A climate change report card for Infrastructure

Working Technical Paper

Wastewater infrastructure: collection, treatment and disposal

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Executive summary

This working technical paper focusses on climate change impacts on UK wastewater infrastructure. The paper considers impacts such as those caused by changes in precipitation (seasonal and event-based), temperature and sea level rise on infrastructure, services, society and the environment before discussing adaptation strategies including those to manage uncertainties. The paper is based on a review of published and grey literature and as such will not reflect current activities, for example those of wastewater companies. The paper is aimed at academics and researchers working in collaboration with the water industry.

The recent floods events in the UK highlight the vulnerability of infrastructure and essential services to disruption from natural hazards. The failure of wastewater infrastructure to withstand intense weather events demonstrates the need for new adaptation. Amongst the future impacts on the wastewater systems, sewers have been identified to be at significant risk of flooding from surface water runoff, which in turn may cause sewer backups, external flooding and internal flooding in buildings. This not only affects wastewater company assets but also customers who have to deal with the consequences of their properties being flooded by runoff contaminated with sewage.

Increased runoff will also impact sewage pumping stations (SPS) and wastewater treatment works (WWTW). During the UK summer floods in 2007, hundreds of SPS and WWTW were flooded and put out of action as sewers in many places were overwhelmed by runoff. These impacts were often exacerbated by elevated river levels causing backup in the sewerage systems. Increases in combined sewer overflow (CSO) discharges are expected in future, leading to increased pollutant loads from untreated wastewater discharged into receiving watercourses.

Prolonged periods of dry weather may result in increased sedimentation of solids in sewerage systems, contributing towards increased ‘first flush’ pollutant loads and concentrations of untreated wastewater from CSOs. Lower flows combined with higher temperatures also increases the probability of hydrogen sulphide gas production, septicity and associated odour-related issues, and an increasingly corrosive effluent in periods of prolonged dry weather.

Overall treatment processes are expected to improve due to increased retention times and higher temperatures. However, at the same time, climate change is likely to result in reduced river flows, in summer at least, requiring increased treatment to meet consents. Infiltration of saline water into sewers will adversely affect the performance of wastewater treatment predominantly in relation to interceptor sewers that have been laid along the coast.

Many of the risks imposed by climate change on wastewater infrastructure are already being addressed to some extent by the wastewater companies. This is evident in the reports produced under the Adaptation Reporting Power (ARP) in 2011. Previously, the focus of adaptation was on ensuring that no critical assets were seriously affected by extreme weather events over their estimated lifetime, taking into account the latest climate projections. However more recently, the adaptation strategies endorsed by Government Agencies are less prescriptive and encapsulate a broader strategy for adaptation as described by the UK Government's *Guide to improving the resilience of critical infrastructure and essential services*.

Although adaptation strategies are becoming increasingly more sophisticated, with a wide variety of different types of interventions, there is likely to be a need to increase capacity of critical wastewater infrastructure where deemed necessary by the sewerage companies be, and demonstrated to be cost-beneficial. But in general there remains considerable uncertainty about the effectiveness of adaptation measures, because impacts are not fully understood (and are uncertain) and because the effectiveness of these measures has not been evaluated in detail.

The main findings and recommendations identified by this report are:

- Climate change is affecting wastewater infrastructure and this has implications on the wastewater companies' performance indicators. These impacts are greater in some regions more than others. Further work is recommended to develop a set of indicators which can be applied at the catchment level to identify catchments that are most prone to the adverse effects of climate change. In the absence of accurate and precise climate predictions, a risk-based approach can be used to explicitly accommodate a range of possible futures.
- Designers and operators of wastewater systems have developed a good understanding of climate variability but the onset of climate change has increased the unpredictability of hazardous events in terms of location of occurrence, timing and magnitude. These uncertainties could be investigated further using integrated catchment and sewer system models, stochastic weather generators and the latest climate science on extremes.
- The consequential impacts on society and the environment are not well quantified. The development of vulnerability and risk assessments for potentially affected communities would help to better understand these impacts in a way that can inform decision making and adaptation strategies.
- The development of monitoring programmes by wastewater companies is recommended to capture the impacts of a changing climate, define climate-related performance thresholds and relate these to service indicators. Monitoring

programmes should therefore be supported by long-term data management strategies.

- The development of an 'adaptation strategies guide' for wastewater companies is recommended to promote a wider range of adaptation interventions based on the projected climate impacts for different regions. Wastewater companies could use the information included in the guide to develop plans containing adaptation options suited to their specific needs, taking into consideration their location, climate impacts of concern, and available resources.
- Given the increasing emphasis on customer demands and willingness to pay, information on cost-effectiveness will be vital to inform stakeholder consultation. Very little information was found on cost-effectiveness of adaptation options but this could be in part due to commercial sensitivity. In particular, a systematic assessment of the extent of benefits of SUDS to reduce sewage flooding-related problems is recommended.
- Studies to enhance the understanding of the drivers and challenges/barriers to uptake of adaptation measures strategies are also recommended. A focus should be given to social perception of impacts and acceptability of proposed adaptation strategies, considering economic incentives and disincentives, the roles of different actors in uptake of these strategies and any requirements for reforms in policy and regulatory frameworks.

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Acronyms

ARCC	Adaptation and Resilience to a Changing Climate
BOD	Biochemical oxygen demand
CIWEM	Chartered Institution of Water and Environmental Management
COD	Chemical oxygen demand
CCRA	Climate Change Risk Assessment
CSO	Combined sewer overflow
Defra	Department for Environment Food and Rural Affairs
DO	Dissolved oxygen
IUD	Integrated Urban Drainage
IUWS	Integrated Urban Wastewater System
LWEC	Living with Environmental Change
IPCC	Intergovernmental Panel on Climate Change
MLSS	Mixed liquor suspended solids
Ofwat	Water Services Regulation Authority
PHE	Public Health England
UKCP	UK Climate Projections
UKWIR	UK Water Industry Research Organisation
UWWTD	Urban Wastewater Treatment Directive
SCADA	Supervisory Control and Data Acquisition (SCADA) investment
SUDS	Sustainable urban drainage systems
UKCIP	UK Climate Impacts Programme
VTEC	Verotoxigenic Escherichia coli
WFD	EU Water Framework Directive
WRA	Water Resources Act
WRA91	Water Resources Act 1991
WWTW	Wastewater treatment works

Key terms

Adaptation: Adaptation is the adjustment of natural or human systems in response to expected climate hazards.

Hazard: Actual or expected climate change manifestation.

Exposure: Contact of a system with climate change hazards.

Infrastructure assets: Mainly below- or underground assets, such as sewer that last for a long time. A distinction is drawn between infrastructure and non-infrastructure assets because of the way the appointed wastewater companies manage, operate and maintain them.

Mitigation: Climate change mitigation aims to reduce climatic hazards either by reducing emissions of greenhouse gases that are the source of climate change or by enhancing sinks to absorb these gases.

Non-infrastructure assets: Mainly above-ground assets, such as water and sewage treatment works, pumping stations, company laboratories, depots and workshops.

Wastewater: (used in preference to 'waste water' in this report) surface runoff and raw sewage collected by wastewater companies.

Wastewater company(ies): (definition used in this report) water company(ies) that provides and operates sewerage services.

Preface

The Living with Environmental Change (LWEC) partnership consists of 22 public sector organisations that fund, carry out and use environmental research and observations to work out what the UK's future knowledge and capacity needs are. The partnership includes the UK research councils, government departments with environmental responsibilities, devolved administrations and government agencies. The private sector is also represented by a Business Advisory Board.

LWEC aims to facilitate a multi-perspective approach to research investment strategy and promote collaborations resulting in increased efficiencies, rapid innovation and quicker delivery of results. For cross-cutting issues, LWEC can enable individual organisations to align their strategies to achieve a more holistic approach and avoid the risk of over-representation by one discipline or interest group.

The Adaptation and Resilience to a Changing Climate (ARCC) programme brings together a range of research projects, which look at the impacts of climate change and possible adaptation options in the built environment and its infrastructure. As part of the ARCC programme, the LWEC has commissioned a series of working papers focussing on different types of infrastructure including water resources, transport systems, telecommunications, energy and waste, in order to then produce a set of report cards which synthesise the information contained in the report cards.

These working papers will be summarised by LWEC in a report card. The report card will complement existing cards on other key areas such as biodiversity, water and health. The report card has been commissioned at the request of the Adaptation Sub-Committee of the UK's Committee on Climate Change to be used as evidence to:

i) synthesise current understanding and point towards future research priorities;
ii) inform the next UK Climate Change Risk Assessment (CCRA); and
iii) inform the evolution and priorities of the LWEC research programme.

1. Introduction

1.1 Scope and structure of the working paper

The scope of this working technical paper is on climate variability and change that impact upon wastewater systems such as those caused by changes in precipitation (seasonal and event-based), temperature and sea level rise. The wastewater system considered includes sewerage, pumping and other ancillaries (e.g. combined sewer overflow - CSOs) and treatment systems. The paper considers the impacts on society and the environment before going on discussing ways in which to manage the uncertainties related to these impacts through adaptation strategies. It is however important to note that climate change is only one of the drivers that influences the wastewater companies' business plans. Other factors, such as those related to population change and development creep, are not considered by this paper.

