 sites) of the dataset used by des Clers et al. (2008; as described in WCCRC 2012) to identify temperature increases at 86% of locations, and a mean annual increase in water temperature of 0.03 °C year^{-1} (also the rate reported by des Clers et al., 2008) for the period 1990-2006. This change is similar to increases in air temperature over the same period (as reported by Jenkins et al., 2008) and was inferred to be driven (in the absence of other systematic influences) by anthropogenic climate change. Garner et al. (2014) analysed the same dataset but observed no trend in the frequency of occurrence of shape (timing of features) or magnitude (size) of annual river temperature regime classes for the period 1989-2006.

WCCRC 2012 suggested that changes in river water quality have occurred and were driven predominantly by changes in land-use (e.g. Battarbee et al., 2014; Malcolm et al., 2014; Montieth et al., 2014), land-management (e.g. Battarbee et al., 2014) and pollution (e.g. Howden et al., 2010; Curtis et al., 2014; Watts et al., 2015b). However, there remains no evidence to suggest a link between anthropogenic climate change and historical changes in river water quality (after Watts et al., 2015b). There remain (after Watts et al., 2015b) no studies that link historical change in groundwater quality to anthropogenic climate change. Studies published since 2012 have considered industrial (e.g. Rivett et al., 2012) and agricultural sources of pollution (Zhang et al., 2013), but not anthropogenic climate change.

WCCRC 2012 reported that freshwater ecosystems should be considered to be among the most sensitive to anthropogenic climate change (after Durance and Ormerod, 2007, 2009) because they are influenced by many interacting factors (i.e. discharge, light, water temperature, nutrient availability, habitat connectivity, species interactions and management practices; Laize et al., 2014). However, due to a lack of long-term, systematic records there were only a few geographically isolated studies that supported this statement (i.e. Clews et al., 2007; Durance and Ormerod, 2007, 2010). Since 2012, Vaughan and Ormerod (2014) used data collected in 21 sampling years (1991-2011) from > 2300 rivers across England and Wales to detect evidence of climate-induced changes in spatial distribution of freshwater invertebrate taxa, but identified no clear evidence of a climate change influence. Instead, the only observation consistent with climate warming (i.e. a northward expansion of the range of many taxa) was accounted for by water quality improvements in northern England. However, taxa were extremely sensitive to shorter-term (< 2 years) inter-annual variation in temperature and discharge. Therefore, some of the long-term changes observed may have been driven by a changing climate, but these were not as influential as changes in the magnitude and geographical extent of water quality improvements (Vaughan and Ormerod, 2014). There remains little historical evidence to suggest that freshwater ecosystems have responded to anthropogenic climate change. An environment of improved water quality should allow ecological responses to climate-induced drivers (such as discharge and temperature) to be more easily identified (Durance and Ormerod, 2009) as long as long-term, systematic data collection continues.

2.4 Summary of historical changes and links to anthropogenic climate change

Changes have been detected in most parts of the UK water environment during the last century; however, groundwater quality is a notable exception. As was the case in 2012, there has been no robust, formal attribution of observed changes in any component of the UK water environment to anthropogenic climate change. Nonetheless, there is further systematic, spatially and temporally comprehensive evidence for change, especially in precipitation and river flows. Less evidence is available for evapotranspiration, groundwater levels, river and groundwater quality (including water temperature) and freshwater ecosystems.

Confidence assessments for the level of agreement for evidence of historical changes and the robustness of that evidence for each reviewed component of the UK water environment are provided in Table 1.

3. POTENTIAL FUTURE CHANGES

This section considers the impact of projected climate changes on the UK freshwater environment over the 21st century. Most of the studies presented used a simulation model-based framework to make projections. The dynamics of future climate must be projected before these data can be used to project future hydrological characteristics. Within this framework, general circulation models (GCMs, often using an ensemble approach to represent climate model uncertainty) are used to simulate global climate processes and account for anthropogenically driven increases in greenhouse gas concentrations (see Prudhomme et al., 2003). Then, because GCMs model climate at coarse resolution (50- 100 km; Maraun et al. 2010), outputs are sometimes downscaled to smaller spatial domains (12-50 km; Maraun et al. 2010) using regional climate models (RCM) or statistical methods (see Wilby et al., 1998; Prudhomme et al., 2003; Wood et al., 2004). In turn, these climate data are used to drive (sometimes multiple, to account for uncertainties in hydrological and associated model structure) process-based models of projected changes in the water environment.

