A Climate Change Report Card for Infrastructure

Working Technical Paper

Potable Water: water supply, treatment and distribution systems

Steven D Wade
Met Office, Fitzroy Road, Exeter EX1 3PB United Kingdom
E-mail: steven.wade@metoffice.gov.uk

Abstract

This paper considers the potential impacts of climate change on water supply, treatment and distribution in England and Wales. It finds that there is wide recognition of impacts in the water industry but limited evidence of impacts in these specific areas in the peer reviewed literature. It focuses on four impacts: the demand for household water supply; changes in water quality that affect water treatment processes; pipe bursts that affect water distribution and leakage and finally flood impacts on water company assets. It briefly considers the management of risks and adaptation planning by water companies and draws some conclusions on three of the selected impacts, rating increased flood risk as the main climate change threat to water supply infrastructure.

1. Introduction

In the UK, water supplies and sewerage services are delivered by 26 water supply and water and sewerage companies[1,2]. In 2012/13 these companies invested £4.5 billion and spent around £5 billion on providing their services, which provide essential public health and environmental benefits to the UK economy. The long term nature and significant value of water company investments requires consideration of climate change and other sensitivities, including future energy costs, changes to environmental regulation, population growth and economic growth. For this reason the industry has been actively involved in climate change adaptation since the 1990s, with strong commitments on environment improvement and inclusion of climate change in long terms plans with horizons of 25 to 40 years (Charlton and Arnell. 2011; EA, 2012; Ofwat, 2008a; 2008b, 2010). Although initial climate change assessments focused on capital expenditure, water availability and sewerage, more subtle long term impacts and operational sensitivities are now being explored with the aims of reducing operational expenditure, improving resilience and reducing long term risks.

The impacts of climate change on river flows, groundwater, reservoir storage and water availability has been covered in detail elsewhere, including the LWEC Water Report Card (e.g. Charlton and Arnell, 2011; Christierson et al., 2012; Prudhomme et al., 2012; Watts et al., 2013). This paper focuses on the impacts of climate change on water supply, treatment and distribution systems whereas [Sayers et al., 2014] considers the impacts of sewerage systems. It considers water supply, treatment systems and distribution systems that are the responsibility of water companies. These infrastructure systems include reservoirs, abstraction systems, bank side storage, raw water transfers (gravity flow or pumped), water treatment, distribution networks including storage reservoirs, pumps and boosters and supply pipes to the point of delivery to customers. Systems may include desalinisation plants, although there is currently only one major plant in the UK providing up 40 Ml/d to London during peak demand periods.

[1] http://www.water.org.uk/home/our-members/list-of-companies

[2] A very small proportion, around 1%, of rural households maintain a private water supply http://dwi.defra.gov.uk/stakeholders/private-water-supplies/

This paper adopts a narrow definition of the water supply system, excluding private water supplies, the broader supply chain and complex links with energy and other systems. Section 2 introduces the UK Climate Projections 2009 (UKCP09) that have been used for climate change impacts, adaptation and vulnerability assessments in the water sector, highlights the vulnerability of water systems as evidenced by recent events and then describes the potential impacts of climate change. It is based on the peer reviewed literature and grey literature (guidelines and consultancy reports) used in the UK water industry. Following a very broad overview it focuses on four impacts: the demand for water; changes in water quality that affect water treatment processes; pipe bursts that affect water distribution and leakage and finally flood impacts on water company assets. Section 3 briefly considers the broader interactions between climate and socio-economic change and how the water industry manages risks and adaptation. Section 4 draws some conclusions and highlights the need for more research on three significant impacts.

2. Potential impacts of climate change

2.1 The UK Climate Projections The UK Climate Projections 2009 (UKCP09) provide probabilistic projections of climate change for the Low, Medium and High emissions scenarios for seven overlapping time periods to the 2080s (Murphy et al., 2009). By the 2050s, projected rates of warming are approximately 1°C to 3°C in winter and from 1°C to 4°C in summer. There is a wider range of uncertainty for seasonal precipitation (for the direction and magnitude of change) with some differences between emissions scenarios by the 2050s as well as spatial variation across the UK. In London for the Medium Emissions scenario, winter precipitation is very likely[3] to increase in the range 2% to 32% while summer precipitation is likely to change between +7 and minus 41% (Murphy et al., 2009).

Increases in winter precipitation are projected over most of the UK (Murphy et al., 2009) leading to higher winter flows (Christierson et al., 2012; Prudhomme et al., 2012) and increases in peak river flows by the end of the century (Reynard et al., 2009; Kay et al., 2010). New research using higher resolution (1.5km) climate models with improved parameterisation of convection suggest that summer rainfall intensities may increase more sharply than indicated in UKCP09. By the end of the century for High emissions scenario (RCP 8.5) there may be a five-fold increase in intense summer storms (Kendon et al., 2014; Chan et al., 2014). However, these findings are provisional and based on a single model run; more research is required to understand the uncertainties related to convective summer storms.

2.2 Vulnerability of water infrastructure

Over the last 15 years, the vulnerability of water supply, treatment and distributions systems has been highlighted during periods of severe weather. The most significant threats have been:

- ***River flooding threatening critical water supply infrastructure.*** The flooding of the Mythe water treatment works in Gloucestershire in 2007 demonstrated that the existence of 'single points of failure' in the water network that, in the event of failure, have massive consequences

[3] Here 'very likely' defines the ranges between 10 % and 90 % probability levels.

for whole regions. The loss of Mythe cut off water to 350,000 people for up to 17 days. In total, five water treatment works and 322 sewage treatment works were affected (Pitt, 2008). In addition flooding caused damage to Ulley reservoir, Rotherham, leading to the evacuation of more than 1000 people downstream. Water supply infrastructure performed better during floods in 2013 but again some new problems emerged due to groundwater flooding although this impacted mostly on sewerage systems. The winter of 2013/14 was exceptional due to the sequence of storms, number of days with rain and overall volume of rainfall over December 2013 and January 2014 (Met Office, 2014).

- ***Drought leading to restrictions, and in a few cases, failure of public water supply systems.*** Significant droughts in 1989-1992 and 1995/6 affected large areas of the England and Wales and the latter event had severe impacts for Yorkshire, requiring a major emergency tanker operation to maintain supplies (Marsh, 2004; Cole and Marsh, 2005); major revisions to UK water resources and drought planning guidelines followed (DoE 1996, EA, 1997) as well as investment in improving drought resilience by building water transfers (Yorkshire Water, 1998). Moderate droughts affected parts of the UK in 2003, 2004-6 and 2011/12 (Marsh et al., 2014)[4].
- ***Low temperatures leading to freeze/thaw activity, soil movement and pipe bursts.*** Thousands of homes were left without water in Northern Ireland in December 2010 following record low temperatures. Sustained low temperatures followed by a rapid thaw led to burst water pipes on an unprecedented scale, triggering a water shortage crisis that attracted global media attention. The links between cold and dry conditions and pipe burst frequency is well established, although many other factors are also important (e.g. Boxall, et al., 2007). The drive to reduce leakage volumes to sustainable levels has led to major network upgrades but it will take a long time to replace older infrastructure with more resilient networks, so extreme cold periods still present a risk.