The evidence documented in this review is sourced from published and 'grey' literature. Most of the information referring to the UK wastewater companies' experience and response to the challenges imposed by climate change was obtained from their adaptation strategies prepared for the Water Services Regulation Authority (Ofwat) in 2011. More up-to-date information to state how extensively the wastewater companies are implementing their proposed adaptation interventions, and how effective they are in adapting to the impacts of climate change, was not available at the time of this review.

1.2 Functions of the wastewater system

In the UK, the average total volume of wastewater produced every day is estimated to be 10 - 11 billion litres[1]. Urban wastewater is defined in the EU Urban Wastewater Treatment Directive (91/271/EEC) as the mixture of:

- domestic wastewater from residential settlements and services which originates predominantly from the human metabolism and from household activities;
- industrial wastewater discharged from premises used for carrying out any trade or industry, other than domestic wastewater ; and
- rainwater run-off from roads and other impermeable surfaces such as roofs, pavements and roads draining to sewers.

Properties in the UK are either connected to a combined sewerage system which collects both rainwater run-off and wastewater from domestic, industrial, and commercial sources or are connected to a foul drainage system for wastewater effluents and a separate surface-water drainage system for urban run-off. Housing developments built since the mid-1960s generally have separate systems, while those built before tend to have combined systems.

Thus, from the customer perspective the primary function of the wastewater system in urban areas is to collect and drain wastewater, maintaining a sanitary environment and mitigating flood risks. In addition the wastewater system minimises the adverse impacts on water resources and flora and fauna, in both inland and marine waters by managing the quality of wastewater and also maintaining river flows, which is important for downstream abstraction, biodiversity and fisheries, and direct reuse.

Another important added benefit of the wastewater system is to mitigate problems related to resources recovery. There is an increased interest in wastewater reuse and recovery of nutrients such as nitrogen and phosphorus and production of gas and energy.

1.3 Institutional and regulatory framework

Broadly speaking, the role of the UK's water industry is to support the development of wastewater infrastructure that allows society to live within environmental limits and that helps ensure a strong, healthy and just society, having regard for environmental, social and economic considerations (Defra 2012a). More specifically, the wastewater companies have various statutory requirements to

[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69592/pb13811-waste-water-2012.pdf

uphold standards of water quality, protect public health, and maintain and improve the quality of the environment. In particular, there is still a need for investment in wastewater infrastructure in order to fulfil obligations principally related to the following EU Directives:

i) The ***Urban Waste Water Treatment Directive*** (UWWTD) (1991/271/ EEC) by providing suitable collection and treatment systems to protect public health and the environment from the adverse effects of wastewater. The UWWTD sets treatment levels on the basis of sizes of wastewater discharges and the sensitivity of waters receiving the discharges.

ii) The ***EU Water Framework Directive*** (WFD) is designed to improve and integrate the way water bodies are managed throughout Europe. It aims to enhance the status and prevent further deterioration of aquatic ecosystems, groundwater and associated wetlands, which depend on them.

Increasingly stringent environmental standards have driven and are continuing to drive improvements to wastewater treatment. The Environment Agency is the authority responsible for implementation of the UWWTD in England and Wales. Environmental laws include the Environmental Permitting (England & Wales) Regulations 2010, Section 94 – general duties of sewerage undertakers (duty to maintain sewers and lateral drains so as to effectually drain its area, and to deal effectually with the contents of sewers).

1.4 Main impacts of climate change on wastewater infrastructure in the UK

Climate change impacts in the UK on wastewater infrastructure related to warmer summers, wetter winters and more extreme weather conditions, combined with rising sea levels and increased river flows potentially leading to additional flood risk, are expected to worsen over the next few decades (Arkell *et al*. 2011). Sea level rise affects both flow and quality as a result of increased saline flows caused by infiltration, but concurrently a general reduction in pollutant concentration. Increased flood risk affects both wastewater company assets and customer properties. Overloading of the wastewater infrastructure causes damage to sewerage infrastructure, pump stations, wastewater treatment facilities and other ancillaries (Arkell *et al*. 2011).

Most of the highest order risks for the built environment highlighted in the Government's latest national Climate Change Risk Assessment (CCRA) are associated with the impacts of flooding, which are expected to become more severe. The CCRA highlights power generation, energy supply, strategic transport networks and sewers as being at significant risk of increased flooding (Defra 2013). As a result of more intense rainfall events, there are increased flood risks affecting areas already affected and other areas which are not currently thought of as being at risk (Defra 2012a), especially in coastal areas which are subject to the impacts of sea level rise.

In general, those areas that already experience the most significant climatic conditions are likely to experience further increases (both extremes and averages) and therefore further disparities across the country are to be expected. These changes need to be taken into consideration alongside any other physical or environmental conditions – both regional and local – which may exacerbate, or potentially mitigate, the effects of climate change.

1.5 The need for adaptation in the UK water industry

Climate change mitigation aims to reduce climatic hazards either by reducing emissions of greenhouse gases that are the source of climate change or by enhancing sinks to absorb these gases (Parry 2007). These strategies are required to help deliver the UK's obligation to reduce greenhouse gas emissions by 80% by 2050 meeting carbon budgets stipulated by the Climate Change Act 2008 (Defra 2012a). However, although the rapid introduction of mitigation measures is of critical importance, adaptation strategies are still necessary because previous global greenhouse gas emissions mean that we can expect continuing climate change for at least the next 30 years. Therefore, although mitigation measures will help support catchment based approaches and some adaptation strategies may have mitigation related benefits, the main focus of this review is on strategies for adaptation rather than mitigation.

The recent floods events in the UK highlight the vulnerability of essential services to disruption from natural hazards, including floods (Cabinet Office 2011). The failure of water and wastewater infrastructure to withstand intense weather events demonstrates the need for infrastructure adaptations that are able to resist a changing climate. Research by the UK Water Industry Research Organisation (UKWIR 2006) concluded that extensive modifications are needed to network infrastructure in response to the long term impacts of climate change.

Defra (2011a) acknowledges that climate change will create real challenges in the future and the Governmental White Paper highlights the urgent need to take action to ensure a resilient and sustainable wastewater sector in future (Defra 2011b). One approach is for water service providers to identify sewer and treatment works requiring adaptations based on process/asset performance thresholds and to develop strategies based on a business case providing economic justification for investment. However, increasingly, a more systematic approach to building resilience in critical infrastructure is being undertaken as initially recommended by the Pitt Review (Pitt 2008) (see Section 5).

2. Climate change variables related to wastewater systems

Tables 1 and 2 summarise the serviceability indicators applied to sewerage infrastructure and non-infrastructure respectively. These are included for reference to enable a consideration of potential impacts of climatic changes on performance of wastewater systems with respect to the level of service to a) customers and b) the environment. Although Ofwat and the wastewater companies make a differentiation between infrastructure and non-infrastructure assets (see Key Terms), the rest of this report uses the term infrastructure to cover both asset types.

Table 1 : Serviceability Indicators : sewerage infrastructure

Number of sewer collapses	Includes collapses of gravity sewers and repairs to rising mains caused by poor structural conditional and accidental failures but not those caused by a third party damage where costs can be recovered from the third party.
Number of sewer blockages that require cleaning	A blockage is an obstruction in a sewer which causes a reportable problem such as flooding or discharge to a watercourse, unusable sanitation, surcharged sewers or odour.
Properties internally flooded in year because of other causes	The number of properties in a year affected by flooding incidents from i) equipment failures, ii) blockages or collapses (collectively grouped as other causes). A property affected by more than one incident in the year under this definition is only reported as one property.
Properties internally flooded in year due to hydraulically overloaded sewers	Number of properties affected by internal flooding per year because of overloaded sewers (excluding flooding attributed to severe weather).
Number of equipment failures	The total number of sewerage equipment failures which are likely to have a detrimental impact on service to customers or the environment.
Number of pollution incidents	The total number of category 1, 2 and 3 pollution incidents monitored by the EA per 1000 km of sewer per year emanating from a discharge or escape of untreated sewage into controlled waters in the company's licensed area from i) a foul sewer ii) a combined sewer overflow or iii) a rising mains.

Source : Ofwat (2009)

Table 2 : Serviceability Indicators: sewerage non-infrastructure

% of sewage treatment works discharges failing numeric consents	The percentage of discharges from sewage treatment works with numerical discharge consents found to be non compliant with sanitary or non-sanitary consent conditions in the calendar year. This includes both those failing Water Resources Act 1991 (WRA91) consents and UWWTD self-monitored consents.
% of total p.e. served by sewage treatment works in breach of WRA or UWWTD consents	Sewage treatment works effluent sampled during the calendar year found to be non-compliant with i) EA look-up table and ii) Water Resource Act look-up table consent conditions or iii) Urban Wastewater Treatment Directive look-up table consents for biochemical oxygen demand (BOD) and/or phosphorus.
Unplanned non-infrastructure maintenance	Unplanned maintenance required as a result of equipment failure or reduced asset performance.

Source : Ofwat (2009)

The Met Office and partners produced the UKCP09 (Murphy *et al*. 2009) to simulate a range of possible outcomes for climate change and the probability of each outcome, based on how much evidence there is for different levels of future climate change (Defra 2012b). The Projections are presented for three different future scenarios representing High, Medium and Low greenhouse gas emissions. Those that are considered most relevant to wastewater systems are summarized below.