3.1 Rainfall and evapotranspiration

WCCRC 2012 reported on projected changes to annual and seasonal precipitation across the UK. Projections of extreme precipitation during spring, summer and autumn were reported too, but at this time climate models were deemed unreliable at representing heavy and short-duration events (Fowler et al., 2007) that occur often in the UK during summer months (Garner et al., in press). Recently, the first long-term (20-years) simulations were performed with a ‘convection-permitting’ model (as used for short-range weather forecasting) that operates on a very fine resolution grid (1.5 km), which permits more realistic representation of convection over the UK and thus hourly rainfall characteristics, including extremes (Kendon et al., 2012; Kendon et al., 2014). When driven by a single climate model and run for the southern UK, the convective-permitting model indicated that the intensity of short-duration rainfall would increase by around 10% across a range of return periods during summer months (June, July and August), but that dry spells would become longer (Chan et al., 2014; Kendon et al., 2014). Winter precipitation (December, January and February) was also projected to intensify by ≥ 40% across a range of return periods. Although the convective-permitting model incorporates improved process representation, it is computationally very expensive to run (Kendon et al., 2014). Consequently, model results to date are based on one climate model (i.e. Met Office Unified Model) and one emissions scenario (i.e. Intergovernmental Panel on Climate Change RCP [representative concentration pathway] 8.5, highest greenhouse emissions of all scenarios; Riahi et al., 2010) and so uncertainty arising from model structure and emissions scenario has not been assessed (Kendon et al., 2014).

Projections of potential evapotranspiration (PE) are highly dependent on the method of calculation used (Prudhomme and Williamson, 2013), as demonstrated by Sheffield et al. (2012) and Dai et al. (2013). Furthermore, they are confounded further by poor understanding of possible changes in plant transpiration and growth (Kay et al., 2013a; Van den Hoof et al., 2013). Most projections indicate annual PE increases, but some project decreases for some months (Kay et al., 2013a; Prudhomme and Williamson, 2013). Prudhomme and Williamson (2013) projected percentage changes in PE using 12 equations of varying complexity driven by the Hadley Centre's HadRM3-Q0 model outputs representative of 1961-1990 (with MORECS PET used as reference PE) and 2041-2070. In broad agreement with the studies reported in WCCRC 2012, Prudhomme and Williamson (2013) project predominantly increased PE across the UK. The largest increases in PE were anticipated in northwestern Great Britain in January, while the smallest were anticipated in the same region in July and October. Exact magnitudes were largely dependent on the method of calculation: *Turc*, *Jensen-Haise* and calibrated *Blaney-Criddle* methods systematically projected the largest increases across Great Britain in all months while *Priestly-Taylor*, *Makkink* and *Thornthwaite* projected the smallest (Prudhomme and Williamson, 2013). Prudhomme and Williamson (2013) recommended the use of the *FAO56* method which reproduced the reference MORECS PE data with greatest accuracy (when driven by the HadRM3-Q0 climate data) and was within the range of uncertainty defined by the ensemble of 12 PE equations.

3.2 River flows and groundwater levels

WCCRC 2012 reported regional and seasonal variability in projected river flows derived from various global climate models (GCMs), or ensembles thereof, which had been forced by different emissions scenarios, sometimes followed by differing downscaling approaches and subsequently methodologies for modelling river flows, all with associated uncertainties. Projections of seasonal river flows (i.e. increased winter flows, decreased summer flows and low agreement between models on the direction of change during spring and autumn) reported in WCCRC 2012 (by Christierson et al., 2012 and Prudhomme et al., 2012) are confirmed broadly by a subsequent study conducted by Sanderson et al. (2012). Sanderson used runoff data from an eleven-member regional climate model (RCM, HadRM3) ensemble (Jones et al., 1997) driven by the SRES A1B (i.e. medium emissions) scenario (Nakićenovć and Swart, 2000). Projected increases in winter flows are greater than decreases in summer flows, driving an overall increase in annual average river flow during the 21st century (Sanderson et al., 2012, also projected for the Eden catchment in Scotland by Ledbetter et al., 2012). This is in contradiction of Christierson et al. (2012) and Prudhomme et al. (2012); these authors projected smaller increases in winter flows and, therefore, little change in annual flow regimes. Notably, Sanderson et al. (2012) used runoff data generated within an ensemble of RCMs, as opposed to using the climate data output from the RCM to drive a conventional 'offline' hydrological model (e.g. Christierson et al., 2012 and Prudhomme et al., 2012). Furthermore, the eleven-member RCM data do not sample the full range of uncertainties (Murphy et al., 2009) (unlike the UKCP09 probabilistic projections used by Christierson et al., 2012), and so the range of possible future river flows is likely greater than those projected (Sanderson et al., 2012).