[4] Water company plans state levels of service or frequencies of drought restrictions of ca. 1 in 10 or 20 years. Published data on drought orders indicate high frequencies in some regions in the south east, south west and northern England (http://publicdata.eu/lv/dataset/number-of-drought-orders-1976-to-2011). The reasons for this are complex but these data suggest that droughts remain a significant risk even after major investments since the 1990s.

Other operational sensitivities include (i) coastal, groundwater and pluvial flooding on water supply assets (Henriques and Spraggs, 2011), (ii) influence of temperature of water treatment processes (Ritson, et al., 2014), (iii) water quality problems related to both heavy rainfall events or hot/dry/low flow periods (Ritson, et al., 2014; Burt et al., 2010, Thorne and Fenner, 2011), (iv) dry soil conditions that may also lead to soil movement and cracking of water pipes (Boxall et al., 2007) and (v) increases in the peak demand for water during hot and dry periods (Parker and Wilby, 2013). The UK water industry's own guidance on climate change adaptation describes 12 business areas sensitive to climate variability and change, 9 of which are relevant to water supply, treatment and distribution and over 50 potential impacts on water treatment alone (Bain et al., 2012 - see next section).

2.3 An overview of impacts on water supply, treatment and distribution

The Climate Change Risk Assessment, 2012 (Wade et al., 2012) described the potential impacts of climate change on the UK, including biophysical impacts, such as soil erosion, river water quality, high and low river flows relevant to water supply and distribution systems. As part of an initial screening exercise (including workshops with the water industry) around 700 climate risks and opportunities were narrowed down to around 100 risks for more detailed assessment. Direct impacts on water treatment or distribution did not make the final list for detailed assessment whereas flood risks to infrastructure and impacts of combined sewer overflows on water quality were selected. This implies that these direct impacts were regarded as less important in economic, environmental and social terms at the national scale. With its focus on potable water supply this review includes several impacts that were excluded from detailed assessment in the first CCRA.

In the context of climate change adaptation Bain et al., (2012) describe a number of water company business areas that may be affected by future climate change. Those relevant to water supply, treatment and distribution are summarised in Table 1. A more detailed list of impacts are provided in Table 2 with potential impacts categorised under water treatment in the UK industry guidance on adaptation and linked to specific climate drivers; the full list is exhaustive including 59 impacts but there is some overlap and obscure impacts that are not repeated here due to lack of evidence in other literature. There are some positive impacts, for example if warmer conditions lead to more efficient chemical or biological treatment processes. The impacts have been grouped here into seven impact categories and four of these are discussed further as small case studies.

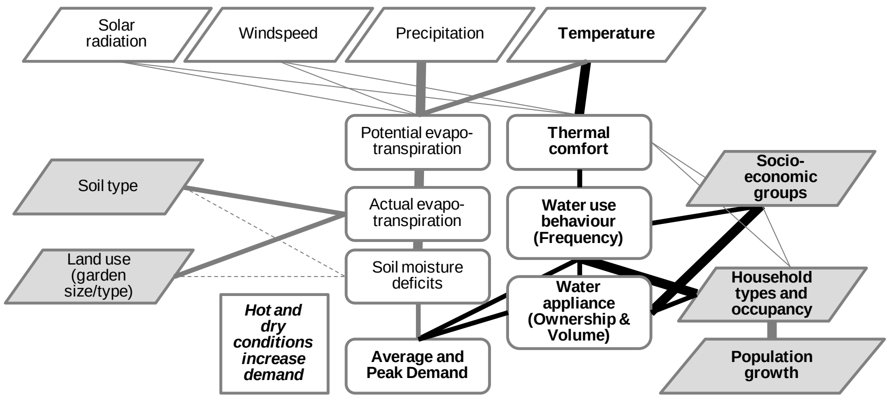
The demand for water

The impacts of climate variability and change on demand are important for water supply and distribution because increased demand places pressure on existing systems, requiring greater abstraction, treatment, storage, distribution, leakage control and pressure management. An early study by Herrington (1998) found that warming of 1.1 ^{o}C could add a further 10 percent to peak per capita consumption. Subsequent studies suggested lower impacts on average demand (Downing et al., 2004) and reinforced a view that social and economic factors were the key long term drivers of demand (Environment Agency, 2001, 2008). Overall there is a paucity of research studies on climate and demand partly due to the lack of high quality monitoring data sets (Parker and Wilby, 2012).

Recent work by Parker suggested that the sensitivity to climate was highly dependent on occupancy type and that the climate signal was lost with averaged data sets, such as larger area distribution input or 'water into supply' data. For one case study in East Anglia using detailed data from Anglian Water, households with four occupants consumed on average 6.5 litres per capita more per 1^{o}C temperature rise (Parker and Walker, undated). This finding is closer to Herrington's original work and indicates that impacts could be significant under higher rates of warming. For example, in the East of England under High Emissions the UKCP09 projections central estimate of increases in summer mean daily maximum temperature is 6.2ºC, suggesting a potential increase in peak demand of around 40 litres per person per day; it is very unlikely to be less than 2.8ºC (18 l/h/d) and is very unlikely to be more than 10.6ºC (69 l/h/d)[5].

Figure 1 illustrates the linkages between climate and household demand, which is mainly related to outdoor water use components such as garden watering and car-washing. Social and economic factors are key indicators of consumption and new modelling approaches are emerging from social science that focus on the water use behaviour of specific groups of people (Browne et al., 2014). Non-climate factors, such as consumer behaviour and uptake of water efficient fixtures, fitting and devices ('ownership' and 'volume' in Figure 1) are likely to be more important factors for average demand than climate change. Warmer conditions are likely to have low to moderate impacts on average demand but this may be locally significant in parts of the south-east of England with marginal supply-demand balances. Higher maximum summer temperatures may have moderate impacts on peak demand. Heat waves combined with periods of hydrological drought are likely to present a more significant risk and this is an area where more monitoring and research is required. Under normal, dry and more extreme heatwave conditions understanding the impact of weather on demand can support operational management and reduce pumping costs.

Figure 1. Inter-relationships between climate and non-climate drivers influencing household water demand (the dominant factors shown in bold with black connectors)



[5] This illustration is only relevant for large households in East Anglia, lower sensitivities were found for smaller households.

Table 1. A summary of key areas of water company business, example impacts and consequences (based on Bain et al., 2012 but only including the most relevant components)

Business components	**Potential consequences of climate change**	**Comments on relevance to water supply, treatment and distribution**
Supply-demand balance[6]	Any biophysical or secondary impacts that may affect the balance of supply and demand of water resources. (Due to warming and increased evapotranspiration, changes to precipitation, soil moisture deficit, changes in river flows and groundwater levels, floods, droughts, water quality impacts)	The supply and demand balance was the focus of early work on climate change in the water sector (CCIRG, 1996; Arnell; 1998; 2004; Downing et al., 2004). Impacts on river flows, groundwater recharge and deployable outputs has been covered in detail elsewhere (and as part of other LWEC scorecards) (Charlton and Arnell, 2012; Wade, S.D. et al 2012). Some authors have indicated that the water resources planning process is poorly conceived and unable to properly address climate risks (Hall et al., 2012). Outage or unplanned closures of works may be caused by flooding or climate related water quality problems (Pitt, 2008).
Service performanc e[7]	These consequences *directly* affect the water supply or other service performance. These involve conveying flows (Quantity), and providing the correct hydraulics (including pressure) and processes (Quality). (Due to changes in flow or water quality, sedimentation or erosion at water intakes, algal problems, drought)	The main areas of research on climate change and performance relate to water resources system performance, treatment works processes (Ritson, et al., 2014) and leakage/pipe burst frequency modelling (Boxall et al., 2007; Wols, B. A.; van Thienen, 2014). Performance can be measured using a range of metrics including costs, carbon costs, environmental performance, risk and reliability all of which may be affected by climate change (e.g. see Matrosov et al., 2013 on London's water supply) Companies operate to defined levels of service and new investment or changes on operations may be needed to adapt to climate change. Certain biological processes are affected by temperature so that process efficiency may improve