2.1 Wet weather

2.1.1 Seasonal variations

Although annual precipitations are projected to remain largely unchanged, climate change is expected to bring wetter winters across the UK. Precipitation on the wettest day of the season is projected to increase in winter by up to 40-50 % in the south of the UK (Murphy *et al.* 2009).

Also climate change has the potential to bring longer, heavier spells of winter rainfall (Mott MacDonald, 2011) and central estimates of increases in average winter precipitation by the 2080s are projected to be in the region of +14 % in the North East and up to +23 % in the South-West. Projections for London and the Southeast are similar (average +23 % but with a large margin for error related to the minimum increase of +6 % and a maximum of +54 %). Projections of mean winter precipitation change in the North West are expected to rise by 6 % (min -1% / max +14 %) during the 2020s, +10 % (min +1 % / max +21 %) by the 2040s, and +16 % (min +3 / max +35 %) by the 2080s for a medium emissions scenario (Murphy *et al.* 2009).

2.1.2 Storm event changes

Climate change is expected to increase the frequency and duration of rainfall events and also result in longer high-intensity frontal rain, together with more intense convective storms.

Under medium emission projections, central estimates for heavy rain days (rainfall greater than 25 mm) over most of the lowland UK is projected to increase by a factor of between 2 and 3.5 in winter, and 1 to 2 in summer by the 2080s (Murphy *et al.* 2009). However, summer convective storms are not well captured in the climate models that were used in developing UKCP09, although more recent research has shown an increase in summer convective storms (Kendon *et al*. 2014); these storms have a significant impact on rainwater volumes in some catchments (Mott MacDonald 2011).

Sanderson (2010) has estimated the magnitudes of daily rainfall events with return periods of 1 in 5, 10, 20, 30, 50 and 100 years from observed rainfall amounts in 40 UK towns and cities. For winter (December, January and February), these extreme events are projected to become more frequent in future.

Furthermore, the conclusions of the Weather Generator analysis (Arkell *et al*. 2013) are that extreme winter rainfall events become more intense in future, particularly for the longer (12 hour) duration events, although there are large uncertainties in the sizes of the increases; the numbers of intense events are similar to the baseline.

2.2 Dry weather

In contrast to winter, summer precipitation is projected to decrease for the whole country – by up to 10 % under medium emissions for the 2080s. Central estimates of regional average summer precipitation change are projected to be between -17% to -23% in the 2080s. The largest reductions are projected for the Channel Islands (Central estimate -28 % min, max -56% / min +8%). In the

South West, projections of central estimates of average summer precipitation reductions increase from -7% during the 2020s, to -13% by the 2040s and to -23% by the 2080s (Murphy *et al.* 2009).

Analysis of UKCP09 Weather Generator runs across several catchments show increases in the mean summer dry period and the mean maximum summer dry period, although there are fairly large uncertainties regarding the size of the increase (Arkell *et al*. 2013). Using a 'higher' scenario (the 10th climate percentile probability level and 75th percentile level in the uncertainty analysis of UKCP09 Weather Generator runs, the mean summer dry period increases to 37 hours for the 2020s medium scenario and 55 hours for the 2050s high scenario, averaged across a number of catchments (Table 3). Under the same scenario, the length of the mean maximum summer dry period increases from a catchment average of 316 hours in the baseline to 484 hours for the 2020s medium scenario and 586 hours for the 2050s high scenario.

Table 3: Mean summer dry period and maximum summer dry period (hours) under the baseline and climate change scenarios (central and higher estimates) (modified from Arkell *et al*. 2013)

Catchment average	**Baseline**	**2020s**		**2050s**	
		Central*	**Higher^**	**Central***	**Higher^**
Mean dry period in hours (range)	24 (16 to 34)	31 (**19 to 6**0)	36 (23 to 58)	37 (25 to 57)	55 (35 to 77)
Mean maximum dry period in hours (range)	316 (202 to 427)	390 (261 to 543)	484 (312 to 628)	439 (285 to 548)	586 (374 to 737)

*50th percentile probability level, and 50th percentile of the uncertainty distribution;
^10th percentile probability level, and 75th percentile of the uncertainty distribution.

2.3 Changes in temperature

Murphy *et al.* (2009) project a warmer climate for the whole of the UK and across the whole year, with some large variations on a seasonal basis. Mean temperature increases in all areas of the UK are projected to be greatest in the summer season and for southeast England (3.9°C (2.0 to 6.5°C)). Central estimates of the average regional summer (June, July, August) temperature rise in the 2080s are between 3 and 4°C. In the South East, projected increases in average summer temperatures are 1.6°C (0.6-2.7°C) during the 2020s, 2.3°C (1.0-4.0°C) by the 2040s and 3.9°C (2.0-6.4°C) by the 2080s. Winter mean temperature rises are less significant but highest in London and the eastern and southeastern UK (2080s: 3.0°C (1.6 to 4.7°C)).

2.4 Sea level rise

Projections for relative sea-level rise show a range of 0.12 to 0.76m by 2095 for high emissions (Murphy *et al.* 2009), compared to a range of 0.16 to 0.69m at UKCIP02 (Lowe *et al*. 2009; Hulme *et al.* 2002). Murphy *et al*. (2009) projections are based on the outputs of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), for which the worst-case scenario for global sea-level rise was 0.59m. The AR4 projections do not take into account accelerated disintegration of ice sheets that would lead to much larger sea-level changes, and can therefore be viewed as conservative estimates. The IPCC Fifth Assessment Report (IPCC 2013) uses different emissions scenarios, the highest of which (RCP8.5) gives a sea level rise of up to 0.98m by 2100. Only a collapse of marine-based sectors of the Antarctic ice sheet could cause global mean sea level to rise substantially above this, but it is anticipated that this would not exceed several tenths of a metre before 2100. According to the Met Office (2014) sea level along the English Channel has already risen by about 12cm in the last 100 years, and it is expected a further 11-16cm of sea level rise by 2030.

UKCP09 projections also include a High^{++} scenario to account for larger, though much less likely, changes to sea-level rise caused by dynamical ice sheet changes (Murphy *et al*. 2009). Using a global sea level rise figure of 2.5m (derived from Rohling *et al.* 2008), a UK-wide range of sea level rise is given as 0.93 – 1.9m for 2095 (Lowe *et al.* 2009).

3. Impacts of climate change on wastewater systems

In this section, the climate changes described above are considered in terms of their impacts on:

i) Wastewater flows (inflows into the wastewater system);
ii) The operational performance of wastewater networks and treatment systems; and
iii) The resultant flows of wastewater from the wastewater system.

These impacts are the impacts that are expected without taking into consideration the adaptation strategies and the types of interventions described in the following sections that are already being adopted by the wastewater companies to varying degrees.

3.1 Wet weather impacts

3.1.1 Sewer and wastewater treatment flooding

Climatic effects are particularly important when considering the frequency and extent of sewer flooding. Any change in such events is likely to be significant in future sewer system performance. Short duration, very intense convective storm events are those which are linked to sewer surcharging and flooding. Wetter winters increase the risk of sewer flooding from manholes due to overloaded sewers, which in turn causes sewer backups, flooding and basement flooding (Nilsen *et al.* 2011) if no remedial action is taken. This may lead to an increased number of properties registered at risk from internal flooding on the DG5 and DG10 flood risk registers[2], which are key indicator used by Ofwat (2009) to monitor the wastewater companies. However, properties can be excluded from being added to these register if the company can provide evidence that the flooding was caused by severe weather (Ofwat 2008). There is however lack of a consistent definition of what constitutes severe weather.

[2] DG5 and DG10 refer to the properties at risk from flooding according to 5 and 10 year return frequencies.

A hydraulic modelling of impacts of climate change, population and growth in impermeable areas on sewer systems showed that climate change has the potential to bring a significant increase in sewer flooding. The median increase in 1:10 year flooding across 97 catchments, at the 50th percentile weather simulation under the medium emissions scenario, was 27%, compared with current predicted flooding (Mott MacDonald 2011).

No catchments can be expected to see a reduction in flooding unless climate change reduces inputs by more than the increase from creep and population growth – which the currently available data suggests to be unlikely (Mott MacDonald 2011). If nothing is done, it is reasonable to expect a significant increase in the number of flooded properties across England and Wales, as well as an increasing frequency of flooding for those already at risk. Although the problems are most significant for combined sewers, it is also a problem for separate foul sewer systems, which although not designed to convey large amounts of rainfall – often have a proportion of stormwater flow as a result of misconnections of gullies or roof gutters (Defra 2012a).

Flooding can also impact on wastewater treatment works (WWTW) and sewage pumping stations (SPS). During the UK summer floods in 2007, hundreds of WWTW and SPS were flooded and put out of action as sewers in many places were overwhelmed by runoff combined with elevated river level. For example Yorkshire‘s Saltend WWTW in Hull was flooded to 0.6m, while Yorkshire’s Blackburn Meadows WWTW (near Meadowhall) was flooded to depth of two metres. The repair and recovery were estimated to cost Yorkshire Water more than £50 million and take 18 months to completed (Ofwat n.d.).