Drought projections reported in WCCRC 2012 were limited because studies had considered meteorological droughts (i.e. precipitation deficit; Garner et al., in press) predominantly. Prudhomme et al. (2014) investigated the effect of climate change on hydrological droughts (i.e. river flow deficit, Garner et al., in press) in a multimodel experiment in which seven global impact models (GIMs, which represent the terrestrial water cycle at global scale and incorporate current understanding of hydrological systems) were driven by seven GCMs under four representative concentration pathways (RCPs, each is a time-dependent projection of atmospheric greenhouse gas concentrations). Under RCP 8.5, Prudhomme et al. (2014) anticipate that drought frequency (proportion of time under drought conditions) and severity (defined as proportion of land under drought conditions) are very likely to increase across Western Europe by the end of the 21st century. Two drivers of increased drought frequency and severity were identified: (1) the greatest increases were driven by decreased precipitation and increased evaporation, and (2) lesser increases were associated, paradoxically, with increased precipitation (up to 20%) that was offset by increased evaporation (Prudhomme et al., 2014). These projections are in agreement with Vidal and Wade (2009) and Rahiz and New (2013) but contradict Blenkinsop and Fowler (2007) (all reported in WCCRC 2012); the latter suggested that the longest meteorological droughts are likely to become shorter and less severe.

WCCRC 2012 anticipated increases predominantly in flood magnitude controlled by climate and physical characteristics of river catchments (Prudhomme et al., 2013a; 2013b). Kay et al. (2014a and 2014b) extended the work of Prudhomme et al. (2013a and 2013b; as reported in WCCRC 2012) to a larger set of catchments across Britain and projected regional impacts of climate change on 20-year flood flows during the 21st century. Predominantly, increases were projected between the 2020s and 2080s (also projected for the Derwent basin by Ramesen et al., 2014). For England and Wales, changes were greatest in the south east and smallest in the north east while impacts were described as median elsewhere (Kay et al., 2014a). For Scotland, increases were greatest but more uncertain in the north and west, and lower but less uncertain in the south and east (Kay et al., 2014b). A monotonic change in flood impacts throughout Britain is not anticipated; the range of impacts within Scotland was projected to be less severe than in England and Wales (i.e. no change < -5% or > +75%; the latter is projected for the 2080s in south eastern England) (Kay et al., 2014b). Geographical variation in past river flows and, by extension projected river flows, is controlled by variability in climate and basin processes (Garner et al., in press). Charlton and Arnell (2014) applied the UKCP09 projections (for the 2020s, 2050s and 2080s) to catchment models for six catchments representing a range of hydrological conditions in England. Their results suggest that the magnitude of future high flows may be especially sensitive to basin geology; *Q5* (the flow that is exceeded 5% of the time) could increase by 40-50 % in impermeable catchments compared to 20% in permeable catchments.

WCCRC 2012 reported on a handful of studies that investigated the impact of climate change on UK groundwater recharge (i.e. the downward vertical flux of water to the water table, Jackson et al., 2015). Typically, reductions in annual recharge are projected (Jenkins et al., 2002; Herrera-Pantoja and Hiscock, 2008; Jackson et al., 2011). Previously unreported results of a study by Prudhomme et al. (2012) are presented by Jackson et al. (2015). Prudhomme et al. (2012) used two climate projection products: (1) the ensemble of eleven-member ensemble of the UK Met Office Regional Climate Model (HadRM3-PPE) as continuous time-series of climate variables from 1950 to 2099 (Prudhomme et al., 2013a), and (2) probabilistic projections of changes in climate variables as ensembles of 10,000 monthly change factors for the following three 30-year time-slice and greenhouse gas emission scenario combinations (i.e. 2050s and medium emissions scenario [A1B]; 2080s and medium emissions scenario [A1B]; and 2050s and high emissions scenario [A1F1] (Murphy et al., 2009)]. These climate projections were input to the distributed ZOOMQ3D groundwater model (of the Chalk aquifer) (Jackson et al., 2011) and to