[6] The balance between the water available for supply and the demand; in the UK planning system specific design conditions are considered, such as a 'normal year' or 'dry year.'
[7] The UK water industry is highly regulated and water service providers (mostly private companies) operate according to specific performance measures.

		up to a threshold and then deteriorate, increasing costs.
Asset damage/failure[8]	Service is affected indirectly, through asset condition, to cause asset damage or failure of structure or treatment plant. (Due to flooding, erosion, landslides or subsidence)	The main climate related drivers of loss and damage are flooding, storm surge, landslides and subsidence and these have been considered in detail in both Environment Agency and Committee on Climate Change studies (Panzeri et al., 2013). The risks to dams and reservoirs of extreme floods have been a major area of concern due to significant risks to life in the event of dam failure (Pitt, 2008). As well as dramatic failure, assets may deteriorate over time and asset lives shortened by exposure to environmental hazards, such as scour of pipe crossings.
Staff Health and Safety issues	*Impacts may have consequences for the health and safety of water company staff.*	*This area has not been researched in detail but it appears on the risk registers of many companies, particularly for those servicing remote areas. As well as health and safety issues there are business continuity concerns if staff are unable to reach water treatment works or locations with pipe bursts due to extreme floods or cold weather conditions.*
Supply chains[9]	*Business supply chains may be affected by climate risks in the UK or overseas.*	*This area has not been researched in detail. However the UK industry relies on chemical suppliers from outside the UK and complex UK supply chain to maintain its services.*

Table 2. Selected potential impacts of climate change on water treatment based on the UK water industry's adaptation framework and associated climate drivers (based on Bain et al., 2012)

Group	**Impact**	**Example consequences**	**Less rain**	**More rain**	**Temp.rise**	**Sea level rise**	**Cloud cover**	**Intense rainfall**	**Wind**	**Storm surge**	**Extreme cold**
The demand for water*	**Increase in daily and peak demand for**	Impacts security of supply; increase in	Y		Y						

[8] Asset damage refers to any event or activity that damages water company assets (pipes, treatment or water recycling works) or other assets that the water companies rely on to operate their services (flood defences, roads, energy or communications networks).
[9] Supply chains refer to goods and services that water companies rely on in order to operate their services, for example chemicals, engineering expertise, finance and investment.

Group	Impact	Example consequences	Less rain	More rain	Temp.rise	Sea level rise	Cloud cover	Intense rainfall	Wind	Storm surge	Extreme cold
	water	volume of water and wastewater requiring treatment									
	Redistribution of / increase in tourism increases seasonal demand	Impacts security of supply; impact on pump and process run-times; increase in volume of water and wastewater requiring treatment			Y		Y				
Water quality problems *	**Discolouration and odour problems***	Increased drinking water quality risk		Y				Y			
	Increased algal growth and risk of microscopic organisms within the water supply system	Raw and drinking water quality risk; increased maintenance of reservoirs etc; increased treatment cost	Y		Y						
	Increased rate of microbiological growth	Contamination of supplies; increased drinking water quality risk; increased treatment required			Y						
	Increased risk of *Cryptosporidium*	Increased raw and drinking water quality risk			Y			Y			
	Increased risk of turbidity*	Impact on raw water quality; deterioration in aesthetic quality of lakes and rivers; ecological impacts		Y				Y			

Group	Impact	Example consequences	Less rain	More rain	Temp.rise	Sea level rise	Cloud cover	Intense rainfall	Wind	Storm surge	Extreme cold
	Increased runoff leads to greater sediment levels and suspended solids*	Increased drinking water quality risk; customer complaints; higher costs and risk of regulatory failure		Y				Y			
	Reduction in dilution from reduced raw water volumes	Deterioration in raw water quality; increased treatment requirements	Y		Y						
	Reduction in raw water quality	Impacts on environment; drinking water quality risk; tightening of discharge consents, increasing the risk of a consent failure/pollution incident; reduced filter run times and increased backwashing			Y			Y			
Water treatment processes *	**Accelerated chlorine depletion**	Failure to meet drinking water quality standards			Y						
	Increase in surface water temperature affecting coagulation and filtration processes	Increased treatment required			Y						
	Increases in rates of biological and chemical	Digesters become more efficient; improvement in treatment			Y +						

Group	Impact	Example consequences	Less rain	More rain	Temp.rise	Sea level rise	Cloud cover	Intense rainfall	Wind	Storm surge	Extreme cold
	processes	performance and effluent quality; increased biogas production at sludge plants; power generation									
Asset loss and damage due to floods and erosion*	**Coastal erosion or 'planned retreat' affects assets**	Service failure and asset loss				Y				Y	
	Direct asset flooding (fluvial and pluvial)	Service loss and outage; pollution incidents and compliance failure; submersion of electrical assets; staff H&S risk		Y				Y			
	Increased soil erosion	Siltation of dams and reservoirs; water quality problems		Y				Y			
	Storm damage to assets	Service failure and asset loss				Y			Y	Y	
Pipe bursts on water supply networks *	**Greater extremities in wetting and drying cycles lead to greater soil and pipe system movement**	Increased pipe burst frequency; accelerated asset deterioration; customer flooding	Y	Y	Y						
	Increased variability of winter temperatures with 'cold snaps'	Increased pipe burst frequency; accelerated asset deterioration.									Y
Impacts of staff	**Flooding affecting transport**	Increased costs; H&S risk to site staff; interruption		Y				Y			

Group	Impact	Example consequences	Less rain	More rain	Temp.rise	Sea level rise	Cloud cover	Intense rainfall	Wind	Storm surge	Extreme cold
	routes/access to assets	to supply chain - problems in obtaining treatment chemicals									
	Increase in heat exhaustion of supplier staff	Essential supplies not available when required			Y						
Supply chains	**Storm events and flooding leading to loss of power supply**	Service failure		Y				Y	Y		

Items marked * are discussed in more detail in the text.

Water quality and water treatment processes

Raw water quality is important for water treatment as it impacts on treatment processes, treatment costs and energy use, maintenance requirements and may disrupt supply causing unplanned ‘outage’. The quality of water abstracted depends on catchment characteristics and management, antecedent conditions and engineering factors (depth of abstraction or borehole depth, use of filters, storage, and use of aerators on reservoirs). Most water treatment works will operate with reference to specific thresholds and treatment ceases when raw water quality is poor. The important water quality variables for water treatment include nitrates and phosphates, pesticides, suspended sediments, colour, dissolved organic matter and cryptosporidium.

A comprehensive summary of climate change impacts on water quality was included in Watts et al., (2014) and a range of studies have assessed impacts on freshwater systems (Conlan et al., 2007; Dunn and Brown, 2010; Johnson et al., 2009; Whitehead et al., 2006a, 2006b, 2008, 2009a, 2009b), impacts of sewer discharges (Environment Agency, 2010) and pesticides (Bloomfield et al., 2006).