3.1.2 Overflows from CSOs

More intense rainfall results in extended high flows driven by increased rainfall and higher winter infiltration rates, but also reduced pollutant concentrations due to higher dilutions; however there may be increased ‘first flush’ flow magnitude driven by increased rainfall intensity. Increases in combined sewer overflow (CSO) discharges are also expected; this leads to water quality problems relating to increases in pollutant loads from untreated wastewater discharged into receiving watercourses.

Nilsen *et al*. (2011) used the software MOUSE to assess the performance of the sewer networks under expected rainfall regimes affected by climate change. The results of the simulations show future increases in annual CSO discharge of 33% when comparing years of maximum annual runoff. When comparing years of maximum annual precipitation, the increase was much greater; showing an 83% increase in total CSO discharges over the year.

As well as wetter winters increasing the volume of CSO spill, higher intensity rainfall results in greater scouring of sediment - both on the surface and in-sewer – and consequently greater ‘first flush’ impacts from CSOs. As described below, this problem will be further exacerbated as a result of dry periods preceding wet weather when sediment is deposited on the invert of the sewers.

Modelling of storm flows undertaken in the UKWIR (2010) suggests an increase in the spill volumes associated with more intense rainfall events. However, for intense events of a 1 hour duration (conditioned on winter changes) the mean annual number remains similar with respect to the baseline under the 2050s high emissions scenario. More recent research has shown an increase in summer convective storms (Kendon *et al.* 2014).

UKWIR (2010) also indicated that longer duration spills may impact on the functioning of screens at CSO resulting in increased headloss due to blockage. This would then lead to surcharge and sewer flooding and the potential for discharge of unscreened flows into receiving waters.

3.1.3 Impact on wastewater treatment processes

Primary settling tanks are generally designed to accommodate the maximum flow that can be treated by a plant and are therefore considered to be relatively resilient to high flow conditions (UKWIR 2012).

'First flush' events are unlikely to impact on works with multiple settling tanks as the incoming flow can be spread across all tanks. For smaller works operating single tanks the 'first flush' may cause instability resulting in rising sludge blanket and increased carry over to secondary processes.

In general, upstream storm water management, flow balancing, and primary tank operation, should protect secondary processes from significant variations in flow. As such, minimal impacts would be expected within secondary treatment processes from extended periods of high rainfall. But, for companies that operate effluent recycling, increased OPEX costs may be incurred through increased pumping rates to maintain consistent surface overflow rates.

3.2 Dry weather impacts

3.2.1 Increased in-sewer sedimentation

Longer summer dry periods result in extended low flows during dry weather and an increase in pollutant concentrations by reducing the extent of infiltration (Arkell *et al*. 2013). Prolonged periods of dry weather may also result in increased sedimentation of solids in sewerage systems, contributing towards the greater 'first flush' pollutant loads and concentrations of untreated wastewater from CSOs. It is expected that this be further exacerbated by increasing concentrations of suspended solids in dry weather flow as a result of decreasing water consumption due to water conservation measures in the home (Parkinson *et al.* 2005).

3.2.2 Increasing septicity of dry weather flows

According to Ashley *et al*. (2008) the prolonged sewer residence times could further lead to septicity where dissolved oxygen (DO) levels are low and allow more in-sewer chemical transformations. Hydrogen sulphide is slowly produced by sewage as it travels through the sewage system. Lower flows combined with higher temperatures increases the risks of hydrogen sulphide gas production, septicity and associated odour related issues and an increasingly corrosive effluent in periods of prolonged dry weather. Not only does hydrogen sulphide create an odour nuisance but it also attacks ferrous and concrete equipment, leading to a reduction in the thickness of concrete pipes and degradation of concrete manholes along pipelines, and impacting upon pumping stations and rising mains.

3.2.3 Impacts on wastewater treatment

There is also an increased risk of septic wastewaters arriving at treatment works as a result of prolonged dry weather and higher ambient temperatures. This may adversely affect primary sedimentation processes due to rising gases from digesting organic matter. However, according to WEF (2005), this is difficult to quantify and for works employing effluent recycling no significant impacts are anticipated.

Primary settling tanks may also be subject to short-circuiting (short retention time) arising from temperature induced convective and density currents which may affect performance, but these effects are difficult to predict (UKWIR 2012). Density current can be developed on the tank bottom followed by stratification of wastewater when the influent temperature is less than the ambient tank temperature (McCorquodale *et al*. 1995). On the other hand, a buoyant plume and surface density current may occur when the influent temperature is greater than the tank temperature. Therefore under the temperature projections for climate change it is likely that short-circuits will become a frequent problem in wastewater treatment works.

During prolonged low flow conditions, overflow rates will be reduced and retention time increased. Under such conditions it would be anticipated that performance would be improved resulting in reduced suspended solids and BOD loadings on secondary processes (UKWIR 2012). The consequence of improved settlement will be an increase in primary sludge being fed to the sludge management processes. This will improve the thickening process and increase biogas production given that primary sludge is easier to thicken and digest than secondary. The reduced load in the settled sewage will also reduce aeration costs in the downstream aerobic process. Under low flow conditions with improved performance it will be necessary to increase the rate at which primary sludge is removed in order to prevent septic conditions developing in the tank. Therefore, there needs to be sufficient capacity in downstream sludge management processes to take account of the increased rate of sludge removal.

Climate change is also likely to mean hotter drier summers with increased risk of drought events, with reduced river flows requiring increased discharge consents. Although some deterioration in performance may be seen in attached growth processes that require constant wetting, overall the expectation is that treatment processes are likely to improve, but at the same time climate change is likely to result in reduced annual and particularly seasonal river flows (Romanowicz *et al*. (2006) leading to consent compliance issues because of the lower dilution (UKWIR 2012). This may in turn require higher standards of sewage treatment in order to meet statutory environmental requirements (Defra 2012b). Some wastewater companies may not have a plan in place for the next 25 years to deal with the risk of consent failure because at present there is little observed deterioration in water quality (Welsh Water 2011). However, companies may recognise that there is a high level of impact combined with a medium level of likelihood.

3.3 Sea level rise

Infiltration of saline water into sewers is recognised to adversely affect the performance of wastewater treatment predominantly where interceptor sewers have been laid along the coast. The duration of immersion of sewers by saline water rises significantly due to the nature of the tidal cycle which increases volumes of saline water entering the sewers and consequently cause a number of problems at treatment plants:

i) Increased pumping costs due to increased volumes of wastewater;
ii) Impact on treatment performance - salinity fluctuations disrupt microbiological processes and affect the surface tension of the mixed liquor suspended solids (MLSS) flocs, which reduce the settleability of activated sludge in the secondary sludge clarifiers
iii) Increased rate of hydrogen sulphide production; and
i) Impact on COD monitoring which suggest that wastewater treatment plants are failing their consents set by the Urban Wastewater Treatment Directive.

Problems caused by sea level rise are not expected in all parts of the UK and therefore no adaptation action is being taken by some companies (Welsh Water 2011; South West Water 2011; United Utilities Water 2011).

3.4 Temperature increase

Increase in temperature will almost certainly improve the rates of reaction in wastewater and sludge treatment processes (South West Water 2011). In addition, temperature increase may also enhance the use of anaerobic digestion for wastewater treatment which is used in warmer countries (Northumbria Water 2011). Anaerobic treatment of sewage would allow greater volumes of biogas to be produced, enabling the generation of renewable energy and greenhouse gas emission reduction. However, the current forecast of rise in temperature makes this unlikely on its own but new technology developments may make it possible with even modest temperature rise (Arkell *et al*. 2013)

4. Wastewater system impacts on society and the environment exacerbated by climate change

This section focuses on the impacts that wastewater systems may have upon society and the environment that are expected to be influenced by climatic changes.

4.1 Health impacts

Contamination of water supply systems

Increased flooding can disrupt wastewater services and flood houses with contaminated water, potentially leading to the increase of infectious disease. In the UK, infections caused by floods are rare (NHS 2012) and there is no strong evidence to show the health effects after flooding are related to sewage backup. For instance, there is no evidence from previous UK flood events, such as those in Carlisle in 2005 (Fewtrell 2011) and Lewes in 2000 (Reacher *et al*. 2004), that there was an increased incidence of gastro-intestinal illness. Enhanced surveillance by Public Health England (PHE) has not detected increased reports of infection in areas affected flooding and this may be due to the following practices (NHS 2012):

i) The high extent of dilution of wastewater;
ii) The low prevalence of enteric waterborne diseases (e.g. typhoid and cholera) in the UK population; and
iii) Water companies ensure that people have access to clean drinking water - either bottled or from bowsers - in flood situation.

Additionally, high pressures in water distribution reduce chances of ingress of polluted water into the UK water systems.

Although mains water supplies are usually safe during flooding events in the UK (HPA 2014), increasing ambient temperatures due to climate change in combination with heavy rainfall may result in reappearance of waterborne diseases which are commonly associated with developing countries. For example, several drinking water outbreaks followed a period of heavy rainfall have been reported in the UK (Atherton *et al*. 1995; Bridgman *et al*. 1995; Willocks *et al*. 1998; Harrison *et al*. 2002) and elsewhere (Jean *et al*. 2006; Aksoy *et al*. 2007; Lee *et al*. 2008). If this trend becomes apparent, there are opportunities to learn from research in humid tropics where it is already well recognised that heavy rainfall can impact upon public health through contaminated flood water (Griffith *et al.* 2006). For example, the prediction of cholera using climate forecasting is becoming increasingly feasible (Anyamba *et al.* 2006; Constantin de *et al*. 2008; Hashizume *et al.* 2010).