R-Groundwater (Jackson, 2012) lumped catchment groundwater models (of 24 observation boreholes in four principal aquifer types: Chalk, Limestone, Sandstone and Lower Greensand across Great Britain). When the median values for the ensemble of 10,000 simulations are considered, annual groundwater levels are projected to decrease at 13 of 24 sites. For monthly values, the direction of change varied: (1) between sites, assumed to be driven by local hydrogeological conditions, and (2) between years, assumed to be due to inter-annually variable meteorological drivers. Prudhomme et al. (2012) reported projections forced by the A1F1 (high) emissions scenario; Jackson et al. (2015) compared these with projections forced by the A1B (medium) scenario in order to assess the sensitivity of the projected values to this source of uncertainty. However, the impact of multiple emissions scenarios on the projections was deemed to be small in comparison to the spread of uncertainty arising from the variability in the climate ensembles. Furthermore, there is some discussion but, as yet, no quantification of potentially substantial uncertainty that may arise from the models used to represent hydrological/ hydrogeological processes (Taylor et al., 2015). Jackson et al. (2015) suggest that hydrological models are used preferentially over groundwater models and that they do not represent key groundwater processes adequately (e.g. delays in the transfer of water from the soil, through both the unsaturated zone and saturated zone, to surface waters and abstraction boreholes).

3.3 River and groundwater temperature, quality and freshwater ecosystems

The published literature contains no new projections of UK river and groundwater temperature since 2012. Consequently, there remains extremely little knowledge of how these properties of the UK freshwater environment will change over the 21st century. River temperature is anticipated to increase (Webb and Walling, 1992); but modifications are likely to be moderated by river basin characteristics, for example water source contributions, basin size (Garner et al., 2014a) and orientation (Hannah and Garner, 2015) plus density and extent of riparian shade (Garner et al., 2014b, 2015). Worldwide, there are extremely few comprehensive projections of increases in groundwater temperature. For the Miramichi river system in central New Brunswick, Canada, Kurylyk et al. (2014) used seven downscaled global climate models for the period 2046-2065 to drive surficial water and energy balance models and, in turn, a variably saturated groundwater flow and energy transport model; groundwater temperature was projected to increase by up to 3.6 °C.

There are no new projections of UK river or groundwater quality and, as was the case in 2012, projections are qualitative and somewhat speculative. Potential changes in precipitation intensity, water temperature and discharge are anticipated to have consequences for UK surface water quality with increased suspended solids, sediment yields, algal growth and nutrient concentration expected (Watts et al., 2015b). Potential changes in groundwater quality may be driven by changing recharge rates plus pollutant and nutrient transport (Watts et al., 2015b).

Finally, the impact of projected climate change on freshwater ecosystems is understudied. This is likely because water-dependent organisms are influenced by various aspects of their habitat conditions, many of which remain poorly understood and for which there exist no projections of future change (see above). In a notable exception, Fung et al. (2013) used 246 transient climate series (based on one GCM) to generate an ensemble of illustrative (given the limited number of simulations) projected river flows in the Itchen (a Chalk basin in southern England) through the 21st century. The severity and duration (in years) of low flow events within the ensembles were used to identify qualitatively (after discussion with ecologists and catchment managers) the range of possible consequences for freshwater ecosystems based on invertebrate community responses. 40% of models suggested that there may be significant changes to freshwater invertebrate communities in the Itchen by 2075; while the remaining 60% of models suggested that communities may recover from the short-term impacts of low flow events (Fung et al., 2013). Consequently, the anticipated effects of anthropogenic climate change on freshwater ecosystems and potential spatial variations remain highly uncertain (Watts et al., 2015b).

3.4 Summary of future projections

The scientific literature published since WCCRC 2012 provides further evidence that the impact of anthropogenic climate change on the UK water environment may be significant. Further evidence suggests that changes in rainfall, evapotranspiration, riverflows and groundwater levels should be anticipated. The robust numerical framework within which these anticipated changes have been estimated and the consideration of multiple uncertainties provides high confidence limits to bound future projections. However, as was the case in 2012, a robust scientific evidence base to suggest future change in river and groundwater temperature, water quality and freshwater ecosystems is lacking severely and thus confidence in the nature of future changes is low.