Temperature influences physical, chemical and biological processes that affect water quality, such as chemical reaction rates, aquatic flora and fauna growth and mortality rates (Thorne and Fenner, 2009). Poor water quality may be caused by ‘hot and dry’ conditions or heavy rainfall events. Warmer conditions will result in higher water temperatures (Hammond and Pryce, 2007; Hannah and Garner, 2014) and may contribute to lower dissolved oxygen concentrations and lower summer river flows (Christierson et al., 2012). Under low summer flow conditions there is less water for dilution of both agricultural and urban pollutants. Changes in the thermal structure of lakes and reservoirs with earlier and more intense thermal stratification may promote algal growth, decreasing water quality (Thorne and Fenner, 2009).

Changes in precipitation, particularly the frequency of intense rainfall events are also likely to impact on water quality. Under current conditions water quality and treatment problems arise when heavy rainfall leads to rapid increases in turbidity, increases in dissolved and sediment-associated nutrients and *Cryptosporidium* above the thresholds for water treatment. In urban environments combined sewer overflows may cause water quality problems particularly for heavy summer rainfall events when receiving waters have lower flows. High concentrations of Dissolved Organic Matter (DOM) from soil and vegetation are known to impact on the performance of water treatment processes (Bursill, 2001) and areas of the north and west of England and Wales are particularly vulnerable due to upland peat soils and reliance on surface waters rather than groundwater sources.

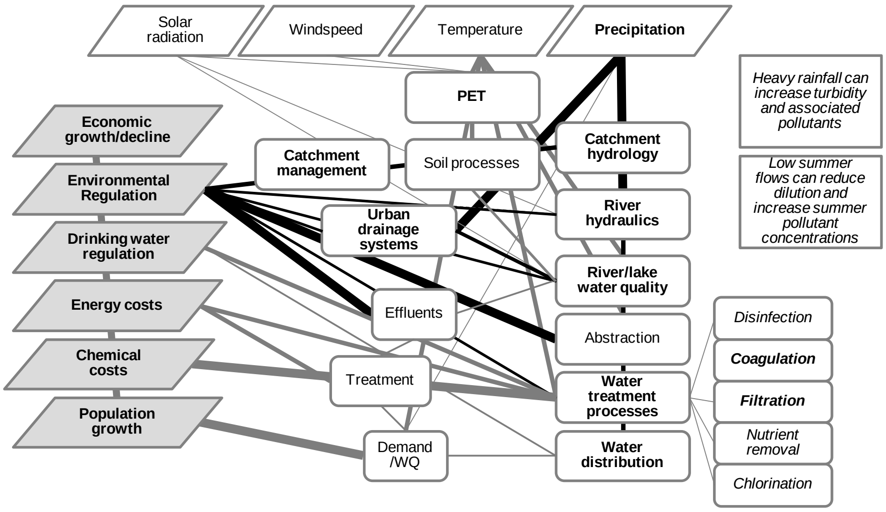
Thorne and Fenner (2009) developed an integrated model for Grafham Water (East Anglia, UK) of the impacts of climate change on reservoir water quality and water treatment works operations. They projected a range of impacts for example:

- An increase in phytoplankton growth in low rainfall scenarios, which was linked to increased filter head loss and more frequent maintenance and assessed as a minor impact.
- Small increases in Dissolved Organic Carbon (DOC) concentrations under all future scenarios, which was linked to increased coagulant dosing, and disinfection requirements and potentially chlorine dosing requirements. They estimated potential increased in costs of up to 6% and classified this as a major impact.
- Thermal stratification of the reservoir, which would require an increase in the use aerators and associated energy costs but the overall impact on the costs was small and equivalent to just 3p/Ml; consequently this was categorised as a minor impact.
- An increase in the chance of failure of nitrate standards in the 2050s and 2080s, which was classified as a major impact requiring new water treatment processes.

A comprehensive review of the impacts of climate change on DOM was completed by Ritson et al., (2014). This suggested that upland catchments would continue to produce more DOM due to changes in seasonal rainfall and the increase in frequency of heavy rainfall events and changes in species diversity and water properties that could encourage greater algal blooms. Several adaptation strategies were proposed including ‘enhanced coagulation’ optimised for DOM removal, the use of different coagulants and activated carbon filtration.

Figure 2 describes some of the complex interactions between climate and non-climate drivers on water quality and treatment. Climate factors influence raw water quality through catchment processes, river flows, the frequency of combined sewer overflows, river and lake water quality processes, which all have an impact on water treatment. Climate directly impacts on water treatment processes and high temperatures may lead to faster depletion of chlorine. Extreme high or low temperatures can affect coagulation and other processes. However non-climate factors, particularly the environmental regulation of point and non-point pollution, catchment management and issues related to energy costs are key drivers impacting on the performance of water treatment works. Overall the impacts of climate change on water treatment is expected to be low to moderate, with the main concerns focused on DOM and associate treatment costs. The north and west of England Wales are particularly vulnerable to high DOM. Understanding the links between weather and poor water quality can help to reduce pollution risks and operational expenditure on treatment processes.

Figure 2. Inter-relationships between climate and non-climate drivers influencing water quality and water treatment process (the dominant factors shown in bold with black connectors)



Assets at risk from storms and floods

Water supply and treatment infrastructure is often located closed to rivers and therefore in the floodplain. Research for the UK Government's Adaptation Sub-Committee shows that around one quarter of England's water treatment infrastructure is exposed to flood hazards under current climate conditions (defined by sites located within the 1 in 30 year floodplain) (Table 3). The level of exposure is projected to increase to 50% of clean water infrastructure by the 2050s implying a greater frequency and depth of flooding for those currently at risk.

Table 3. Number (and proportion of 1718 sites) of clean water treatment sites exposed to different hazards in England

	Coastal erosion	Groundwater flooding	River and coastal flooding[1]	Surface water flooding[2]	Shrink-swell subsidence
Number	0	262	120	57	174
Proportion	0%	15%	7%	3%	10%

Notes: [1]*Present day likelihood of flooding from rivers or the sea.*

[2]*Mid-depth (0.3m<= depth <1.2m; 1 in 1000 year likelihood).*

Flooding can cause direct damage to works, contamination due to high pollutant loads or a range of indirect impacts, e.g. by damaging access roads, preventing staff reaching sites or disrupting local power supplies. Henriques and Spraggs (2011) describe a detailed but practical assessment of flood

risk and resilience planning for Anglian Water's water treatment network. This included an assessment of critical parts of the network, failure of which would affect large numbers of people, as well as flood risk assessment with climate change scenarios. This was used to target 'low regret' adaptation measures and to protect the critical parts of the network from flooding.
The UK Climate Change Risk Assessment (Wade et al., 2012) identified flooding as one of the most important climate change risks for England and Wales. Water companies are improving the resilience of water treatment infrastructure to flooding but overall investment in flood risk management is arguably sub-optimal and is not keeping pace with elevated levels of risk (ASC, 2014). The impact of flooding on water treatment infrastructure is projected to be moderate to high. In addition there are specific risks related to excessive flows on dam spillways, which became clear following the 2007 floods (Pitt, 2008), which have not been fully assessed in the context of future climate change.