Stress and psychological impacts

In the UK and other developed countries, the health impacts related to flooding are mostly non-microbiological (e.g. drowning, car accidents, injury, electrocution, asphyxiation, animal bites) and for affected people/homes there are issues of stress, cleaning, over-exertion and depression (Ahern *et al*. 2005; Du *et al*. 2010; HPA 2011).

Fewtrell and Kay (2008) concluded that most of the public health threats in the aftermath of flooding were found to be associated with population displacement and damage to infrastructure which can lead to distress and strain in the victims. After floods due to heavy rainfall and sewage backup, the householder affected can develop short and long term psychological health problems such as stress, depression, strain and anxiety. The restoration of flooded homes is both physically and emotionally intense with victims usually finding it difficult to identify where to start while avoiding potential health risks and hazards (Minamiguchi n.d.). People who are vulnerable to psychological health problems are particularly at risk from the effects of extreme weather on their emotional wellbeing (IASC 2007).

The Marmot Review (2010) found that people who live in the least favourable environmental conditions in the UK (e.g. with risk of being flooded) are also people who live in greatest poverty. This agrees well with the WHO findings that disadvantaged people are likely to experience more severe consequences following a flood (WHO 2002). However, the floods in 2013/14 along the River Thames were not restricted to low income areas. This indicates a need to investigate the effects of different types of floods on different socio-economic groups.

Contamination of bathing and shellfish waters

Coastal and inland waters used for recreational purposes can be contaminated by sewage overflows following periods of heavy rainfall. However, according to Nichols and Lake (2012) there is strong evidence for faecal contamination of coastal waters but only broad indications that the more contaminated the water is by faeces or sewage the greater is the chance of symptomatic illness associated with bathing in it. Harrison and Kinra (2004) report a Verotoxigenic Escherichia coli (VTEC) outbreak among people who had occupied the same part of a beach where there was prior heavy rainfall.

Although it is clear that there is a risk of the bathing water being contaminated by sewage outflows during floods, there are also other sources (e.g. animal faeces) that may also give rise to higher microbial counts. For example, the VTEC outbreak affecting people on holiday in Cornwall, all of whom had stayed at different places locally, was caused by contamination of a freshwater stream, which flowed across a beach, by cattle faeces and heavy rainfall (Ihekweazu *et al*. 2006).

Although climate change impacts on wastewater infrastructure may increase health risks during wet weather, reduced summer rainfall (Murphy *et al*. 2009) may reduce faecal inputs into coastal and inland waters due to lower CSO contamination (Wither *et al*. 2013). In addition, because there have been improvements in bathing water quality over recent years (European Environment Agency 2009), it is difficult to provide reliable estimates of changes in disease burden due to changes in climate in particular due to contamination by sewage.

In the UK, the potential impact of climate change upon intermittent discharges of CSO was investigated by FitzGerald (2008a) and modelling of future scenarios indicated that £10-15 billion would be required to maintain existing levels of CSO spill containment to protect shellfish and bathing waters (FitzGerald 2008b). Contamination of shellfish beds with sewage can increase during the winter due to high river flows and sewage overflows, but it decreases during summer. An outbreak of norovirus associated with oysters in France was linked to contamination of oyster beds by a period of heavy rainfall and overflow of a WWTW (Doyle *et al.* 2004). Outbreaks of norovirus, leptospirosis and other infections have also been associated to floodwater in other developed countries (Schmid *et al.* 2005; Zitek and Benes 2005; Marcheggiani *et al.* 2010).

As discussed, the contamination of coastal and inland waters are not only due to CSOs but also due to diffuse pollution from farming. Therefore, it is important to understand the relative contributions of CSO and diffuse pollution contributions in the UK and this can be done through microbial source tracking (e.g. Payan *et al.* 2005) to find out if the water contamination is from human or animal.

Workers on sewer operations

Detailed risk assessments for both networks and WWTW have been carried out to identify health and safety issues (UKWIR 2012). For example, increased septicity during summers may result in the formation of hydrogen sulphide and methane which are harmful to human health. The increase of these gases within sewer confines will have health and safety issues for those working on maintaining sewer operations.

4.2 Water quality of receiving waters

With the probability of wetter winters, more intense rainfall events and greater climate variability in the UK, we can expect greater pressure on sewerage systems (Keirle and Hayes 2007). As noted above, increases in rainfall can result in increased pollution from sewer systems during both summer and winter conditions. With increased storm events, especially in summer, there could be more frequent incidences of combined sewer overflows discharging highly polluted waters into receiving water bodies. The assimilative capacity of water bodies to cope with CSO spills will most likely be reduced as well, due to increasing temperatures and lower river baseflows (Marine Conservation Society 2011).

Reduced flows in rivers also results in less dilution leading to higher organic pollutant concentrations downstream of point discharges of WWTW, with increased biological oxygen demand (BOD) and, hence, lower DO concentrations in rivers. Phosphorus in particular increases significantly in summer months as flows fall. This is a direct consequence of reduced dilution of WWTW effluents. According to Whitehead *et al.* (2009), this could affect efforts to improve water quality standards or meet WFD objectives to restore and protect freshwater ecosystems.

Cox and Whitehead (2009) show that, under a range of UKCIP02 scenarios (Hulme *et al*. 2002), DO in the River Thames will be affected in the 2080s by enhanced BOD, and by the direct effects of temperature which reduces the saturation concentration for DO. These impacts are not considered to be too significant but the frequency and intensity of algal blooms may increase, causing large diurnal variations in DO which adversely affects the aquatic ecology. The enhanced growth of algal blooms in rivers and reservoirs which could affect DO levels and water supply.

Conlan *et al.* (2007) investigated BOD, DO, nitrate, ammonia and temperature in rivers as a result of climate change. There were insufficient data to adequately calibrate and validate the water quality model, but a model sensitivity analysis illustrates the links between climate change and water quality. As expected, under reduced flows in summer, BOD and P levels would increase, whereas ammonia levels would fall due to higher nitrification rates. This gives rise to increased nitrate concentrations as ammonia decays to nitrate.

5. Adaptation as a means to manage wastewater risks related to climatic impacts

Adaptation seeks to reduce the impacts of hazardous events by enabling systems to adjust to climate changes. Under the Government's Adaptation Reporting Power, introduced by the Climate

Change Act (2008), the wastewater companies were initially asked to provide details of their understanding and preparations for the impacts on their services. This resulted in the preparation of a series of adaptation reports in 2011 which were based around the latest set of UK Climate Projections, the Government's latest national Climate Change Risk Assessment (CCRA) and in consultation with the appropriate statutory consultees (Defra 2012a).

Whilst the CCRA assumes that adaptation measures are not yet in place, it is important to note that in reality many of these risks are already being addressed to some extent. This is evident in the reports produced under the Adaptation Reporting Power (ARP) by 91 organisations, including the majority of infrastructure operators. It is noteworthy that, as well as adaptation to climate change, demand for additional wastewater infrastructure is also in response to other drivers including population growth and urbanisation and more stringent statutory requirements to protect the environment and water quality.

Previously, the focus of adaptation was on ensuring that no critical assets were seriously affected by extreme weather events over their estimated lifetime, taking into account the latest climate projections. However more recently, the adaptation strategies endorsed by Government Agencies are less prescriptive and encapsulating a broader strategy for adaptation as described by the UK Government's *A Guide to improving the resilience of critical infrastructure and essential services*. Resilience is understood to be the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event. It is secured through a combination of four principal strategic components (Cabinet Office 2011):

i) *Resistance* focuses on providing protection to resist the hazard or its primary impact;
ii) *Reliability* ensures that the infrastructure components are inherently designed to operate under a range of conditions and hence mitigate damage or loss from an event;
iii) *Redundancy* concerns the design and capacity of the system operations to be switched or diverted to alternative parts of the network; and
iv) *Response and Recovery* aims to enable a fast and effective response to and recovery from disruptive events.

To be able to make decisions about where and when to invest and to identify which assets to prioritise for upgrade requires a long term planning perspective. Whereas the need for water infrastructure is assessed over a 25 year planning horizon, there is no equivalent requirement for wastewater infrastructure. However, although there is no statutory requirement, the wastewater companies may consider a long term perspective as part of their 5 year business cycle.

5.1 Design and capacity of wastewater infrastructure

Although adaptation strategies are becoming increasingly more sophisticated in line with the Cabinet Office's recommendations described above, there will invariably be a need to increase capacity of critical wastewater infrastructure where deemed by sewerage companies to be necessary, and demonstrated to be cost-beneficial, by the sewerage companies. In addition, innovative solutions to sewage drainage have been recommended by Ofwat (2013). For example, where companies have tackled sewer flooding by increasing its underground system to store more rainfall during storms, working with customers to manage the rainfall close to source to prevent it from entering the sewer systems is a good practice (Ofwat 2013).