Confidence assessments for the level of agreement for potential future changes and the robustness of that evidence for each reviewed component of the UK water environment are provided in Table 2. Confidence assessments for the level of agreement in future projections were provided in WCCRC 2012. We have revised the assessment for evapotranspiration, from ‘low’ (because no projections existed) to ‘medium’ following the generation of a set of projections from multiple methods and quantification of associated uncertainties. .

4. OUTSTANDING RESEARCH NEEDS

This review aimed to update the findings of WCCRC 2012 and thus provide further reliable, clear information about the possible impacts of climate change on hydrology and the water environment in the UK. In this section we identify the outstanding research needs to improve understanding of the water-related impacts of climate change.

WCCRC 2012 identified several areas where research efforts should be focussed: (1) evapotranspiration, (2) low flows and drought, (3) summer convective storms and consequences for future flood, (4) groundwater temperature, (5) river and groundwater temperature and quality, and (6) aquatic ecosystems. Despite growth since 2012 of the scientific literature on climate change impacts on the UK water environment, there has been little research in these areas (summer convective storms are a notable exception, although the effects of improved modelling capability in this area have not been assessed on summer floods). Instead, there has been further research on areas (i.e. precipitation and high river flows/ flood) for which a (relatively) larger amount of information existed already. Consequently, more research in all of the areas identified as priorities in 2012 is still required. Importantly, the body of evidence for historical changes and the number of future projection studies shrink and uncertainties grow as we move down the hydroclimatological process chain and into the hydroecological process chain (see Tables 1 and 2).

The disparity between historical evidence at the ‘top’ versus the ‘bottom’ of the hydroclimatological-hydroecological process chain has most likely occurred because there has been a lack of spatially and temporally extensive monitoring of variables towards the bottom of the chain. Furthermore, components of the water environment at the bottom of this process chain are influenced by multiple, interacting drivers and understanding of responses is poor, and so observed patterns are confounded by shifts in other drivers of change. Consequently, for most aspects of the UK water environment, adaptation to anthropogenic climate change may need to begin before changes can be formally attributed (Watts et al., 2015b). A disparity of evidence between the top and bottom of this chain exists also for projections. Poor knowledge of interacting drivers, responses and interactions at the bottom of the chain yields an insufficient evidence base from which to build predictive models capable of projecting the effects of anthropogenic climate change. Additionally, the discussed lack of spatially and temporally extensive data (and meta-data) does not allow validation of models. Finally, other than for precipitation and river flow, future projections of other hydrologically –relevant variables consider rarely uncertainties for estimates. For these other variables, there remains incomplete process understanding and/ or validation data, so making projections with confidence is made particularly challenging.

WCCRC 2012 identified that most studies were site-specific whereas countrywide studies were most useful in providing decision-support for adaptive management. Again, there have been further large-scale precipitation and river flow (i.e. at the top of the hydroclimatological-hydroecological process chain) (for which existing information was relatively good) but a distinct lack of studies on other aspects of the water environment. Again, this is due predominantly to a lack of monitoring and (potentially) ease of access to archived data that may be held by several individuals. Such barriers to knowledge generation must be addressed and the impacts of climate change on all aspects of the UK water environment must be studied to provide robust, clear information to inform management and adaptation strategies going forward.

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TABLES

Table 1. Confidence assessment for observed historical changes in components of the UK water environment during the 20th century. Each component is awarded a score of high (H) medium (M) or low (L). Scores address evidence for change but not whether this was driven by anthropogenic climate change

Component of water environment	**Level of agreement**	**Amount of evidence (type, amount, quality, consistency)**
Precipitation	H	M
Evapotranspiration	L	L
River flows	L	M
Groundwater recharge and levels	L	L
River water temperature	M	M
River water quality and ecology	L	L
Groundwater temperature and quality	L	L

Table 2. Confidence assessment for projected future changes in components of the UK water environment over the 21st century. Each component is awarded a score of high (H) medium (M) or low (L).

Component of water environment	**Level of agreement**	**Amount of evidence (type, amount, quality, consistency)**
Precipitation	M	M
Evapotranspiration	M	M
River flows	L	L
Groundwater recharge and levels	L	L
River water temperature	M	M
River water quality and ecology	L	L
Groundwater temperature and quality	L	L