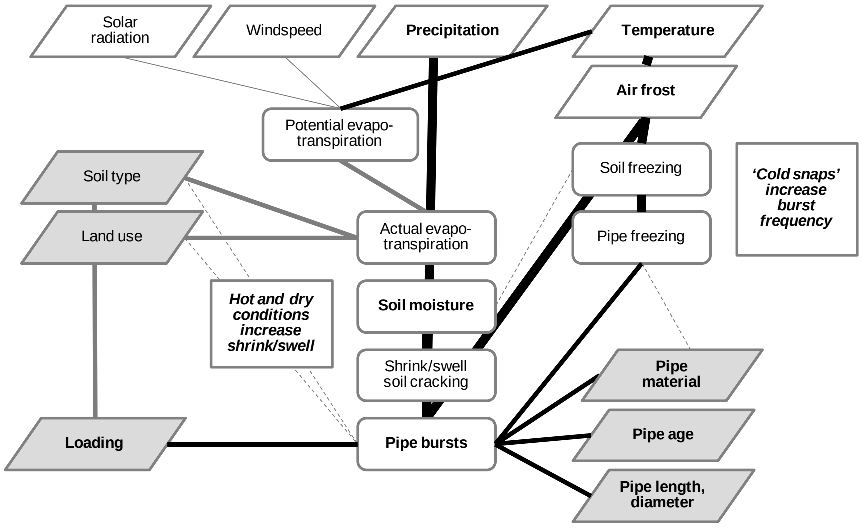
Water distribution, leakage and pipe bursts

The clean water distribution network takes water from water treatment works to customers and includes pipes, water storage and infrastructure for maintaining and managing water pressure so supplies reach all customers. Leakage is a key measure of system performance and is defined as the loss of water from the distribution network which escapes other than through a controlled action. While some leakage can be continuous and gradual, significant volumes of water can be lost through pipe bursts, which are caused by the shrinking and swelling of some soils, subsidence and freezing and thawing. Leakages and pipe bursts are also linked to other key performance indicators such as customer complaints, pH sample, coliform and taste and odour (Lumbers, et al., 2009).

Leakage is affected by operational strategies (for example, pressure management), network characteristics (for example, length of mains), asset condition (for example, age); and customer base composition (for example, rural/urban and water delivered). Boxall et al., (2011) linked burst rates to pipe material and other physical network characteristics. Its frequency is also linked to climate by many water companies as part of their long term assent deterioration modelling studies. Bicik (2010) developed a detailed model that estimated burst frequency as a function of pipe material, diameter, age, soil type, land use, and weather conditions. Lumbers (2009) describes a proprietary model that uses a linear 'weather function' that links burst rate to air frost days, monthly precipitation and monthly mean soil moisture deficit. Similar models are used by some water companies in operational 'weather impact models' that forecast leakage rates one to two weeks ahead. This foresight helps to organise leak detection and engineering teams and minimise the amount of water lost due to leakage.

Figure 3 illustrates some of the linkages between climate and non-climate drivers that affect pipe burst frequency rates. As pipe bursts are sensitive to very cold conditions and hot and dry conditions, it is the interplay between the frequencies of cold winters and hot and dry summers that determines the overall climate impact. While average winter temperatures will decline due to climate change increased inter-annual variability means that there will still be 'cold snaps.' Warmer conditions and changes in summer precipitation are very likely to lead to higher soil moisture deficits by the 2050s (Wade et al., 2012; Knox 2010). The level of sensitivity is very dependent of network characteristics and as older cast iron or cement pipes are replaced with more resilient materials vulnerability will be reduced[10]. Overall the impact of climate change on future leakage is likely to be low but further research is required to understand the influence of climate change on the capital maintenance plans promoted by water companies.

Figure 3. Inter-relationships between climate and non-climate drivers influencing pipe bursts (the dominant factors shown in bold with black connectors)



3.0 Broader drivers and interactions

Water supply, treatment and distribution operations and long term investment are affected by a range of non-climate factors including regulation, technology, demands, population and economic growth and availability of financing for major engineering projects. In the near to medium term (20 years) these are expected to be far more important than climate change. However, increasing the resilience of systems to current climate has benefits in terms of maintaining high quality service to water customers, reducing energy costs and damage and loss of assets in extreme events.

Water treatment, supply and distribution are parts of a broader water resources system and intrinsically linked to other infrastructure systems, such as energy, transport and flood risk management. Therefore to fully understand the risks of climate change an integrated approach to risk assessment is required (Hall et al., 2014). Notable systemic risks, highlighted in the CCRA inception phase included loss of energy supply due to floods or windstorm, travel disruption due to flooding or 'cold snaps' preventing water company teams from reaching work or incident locations, interruptions to the supply of water treatment chemicals, many of which are sourced internationally from a small number of suppliers (Wade et al., 2012).

[10] There are few published papers on the details of asset deterioration as the models may contain proprietary code and commercially sensitive assets data. However UK water companies are clearly using them to promote capital or operational expenditure to modernise water networks.

3.1 Management of risks by water companies

The water industry in England and Wales is highly regulated by Ofwat, the Environment Agency, Drinking Water Inspectorate and Natural Resources Wales. Water service providers are responsible for managing risks to their operations as well as setting out long term plans as part of a statutory reporting process. Within this framework there are a wide range of operational activities, plans and regulatory reports that consider weather or climate change risks. Figure 4 provides examples of some the activities for managing risks at different time scales. Weather warnings are used to flag periods with higher runoff and turbidity enables operators to treat more water (or even close intakes) prior to a period of high turbidity and less water (at higher costs) during pollution events. Weather forecasts out to up to 14 days provide warning of potential cold snaps and increased pipe bursts enabling companies to monitor systems closely and prepare leakage teams. As forecasting skill has improved over the medium term time scales (14 days) some water companies are making greater use of weather and climate information to inform 'production' planning and logistics (staff deployment, contingency planning). As seasonal and decadal forecasting improves companies may use information for financial planning and scheduling investment. Drought plans and water resources management plans are based on specific design conditions (e.g. 'Dry Year Annual Average' demands) and help companies operate according to agreed levels of service.