The translation of adaptation into engineering design means assessing the impacts of climate change driven factors on the potential exceedance of performance thresholds and subsequently translating the desired increase in capacity into design parameters. Coulthard *et al.* (2007) raise concerns about the lack of safety factor or contingency added to designs. When reviewing the drainage and pumping systems for Hull after the floods in June 2007, they noted that they were all designed exactly to the limit of a 1 in 30 year event. In addition they noted that the actual pumping capacity is consistently under-estimated due to different viscosity and solids and the pumps, notably the older ones, have reduced 'effective' pumping capacity due to a lack of regular maintenance and cleaning during pumping operations.

Wastewater companies also design the network to provide protection against flooding during a 1 in 30 year rainfall event (Yorkshire Water 2011). Recent thinking within the industry, supported by UKCP09 (Murphy *et al*. 2009), indicates that this current standard will not provide the same level of protection in the changing climate of the future. In order to consider and manage this effectively it is necessary to better understand the operation of the wastewater networks and changing rainfall patterns (Yorkshire Water 2011). To address this issue, one option is to undertake strategic research into the effects of climate change on the overall infrastructure before revising design standards (Yorkshire Water 2011).

Investments may be required in wastewater treatment due to reduced river flows requiring higher efficiencies of sewage treatment in order to meet statutory environmental requirements within the receiving waters. Additionally, in some situations, there may be a need to increase the capacity of wastewater infrastructure to manage higher flows of peak runoff.

Table 4 presents a summary of some of the adaptive strategies that the UK wastewater companies have adopted or planned to deal with flooding impacts. However, as described below, there are an increasing number of adaptation approaches that may be adopted by the wastewater companies as part of their strategy for maintaining service levels under current scenarios of climate change.

5.2 Source control of stormwater and attenuation of runoff

For the past few decades, there has been increasing focus of attention on stormwater management practices that focus on a) reducing runoff at source, and b) land management approaches that use natural systems to slow the flow of surface water, as a means to reduce requirements to increase the capacity of wastewater drainage infrastructure. However, there have been uncertainties regarding the long-term performance of some types of Sustainable Urban Drainage System (SUDS) that may lead to problems over adoption and maintenance and it is recognized that in certain circumstances conventional storage and treatment options might offer a more cost effective and sustainable approach to CSO control (CIWEM 2004). In addition, although diverting surface water drainage away from sewerage systems reduces the hydraulic loading on wastewater infrastructure, the organic load is not reduced and therefore the capacity of WWTW still has to be increased in response to population or industrial growth (Defra 2010).

Table 4: Adaptive strategies by the wastewater companies in response to flooding: wastewater infrastructure adaptation (Source: Various wastewater company climate change adaptation reports, 2011)

Impact	Adaptation strategy
Customer properties flooded internally or externally	• Strategic research into the effects of climate change on infrastructure before revising design standards. • Increased rainfall monitoring and flow modelling • Increase sewer network capacity as part of planned sewer rehabilitation • Line sewers to reduce infiltration of groundwater into sewers • Pump overflows during river flooding
Wastewater treatment	• Separate storm flow and create foul only system
Power outages and service failures	• Backup generators • Major assets have dual electricity supply from a separate sub-station • Consideration of power outage in design of assets to ensure overflows will not lead to customer flooding

Storm water retention and detention ponds (otherwise known as basins) can provide an effective means to manage storm water runoff and protect downstream areas from flooding, performing a storage function, attenuating peak discharges and contributing towards the control of flooding and discharges from overflows. Butler *et al.* (2007) estimated the required future storage volume for various return periods and indicated the need for a 57% increase in the average volume of storage required to maintain the same level of flood protection. Mott MacDonald (2011) concluded that, if sewers and storm tanks are to be provided (and still to be allowed) for developments these should be sized with an allowance for creep plus climate change as they will otherwise be under-sized for future flows, causing flooding and/or increased flows in the foul/combined system.

SUDS are increasing recognised for the benefits that they provide in relation to improved water quantity, amenity and biodiversity as well as reduction of flooding. In addition, water evaporation also cools the overlying air and reduces the urban heat island effect. This approach is increasingly being considered as a means to adapt to the impacts of climate change (Charlesworth 2010). Charlesworth (2010) provides case studies from around the world to illustrate how vegetated SUDS can sequester and store carbon, cool urban areas and increase perceptions of health and well-being in the population.

In the UK, Defra funded 15 case studies to examine, in detail, various aspects of integrated urban drainage management through partnership between local authorities, the Environmental Agency and various water and sewerage companies. The Integrated Urban Drainage (IUD) pilot projects were located across England and examined partnership development, data sharing issues, modelling approaches to surface water flood risk assessment and options to mitigate surface water flooding. The 'IUD Pilots' were highly informative in helping to identify good practice approaches and contributed to the development of the Surface Water Management Plan Technical Guidance (Defra 2010).

There have been some constraints with respect to the installation of SUDS related to the responsibility for implementation of these systems, but the Flood and Water Management Act (FWMA) 2010 has introduced a range of significant new responsibilities for local authorities in relation their implementation and operation and maintenance. Unitary and county councils are responsible for forming SUDS Approval Bodies (SABs) to evaluate and approve SUDS in all new developments and to adopt and maintain SUDS serving more than one property, and the requirements of National Standards for Sustainable Drainage came into force in 2012. Although it is accepted the Lead Local Flood Authorities (LLFAs) will have a duty through the Flood and Water Management Act (FWMA) to adopt sustainable drainage, there are many existing assets that may or may not be maintained by a variety of different agencies including wastewater companies, the highways agency and private developers that could ultimately discharge to the sewer network including combined sewers. Table 5 summarises some of the adaptive strategies that the UK wastewater companies have adopted or planned to manage storm water.

To assist with the implementation of SUDS, Charlesworth (2010) proposes a simple hierarchy of suitable measures based on the density and land-use of the built-up area:

1) *Densely occupied urban centres*: SUDS is a supporting mechanism, relieving the pressure on conventional systems, which involves small-scale patches of retrofit such as green roofs and walls, areas of porous paving systems and rainwater harvesting;
2) *Suburban areas* that are already developed but have more available space can include the same SUDS as the urban centres but in addition can support larger devices such as roadside swales, ponds/ detention basin incorporated into roundabouts and larger areas of porous paving in combination with constructed wetlands/ponds used for supermarket and industrial estate car parks; and
3) *New developments in the urban periphery* need to incorporate SUDS from the onset of their design, in which a series of ponds, wetlands and swales can provide the area with the multiple benefits associated with a sustainable drainage system.

Table 5: Adaptive strategies by the wastewater companies in response to flooding: SUDS (Source: Various wastewater company climate change adaptation reports, 2011)

Impact	Adaptation strategy
Sewer flooding and river flood impacts on wastewater infrastructure	• Surface water separation/ SUDS implementation • Surface water management plans

5.3 Structural adaptation to sea level rise and saline intrusion

Tide gates are designed to reduce or prevent receiving water from flowing back into sewer outfalls during high tides. These may also be employed to reduce the addition ingress caused by sea level rise and provide greater retention volumes in the collection system (New York City Department of Environmental Protection 2013). Proposed adaptive measures include ensuring asset design standard takes account of sea level rise. Other measures include surface water management plans with stakeholders in tide-locked catchments, drainage area plans and Shoreline Management Plans.

In order to reduce impacts of saline intrusion, one adaptation option is to re-lay the sewers away from the infiltration zone, but this is likely to be expensive and complicated due private ownership of drains. There is little evidence that adaptation measures to deal with saline intrusion are currently in place or being proposed by UK wastewater companies. Other adaptive measures for saline intrusion (Table 6) include identification of vulnerable assets through the periodic review process and monitoring and control of the wastewater quality.

Table 6: Wastewater company adaptive strategy in response to saline intrusion (Source: Various wastewater company climate change adaptation reports 2011)

Impact	Adaptation strategy
Saline intrusion	• Continuous monitoring of effluent quality • Review of data at part of periodic review process, identify areas of saline infiltration and target sewer rehab work on vulnerable assets

5.4 Increasing asset resistance

The resistance of critical wastewater assets (notably treatment works and pumping stations) may be increased by constructing floodwalls to prevent floodwaters from entering (‘dry proofing’). Alternatively, structures may be designed to withstand the effects of floods (‘wet proofing’) or potentially elevated above the expected floodwater. Table 7 presents a summary of some of the adaptive strategies the UK wastewater companies have adopted or planned to deal with flooding impacts. These measures can be incorporated into new developments, but for existing wastewater infrastructure, it may not be cost-effective due to the high costs of retrofitting.

Table 7: Adaptive strategies by the wastewater companies in response to the floods: asset resistance (Source: Various wastewater company climate change adaptation reports 2011)

Impact	Adaptation strategy
Asset deterioration	• Periodic review of structural condition of assets • Change asset design standard to accommodate changing use • Increase in flood defence around treatment works
Inundation of wastewater treatment plants and pumping stations from river flooding	• Increase in flood defence around treatment works • Raising critical equipment to higher level • Surface Water Management Strategy (SWMS)/Surface Water Elimination and Reduction (SWEAR)

5.5 Dry-weather adaptations

A range of dry-weather adaptation strategies focus on the sewerage system itself and are mainly focussed on actions to reduce increased sedimentation in sewers, either by source control measures or sewer maintenance, or on the operational control of WWTW. These may benefit from improved monitoring and the use of real time control to ensure that the treatment processes are adjusted to be able to adapt to the impacts related to low flows and increased concentration of wastewater and associated septicity problems. Table 8 presents some of the adaptation strategies in place/proposed by the UK water industries to deal with dry-weather impacts.