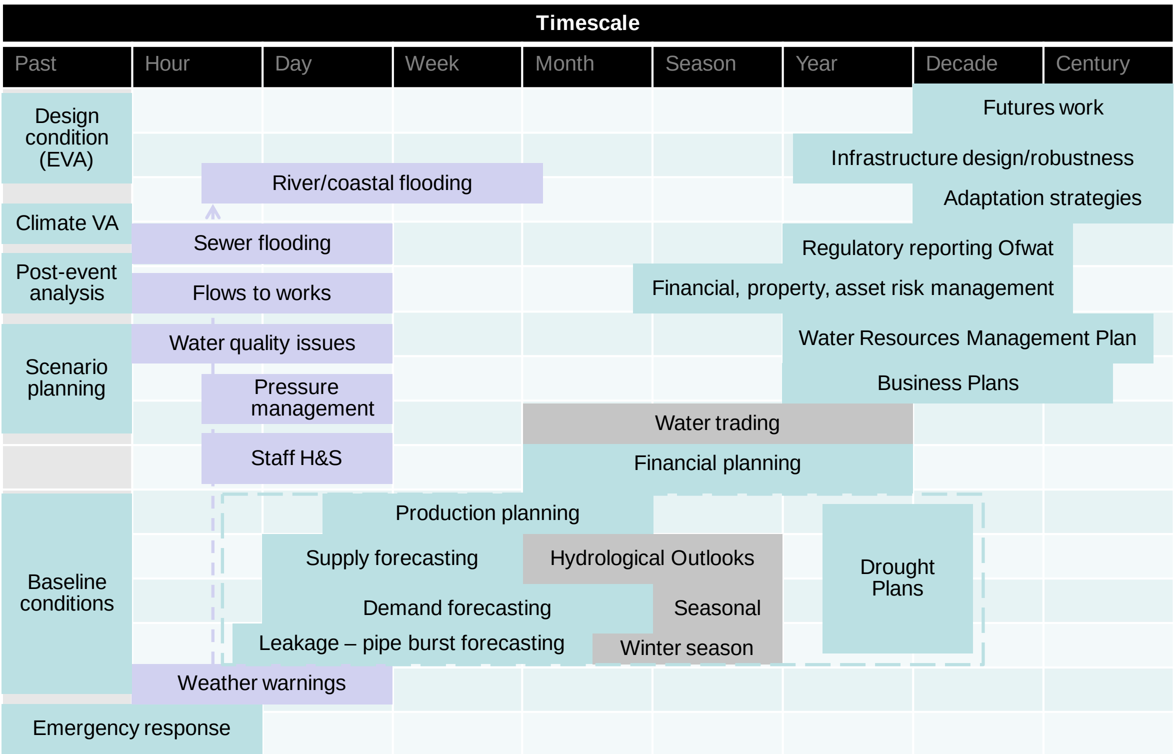
Ofwat and the Environment Agency provide guidelines on how companies should incorporate climate change in their long term plans, and therefore have an important role in climate change adaptation. Climate change risks are considered in water company Strategic Direction Statements and following the Climate Change Act (2008) companies were also required to produce Adaptation Reporting Power (ARP) reports to Defra, which set out their approach to managing climate risks and their adaptation plans.

3.2 Adaptive Capacity

The concept of adaptive capacity describes the ability of organisations to manage climate variability and climate change. Overall the adaptive capacity of UK water companies and the water industry in general is considered to be high (Ballard et al., 2013; Wilby and Vaughan, 2011). A more recent review suggested only partial evidence of good progress on risk assessment, resilience and adaptation reporting (ASC, 2014) although this had a narrow focus of flood risk and specific 'resilience' funds. All UK water companies incorporate climate change into long term planning and most consider climate impacts on water distribution (demand and leakage), network resilience and major infrastructure schemes. Some water companies are developing a comprehensive approach to assessing climate risks, making use of outputs from the UK research community, for example, all companies have made use of UKCP09 for impact assessment and adaptation planning. Thames Water have also used Future Flows (Prudhomme et al., 2012), a transient climate modelling product based on HadGEM*, for sensitivity analysis (Thames Water, 2014) and explored the application of robust decision making (RDM) and real options to inform investment decisions in the context of future uncertainties.

As well autonomous adaptation in response to extreme events that typically prompt additional investment, companies are involved in adaptation planning through long term water resources management plans and business plans. The focus has been mostly on water supply rather than treatment works and distribution systems and mostly on assets rather than broader environmental issues, land management and supply chain security (Ballard, et al., 2013). The increased focus on resilience to weather extremes (particularly post 2007 and 2012/13 floods), drives to reduce operational costs (particularly energy costs) and more sophisticated analytics and modelling, mean the many operators are acutely aware of weather sensitivities and involved in developing systems to manage risks. In many cases these are not reported in detail in the literature as they involve development of proprietary software products that provide vendors or specific water companies with a competitive advantage.

Figure 4. The use of climate information, weather forecasting and climate change projections by water companies in England and Wales



4.0 Conclusions

This review found that a wide range of potential impacts of climate change on water supply, distribution and treatment were recognised by the water industry and risk assessments and adaptation frameworks (Wade et al., 2012; Bain et al., 2012). Evidence in the peer reviewed literature was limited compared to the literature on biophysical impacts on river flows or water quality. This may be because the impacts are generally low or because internal water company research has formed the basis on proprietary asset management systems and this work is not published. Following a broad review this paper focused on four specific impacts, which were supported by evidence in the peer reviewed literature. The main conclusions from this review are as follows, with an indication of magnitude using the same scales as the CCRA (Wade et al., 2012) and the level of confidence based on IPCC confidence scales:

- Warmer summer conditions are likely to have low to moderate impacts on average demand but this may be locally significant in parts of the south-east of England with marginal supply-demand balances. (Medium, medium agreement and evidence)
- Higher maximum summer temperatures are likely to have moderate impacts on peak demand (Low, medium agreement but limited evidence).
- Heat waves combined with periods of hydrological drought may present more significant risks but there is limited research on the impacts of heatwaves on peak demand in the context of future climate change (Low, medium agreement but limited evidence)
- The impacts of climate change on water treatment is expected to be low to moderate, with the main concerns focused on Dissolved Organic Matter and associate treatment costs. The north and west of England Wales are particularly vulnerable (Medium, medium agreement and medium evidence).
- The impact of flooding on water treatment infrastructure is projected to be moderate to high. In addition there are specific risks related to excessive flows on dam spillways, which became clear following the 2007 floods (Pitt, 2008), which have not been fully assessed in the context of future climate change (Medium, based on high agreement but limited evidence).
- Impacts of climate change on future leakage is likely to be low as the frequency of cold snaps declines and networks are upgraded to reduce losses (Low, limited evidence and medium agreement)

The review also found that water supply, treatment and distribution operations and long term investment are affected by a range of non-climate factors that are expected to be far more important than climate change in the near term. These include regulation, technology, demands, population and economic growth and availability of financing for major engineering projects Overall the adaptive capacity of UK water companies and the water industry in general is considered to be high. There is now a strong focus on the resilience of water supply systems and a lot of activity related to managing operational risks. A broader review based on climate resilience and climate services (rather than future impacts and adaptation) may reveal the extent of activities aimed at reducing weather and climate impacts.

Finally the paucity of evidence in some areas highlights the need for more monitoring, access to data, research and reporting of impacts in this area. In particular, more research is required to understand (i) the impacts of peak water demand and risks related to combined heatwaves and droughts; (ii) the magnitude of impacts related to poor water quality (DOM) and whether ongoing efforts on catchment management are reducing risks effectively; (iii) quantifying the sensitivity of treatment costs and network maintenance costs to climate, so that the overall impacts can be monetised at a national scale and finally (iv) national asset deterioration modelling in the context of more frequent river and coastal flooding due to climate change.

References

Bain, V., Hall, E., Lonsdale, K., Rance, J., Street, R., Udale-Clarke, H., Wade, S.D. 2012. Updating the UK Water Industry Climate Change Adaption Framework – Handbook. UKWIR Report.

Ballard, D. 2009. Working paper on adaptive capacity. Working Paper 1 for the UK's Climate Change Risk Assessment 2012. Alexander Ballard Ltd for HR Wallingford Ltd.

Bicik, J. 2010. A Risk-Based Decision Support System for Failure Management in Water. Distribution Networks. Submitted by Josef Bicik to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Engineering in June 2010

Bloomfield, J.P., Williams, R.J., Gooddy, D.C., Cape, J.N. 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, 3691-3: 163-177.