5.6 Adaptation to temperature increase

Some of the adaptation measures (Table 9) to deal with impacts of higher temperatures in place or being proposed by UK water industries include reviewing chemical needs of wastewater treatment process and reviewing operational target parameters, and review bio-solids strategy to cope with increased odour.

Short-circuiting of wastewater through a wastewater tank due to temperature induced flow arising from temperature can be managed by ensuring that adequate baffling in the tank is provided. For smaller works companies will need to ensure that adequate storage volume is available to accept the increased rates of primary sludge removal. Companies will need to ensure that digestion and Combined Heat and Flow facilities can handle the increased biogas production, for instance by flaring biogas.

Table 8: Wastewater company adaptive strategies in response to dry weather (Source: Various wastewater company climate change adaptation reports 2011)

Impact	Adaptation strategy
Sewer blockages	• Maintain self-cleansing systems • Sewer maintenance (jetting) • *Bag it & Bin* it campaign to raise public awareness of dumping inappropriate items down toilets • Improve sewer monitoring
Increased septicity	• Review storm water tank size and mode of operation due increased retention time • Odour strategy to deal with customer complaints
Lower average and peak flows at pumping stations	• Need for more back up pumps as increased failures would have a very high impact • Use of materials which resist corrosion • Design pump stations to resist wear • Chemical dosing to reduce H_2S levels • Self-cleansing pump systems
Reduced water quality of receiving waters (including environmental impacts and impacts on bathing water quality)	• Extend monitoring • Develop and agree more appropriate consents • Improve discharge quality where necessary

Table 9: Wastewater company adaptive strategies in response to temperature rise (Source: Various wastewater company climate change adaptation reports 2011)

Impact	Adaptation strategy
Treatment performance	• Review operational target parameters • Continuous monitoring of wastewater effluent • Monitoring and process control
Increase odour	• Review chemical needs of treatment process • Review operational target parameters • Increased/additional aeration • Review bio-solids strategy

5.7 Integrated modelling and real time control

There is growing recognition of the need for and benefits of integrated simulation of the sewer system, wastewater treatment plant, and receiving water body in order to achieve a better receiving water environment (Rauch *et al.* 2002; Schütze *et al.* 2002; Butler and Schütze 2005; Vanrolleghem *et al.* 2005). Considering sewer and WWTP systems as integrated systems enables sizing integrated urban wastewater system (IUWS) storage capacity adequately so that the system as a whole can deliver the best/target performance (Astaraie-Imani *et al.* 2013).

Innovative approaches for controlling integrated urban wastewater and storm water systems have been made possible by the development of simulation tools combined with the development of sensors, improvement of their reliability, and new strategies for handling the increasing flow of available measurements (Schutze *et al.* 2004; Campisano *et al. in press*).

In recent years, several simulation tools and methods have been developed, for example, SYNOPSIS (Schütze *et al.* 2002), SIMBA (ifak, 2005), WEST (Vanhooren *et al.* 2003), and CITY DRAIN (Achleitner *et al.* 2007), and this provides the opportunity to optimize the urban wastewater system as a whole. In the UK, STAVRoS has been developed by Halcrow as a simplified and integrated urban drainage catchment model that simulates the operation of CSOs in sewerage networks, the receiving river system and interfaces with process models of sewage treatment works. These models enable simulation of water quality impacts of polluting runoff and effluent from urban areas and can be used to rapidly assess the outcome of catchment strategies such as storm separation, real time control and storage construction.

Astaraie-Imani *et al.* (2012) explore the potential for managing water quality within a risk-based framework in the context of an IUWS consisting of a sewer system, wastewater treatment plant by optimising the operational control and/or design of the wastewater system. Risk was defined as the product of the likelihood and impact of water quality standard breaches and, in the case study analysed, climate DO oxygen failure. The researchers indicated that operational control optimisation has the potential to reduce the risk of recipient water quality failure but an acceptable level of risk can only be achieved by combining improved operational controls and system (re)design, which may have considerable costs for implementation.

In a follow up study, Astaraie-Imani *et al.* (2013) demonstrated that operational control optimisation alone, under all the scenarios developed, does not have enough potential to cope with these future conditions and only when combined with design optimisation can adequate performance be guaranteed. The results obtained in the case study analysed illustrate that operational control optimisation has limited potential in terms of improving the quality of water in the recipient under the considered climate change scenarios.

6. Assessment of confidence in the science

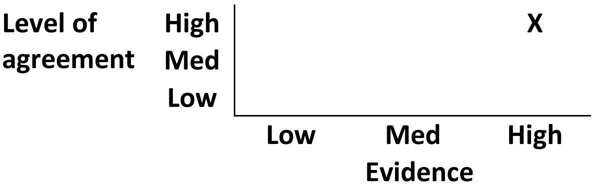
6.1 Confidence in the science related to the level of understanding of the impacts

In this section, the authors subjectively assess and summarise the level of confidence reported in the literature documents in previous sections in relation to two key aspects. The authors assess what evidence is there to support these arguments in relation to:

a) The type, amount, quality and consistency of information; and

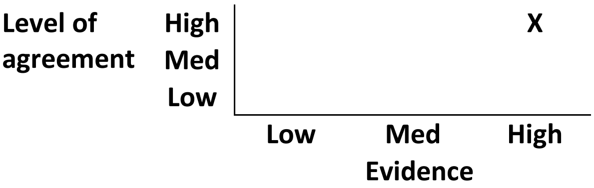
b) What level of agreement exists about the science and the level of understanding of the impacts i.e. in situations where there are recognised links between climate change, the resultant impact on the wastewater system and subsequently the impacts on people and the environment.

Sewer flooding



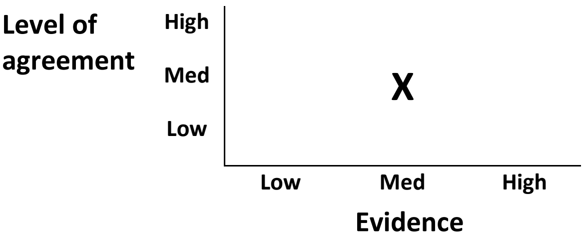
High level of agreement that the evidence for increased **sewer flooding** due to climate change impacts is high.

Overflows from CSOs



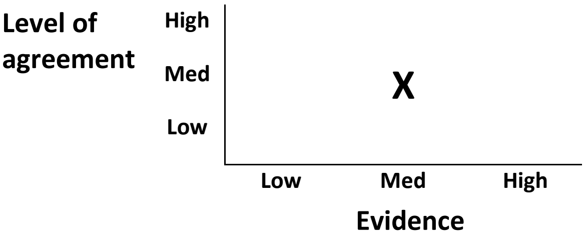
High level of agreement that the evidence for **increasing spill volumes** during intense rainfall events is high.

Wastewater treatment processes - dry weather



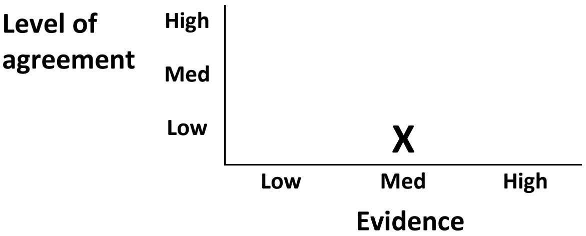
Medium level of agreement that the evidence for, and understanding of, climate change impacts on **wastewater treatment processes** in dry weather conditions is medium.

Wastewater treatment processes - wet weather



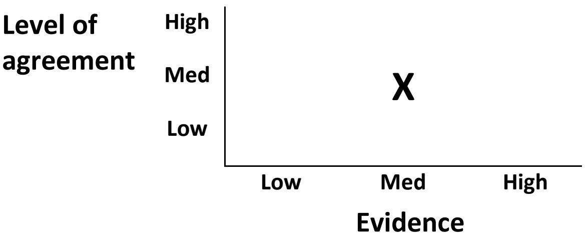
Medium level of agreement that the evidence for, and understanding of, climate change impacts on **wastewater treatment processes** in wet weather conditions is medium.

Increased in-sewer sedimentation



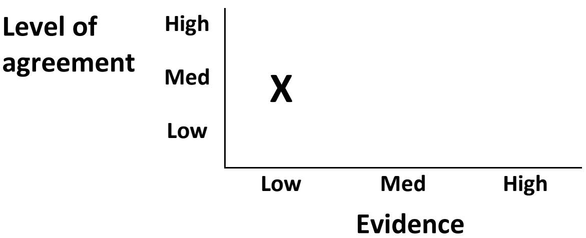
Low level of agreement that the evidence for increased **in-sewer sedimentation** during prolonged dry periods is medium.

Increased septicity of dry weather flows



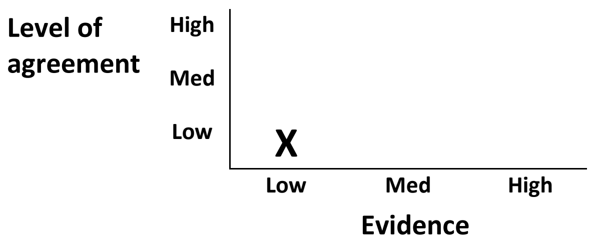
Medium level of agreement that the evidence for, and understanding of, climate change impacts on **increased septicity of dry weather flows** is medium.