Boxall, J. B.; O'Hagan, A.; Pooladsaz, S.; Saul, A. J.; Unwin, D. M. 2007. Proceedings of ICE: Water Management. June 2007, Vol. 160 Issue 2, p73-82. 10p.. DOI: 10.1680/wama.2007.160.2.73

Browne, A, Pullinger, M, Medd, W & Anderson, B. 2014. 'Patterns of practice: a reflection on the development of quantitative/mixed methodologies capturing everyday life related to water consumption in the UK' International Journal of Social Research Methodology, vol 17, no. 1, pp. 27-43., 10.1080/13645579.2014.854012

Bursill, D. 2001. Drinking water treatment: Understanding the processes and meeting the challenges. Water Sci. Technol. Water Supply, 1 1, 1-7.

Charlton M.B. and Arnell N.W. 2011. Adapting to climate change impacts on water resources in England—An assessment of draft Water Resources Management Plans. Global Environmental Change 21 238–248.

Christiersen B.v., Vidal J-P. and Wade S.J. 2012. Using UKCP09 probabilistic climate information for UK water resource planning. Journal of Hydrology 424–425 48–67.

Cole, G.A. and Marsh, T.J. 2005. Major droughts in England and Wales from 1800 and evidence of impact, Science Report SC030298/SR, Environment Agency. July 2005

Conlan, K., Lane, S., Ormerod, S. and Wade, T. 2007. Preparing for climate change impacts on freshwater ecosystems, PRINCE: results. Environment Agency Science Report SC030300/SR, Bristol, UK.

Defra January 2012. http://www.defra.gov.uk/environment/climate/government/risk-assessment/#evidence 2012 CCRA Evidence Report. UK 2012 Climate Change Risk Assessment, Defra, London.

Department of the Environment 1996. Water resources and supply: agenda for action. HMSO, London.

Downing, T. E., Butterfield, R.E., Edmonds, B., Knox, J.W., Moss, S., Piper B.S., Weatherhead E.K. 2003. Climate Change and Demand for Water. Research Report. Stockholm Environment Institute Oxford Office, Oxford.

Dunn, S.M. and Brown, I. 2010. Impact Assessment For Scotland: The Relationships Between Climate, Water Resources, Land Use And Diffuse Pollution In A Changing World. In Climate, Water and Soil: Science, Policy and Practice. Proceedings of the SAC and SEPA Biennial Conference, Edinburgh, 2010, ed. K Crighton and R Audsley, p37-42

Environment Agency 2001. A scenario approach to water demand forecasting. Environment Agency. National Water Demand Management Centre, Worthing, 146pp.

Environment Agency 2008a. Water Resources Planning Guideline. Updated in November 2008.

Environment Agency 2008b Water resources in England and Wales – current state and future pressures. Environment Agency, Bristol, UK. 23pp.

Environment Agency 2010. Scenarios for water quality: SIMCAT estimates of water quality in 2050.

Hall, J. et al.,2014. Assessing the Long-Term Performance of Cross-Sectoral Strategies for National Infrastructure." J. Infrastruct. Syst. , 10.1061/ASCEIS.1943-555X.0000196 , 04014014.

Hall, J. W., Watts, G., Keil, M., de Vial, L., Street, R., Conlan, K., O'Connell, P. E., Beven, K. J. and Kilsby, C. G. 2012. Towards risk-based water resources planning in England and Wales under a changing climate. Water and Environment Journal, 26: 118–129. doi: 10.1111/j.1747-6593.2011.00271.x

Hammond, D. and Pryce, A. R. 2007. Climate change impacts and water temperature. Environment Agency Science Report SC060017/SR, Bristol, UK.

Henriques, C. and Spraggs, G. 2011. Alleviating the flood risk of critical water supply sites: asset and system resilience' 2011, Journal Of Water Supply: Research & Technology-AQUA, 60, 1, pp. 61-68.

Herrington P. 1996. Climate change and the demand for water. HMSO, London.

Johnson, A.C. *et al*., 2009 The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England. Science of the Total Environment, 40717: 4787-4798.

Kendon, E.J. et al., 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. Nature Climate Change. DOI: 10.1038/NCLIMATE2258

Lane S.N., Reid S.C., Tayefi V., Yu D. and Hardy R.J. 2007. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. Earth Surf. Processes Landf. 32, 429–446.

Lumbers, J. Et al., 2009. Optimal Asset Management Planning: Advances In Water Mains And Sewers Analysis Within A New Modelling Environment. LESAM 2009 – 3rd Leading-Edge Conference on Strategic Asset Management, Miami, USA

M.R., Battarbee R.W. and Moss B. eds Climate change impacts on freshwater ecosystems. John Wiley and Sons, Chichester ISBN 1-4051-7913-3, p 65-83.

Marsh T., Cole G. and Wilby R. 2007. Major droughts in England and Wales, 1800–2006 Weather 624 87-93.

Marsh, T. 2004. The UK drought of 2003 - an overview extended version of a paper published in 'Weather' August, 2004, Vol. 59, No. 8. Available at: http://www.nwl.ac.uk/ih/nrfa/yb/yb2003/drought2003/index.html

Moore, J.E., Caldwell, P.S., Millar, B.C. and Murphy, P.G. 2001. Occurrence of Campylobacter spp. in water in Northern Ireland: implications for public health. The Ulster Medical Journal, Volume 70, No. 2, pp. 102-107, November 2001.

Murphy J.M., Booth B.B.B., Collins M., Harris G.R., Sexton D.M.H. and Webb M.J. 2008. A methodology for probabilistic predictions of regional climate change from perturbed physics ensembles. Phil. Trans. R. Soc. A 365, 1993–2028.

Murphy J.M., Sexton D.M.H., Jenkins G.J., Booth B.B.B., Brown C.C., Clark R.T., Collins M., Harris G.R., Kendon E.J., Betts R.A., Brown S.J., Humphrey K.A., McCarthy M.P., McDonald R.E., Stephens A., Wallace C., Warren R., Wilby R. and Wood R.A. 2009. UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter.

Ofwat 2008a. Preparing for the future – Ofwat's climate change policy statement. 28pp.

Ofwat 2008b. Ofwat's response to the Pitt Review's learning lessons from the 2007 floods consultation. Ofwat, Birmingham.

Ofwat 2010. Delivering sustainable water – Ofwat's strategy. Available at: http://www.ofwat.gov.uk/aboutofwat/reports/forwardprogrammes/rpt_fwd_20100303ofwatstrategy.pdf

Ofwat 2011a. Future Impacts on Sewer Systems in England and Wales. Summary of a Hydraulic Modelling Exercise Reviewing the Impact of Climate Change, Population and Growth in Impermeable Areas up to Around 2040.

Ofwat 2011b. Attitudes to Water Services in a Changing Climate.

Ofwat, 2009. Climate change – good practice from the 2009 price review. Water today, water tomorrow.

Parker, J, & Wilby, R., 2013. Quantifying Household Water Demand: A Review of Theory and Practice in the UK', Water Resources Management, 27, 4, pp. 981-1011.

Parker, J, & Wilby, R., undated. Assessing the sensitivity of water demand to climate change. Poster output from the EPSRC ARCC-Water project.

Pitt, 2008. The Pitt Review: learning lessons from the 2007 floods. Cabinet Office.

Prudhomme C., Reynard N. and Crooks S. 2002. Downscaling of global climate models for flood frequency analysis: where are we now? Hydrol. Process. 16, 1137–1150.

Prudhomme C., Wilby R.L., Crooks S., Kay A.L. and Reynard N.S. 2010. Scenario-neutral approach to climate change impact studies: application to flood risk. Journal of Hydrology 390 198–209.

Prudhomme C., Young A., Watts G., Haxton T., Crooks S., Williamson J., Davies H., Dadson S. and Allen S. 2012. The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. Hydrological Processes DOI: 10.1002/hyp.8434

Raghav Pant, Jim Hall, Scott Thacker, Stuart Barr & David Alderson. January 2014. National scale risk analysis of interdependent infrastructure network failures due to extreme hazards.

Rance, J., Wade, S.D., Hurford, A.P. Bottius, E. and Reynard, N.S. 2012. Climate Change Risk Assessment for the Water Sector. CCRA Water Sector Report, January 2012

Reynard, N. 2010. The Water Resources Sector Phase 1 report to the Climate Change Risk Assessment. CEH.

Ritson, J.P.; Graham, N.J.D.; Templeton, M.R.; Clark, J.M.; Gough, R.; Freeman, C. 2013. Science of the Total Environment. Mar2014, Vol. 473-474, p714-730. 17p. DOI: 10.1016/j.scitotenv.2013.12.095.

SNIFFER 2005. Business Risks of Climate Change to the Public Sector in Scotland. Paul Watkiss, Suzanne Evans, Catherine Wasilewski, and John Mayhew AEA Technology Environment in collaboration with Alistair Hunt, Metroeconomica, Eleanor Baker, Risk Solutions, Steven Wade HR Wallingford and Pam Berry Oxford University. Report to SNIFFER. Published at http://www.scotland.gov.uk/News/Releases/2005/11/14083740

Thorne, O. and Fenner, R. A. 2011. The impact of climate change on reservoir water quality and water treatment plant operations: a UK case study. Water and Environment Journal 25, 1. http://dx.doi.org/10.1111/j.1747-6593.2009.00194.x

UKWIR 2006. *Effect of Climate Change on River Flows and Groundwater Recharge, A Practical Methodology:* A Strategy for Evaluating Uncertainty in Assessing the Impacts of Climate Change on Water Resources. UKWIR Report 05/CL/04/6. ISBN 1-84057-396-1.

UKWIR 2007. Effects of climate change on River Flows and Groundwater Recharge, *A Practical Methodology:* Synthesis Report. UKWIR Report 07/CL/04/10. ISBN 1-84057-443- 7.

UKWIR 2008. 'Climate change - towards a UK water industry strategy'. Produced by Atkins. UKWIR Report CL01.

UKWIR 2009. Assessment of the Significance to Water Resource Management Plans of the UK Climate Projections 2009 – Final Report.

UKWIR 2011a Climate change implications for wastewater treatment. UKWIR Project CL12. Ongoing, http://www.ukwir.org.uk/content/default.asp?PageId=65201

UKWIR 2011b CL08B201 – Climate Change Implications for Water Treatment. Draft Interim Report on the likely changes in water quality due to climate change. March 2011

Vidal J.-P. and Wade S. 2009. A multimodel assessment of future climatological droughts in the United Kingdom. Int. J. Climatol. 29: 2056–2071.

Vidal, J.P., Christierson, B. and Wade, S.D. 2011 Using probabilistic climate information for UK water resource planning. Geophysical Research Abstracts Vol. 13, EGU2011-5663-1,

Vidal,.J.P. and Wade, S.D. 2007. A framework for developing high-resolution multi-model climate projections: 21st century scenarios for the UK. Int. J. Climatology. Published Online: 3 Aug 2007. DOI: 10.1002/joc.1593

Vidal,.J.P. and Wade, S.D. 2008. Multi-model projections of catchment-scale precipitation regime. Journal of Hydrology. doi:10.1016/j.jhydrol.2008.02.003

Vidal,.J.P. and Wade, S.D. 2009. A multi-model assessment of future climatological droughts in the UK. Int. J. Climatology. Accepted JOC 07-0335

Wade S.D., Rance J. and Reynard N. 2013. The UK Climate Change Risk Assessment 2012: assessing the impacts on water resources to inform policy makers. Water Resources Management DOI 10.1007/s11269-012-0205-z

Wade, S.D., Townend, I., Udale-Clarke, H., Rance, J., Betts, R., Hames, D. and Nash, E. 2012. The UK Climate Change Risk Assessment Evidence Report.

Watts G., Christierson B. v., Hannaford J., and Lonsdale K. 2012. Testing the resilience of water supply systems to long droughts. Journal of Hydrology 414–415 255–267.

Watts, G., Battarbee R.W., Bloomfield, J.P., Crossman, J., Daccache, A., Durance, I., Elliot, A., Garner, G., Hannaford, J., Hannah, D.M., Hess, T., Jackson, C.R., Kay, A.L., Kernan, M., Knox, J., Mackay, J., Monteith, D.T., Ormerod, S., Rance, J., Stuart, M.E., Wade, A.J., Wade S.D., Weatherhead K., Whitehead, P.G. and Wilby, R.L. 2014. Climate change and water in the UK – past changes and future prospects. Progress in Physical Geography In Review.

Whitehead, P. G., Wilby, R. L. and Futter, M. 2006a. Impacts of climate change on hydrology, nitrogen and carbon in upland and lowland streams: assessment of adaptation strategies to meet Water Framework Directive objectives. Proceedings Durham Meeting, British Hydrological Society, UK.

Whitehead, P. G., Wilby, R. L., Butterfield, D. and Wade, A. J. 2006b. Impacts of climate change on nitrogen in lowland chalk streams: adaptation strategies to minimise impacts. Sci. Total Environ. 365, 260–273.

Whitehead, P. G., Wilson, E. J. and Butterfield, D. 1998a. A semidistributed Nitrogen Model for Multiple Source Assessments in Catchments INCA: part 1–Model Structure and Process Equations. Sci. Total Environ. 210/211, 547–558.

Whitehead, P. G., Wilson, E. J., Butterfield, D. and Seed, K. 1998b. A semi-distributed integrated flow and nitrogen model for multiple source assessment in catchments INCA: part II Application to large River Basins in South Wales and Eastern England. Sci. Total Environ. 210/211, 559–583.

Whitehead, P. G.; Wade, A. J.; Butterfield, D. 2009. Hydrology Research. 2009, Vol. 40 Issue 2/3, p113-122. 10p. DOI: 10.2166/nh.2009.078.

Whitehead, P., Butterfield, D. and Wade, A. 2008. Potential impacts of climate change on river water quality. Environment Agency, Bristol, UK.

Whitehead, P.G., Wade, A.J. and Butterfield, D. 2009a. Potential impacts of climate change on water quality and ecology in six UK rivers. Hydrology Research, 40.2 – 3

Whitehead, P.G., Wilby, R.L., Battarbee, R.L., Kernan, M., and Wade, A.J. 2009b. A review of the potential impacts of climate change on surface water quality. Hydrological Sciences–Journal–des Sciences Hydrologiques, 541 February 2009.

Wilby, R.L. and Vaughan, K. 2011. Hallmarks of organisations that are adapting to climate change. Water and Environment Journal, 25: 271–281. doi: 10.1111/j.1747-6593.2010.00220.x

Wols, B. A.; van Thienen, 2014. P. Journal of Water Supply: Research & Technology-AQUA. May 2014, Vol. 63 Issue 3, p212-223. 12p. DOI: 10.2166/aqua.2013.088.