Sea level rise - saline intrusion



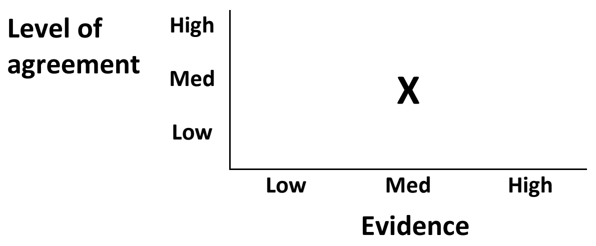
Medium level of agreement that the evidence for, and understanding of, climate change impacts on **saline intrusion** is low.

Stress and psychological impacts



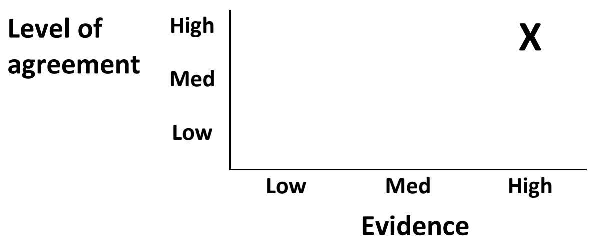
Low level of agreement that the evidence for, and understanding of, climate change impacts on **stress and psychological impacts** is low.

Health impacts



Medium level of agreement that the evidence for, and understanding of, climate change impacts on **population health** is medium.

Water quality of receiving waters



High level of agreement that the evidence for, and understanding of, climate change impacts on **water quality of the receiving water** is high.

6.2 Confidence and cost effectiveness of proposed adaptation strategies to manage these impacts

Although there has been research which quantifies the magnitude of climate change on different parts of the wastewater system, there has been less work that considers the integrated system and the overall effect on serviceability indicators. It is recognised that there will be a significant financial impact on wastewater companies, which are likely to require both increased total life cycle investment. However, although the wastewater companies are expected to present the economic justification for schemes included in their business plans there has been no systematic assessment of the potential impacts to the water industry in financial terms.

In this section, the authors subjectively summarise the level of confidence in the proposed adaptation strategies to manage the impacts (Table 10) and also consider the cost implications of these strategies which can then be used as the basis for a high level assessment of their cost effectiveness. Northumbrian Water (2011) highlights the reasons why the costing of adaptation measures and application of routine cost benefit analysis is difficult:

1. Although the level of understanding of the problems is good and it is developing, further work is needed in to properly assess with sufficient certainty the true impact on service delivery, and to make judgments about how standards of service might best be maintained;
2. For some issues, particularly where uncertainty is involved and where the costs are incurred now and the benefits accrue in the future, routine cost benefit appraisal is not well suited to the decision-taking process; and
3. For many climate change issues, there still remains sufficient time to develop and implement adaptation strategies. Decisions are best deferred until improved information is available to ensure that investments deliver better value.

Table 10 Confidence in key adaptation strategies to manage the impacts.

Adaptation measure	Evidence of effectiveness of proposed intervention	Level of agreement	Cost
Increased capacity of wastewater infrastructure	High	High	High
Mitigation measure against saline intrusion	Low	Low	High
Monitoring and operational control strategies	Medium	Low	Medium
Source control of stormwater and attenuation of runoff	Medium	High	Medium
Flood proofing	Medium	Medium	High

6.3 Managing customer perception and expectations

There are a range of adaptation interventions that can be adopted by wastewater companies but in general there remains considerable uncertainty about the effectiveness of adaptation measures, because impacts are not fully understood (and are uncertain) and because the effectiveness of measures has not been evaluated. However, in addition to the confidence in the science behind climate adaptation strategies is the fact that customer perceptions of climatic impacts and the response strategies adopted by the wastewater companies is of critical important for both commercial and socio-political reasons.

Increasingly there is a move towards meeting customer demands for the level of service that they are prepared to pay for and therefore it is the resultant performance of the assets that is of concern. This means for example that classification of storms as severe is less of an issue because informing customers that flooding was not the wastewater company's responsibility due to severe weather conditions is not going to be good for the company relations with its customers. Therefore, of greater importance is for the wastewater companies to maintain or demonstrate an improved level of service with respect to sewer flooding. The way in which this is framed involves a negotiation between the wastewater companies and customers over what level of service they would like and at what price (in terms of bills).

There is real difficulty in conveying to the public the risks of climate change, the expected impacts and what needs to be done to address these. This will be especially difficult in near future when natural variability will dominate climate change. Consequently, wastewater companies will need the support from stakeholders for implementation – particularly where the costs are high and where there is a need for partnership and collaboration e.g. to develop sustainable drainage solutions this will require working with all agencies with responsibilities for drainage, as well as with regulators and government. Therefore, effective communications between wastewater companies and customers on this topic is critical to define a way forward that is viable from a business perspective and accepted by customers and other stakeholders with vested interests.

This support the argument that adaptation strategies should be based on the likely exceedance of thresholds (where there are marked changes in service level that impact upon serviceability indicators) (Arkell et al. 2013). The approach taken by Arkell *et al*. (2013), building on earlier work (Arkell *et al*. 2011), recommended companies identify system design and operational thresholds, exceedance of which would result in a requirement for changes in operational practices or additional investment.

7. Improving the science

7.1 Adapting rainfall design storms

Currently, the sizing of wastewater infrastructure that performs a stormwater management function is based upon historical rainfall data. But the predicted intensification of precipitation extremes with climate change (Trenberth *et al*. 2003) is a key concern as a result of the large impact through flooding. To do this wastewater companies should apply the latest set of UK Climate Projections to ensure they have identified appropriate adaptation measures. However, for assessing the possible effects of climate change, urban drainage models require data that is finer than the climate-change-adjusted input data based on the above, which has been too coarse to resolve processes relevant to urban drainage modelling, in particular those related to convective precipitation events.

According to the Met Office (2014), more research is urgently needed to deliver robust detection of changes in storminess and daily/hourly rain rates. The attribution of these changes to anthropogenic global warming requires climate models of sufficient resolution to capture storms and their associated rainfall. Such models are now becoming available and should be deployed as soon as possible to provide a solid evidence base for future investments in flood and coastal defences. For example, research from Kendon *et al.* (2014) reports on the results from the first climate change experiments for a region of the UK with a very high resolution (1.5 km grid spacing) model more typically used for weather forecasting. The model simulates realistic hourly rainfall characteristics, including extremes (Kendon *et al*. 2012; Chan *et al*. 2014), unlike coarser resolution climate models (Gregersen *et al*. 2013; Hanel and Buishand 2010) giving confidence in its ability to project future changes at this timescale. The results show increases in hourly rainfall intensities in winter, consistent with projections from a coarser 12 km resolution model and previous studies at the daily timescale (Fowler and Ekström 2009). However, the 1.5 km model also shows a future intensification of short-duration rain in summer, with significantly more events exceeding the high thresholds indicative of serious flash flooding.

Regularly updated climate design values that reflect the latest changes in regional climate, including precipitation variables, are required for the updating of design codes and standards. UKWIR (2010) provided a method and software for producing uplifts and perturbed time series based on the UKCP09 Weather Generator (Jones *et al.* 2009). The approach recommended in Arkell *et al*. (2013) is that system thresholds are developed and compared with the evidence from climate projections. This ensures that full impact assessments are not required each time new projections, or new evidence, are published.

7.2 Data and monitoring

The assessment of the impact of climate changes on sewer systems will be a continuous process. Information about the development of the climate will continue to be improved and refined. It is expected that new information concerning climate changes will be minor adjustments of existing scenarios, e.g. in the form of a better geographical resolution of the variation of precipitation over local areas (Mark *et al.* 2008).

Until more accurate probabilistic data is available to allow the modelling of the effect of climate change on wastewater assets, it is a challenge to wastewater companies to either promote schemes or put a cost on the climate change impact effectively (Thames Water 2011). One option is therefore to collect more detailed rainfall data sets and improved monitoring of wastewater systems to understand between the responses of these systems to changing weather patterns. Monitoring can be used both to define thresholds and to identify trends in impact e.g. threshold exceedance (Arkell *et al.* 2013). This may require further investments into Supervisory Control and Data Acquisition (SCADA) and other information technology infrastructure to monitor, supported by appropriate decision aiding techniques and tools. These can then be used as the basis for a stronger justification for the need for specific investments in the network. However, for this to be possible, utilities need to put these investment requirements into their business plans as seen in Thames Water's business plan, who consider that this is a pragmatic approach for taking climate change into account for wastewater networks[3].

Monitoring may include consideration of routine network flow monitoring, installation of temperature loggers and more widespread dissolved sulphide monitoring. However, monitoring arrangements should be reviewed on a site specific basis. Although a lot of monitoring is undertaken within natural catchments, there may be a requirement for more targeted monitoring for vulnerable sites within catchments. In addition, real-time monitoring may offer adaptation benefits, as well as supporting climate change mitigation and improvements in water quality (Arkell *et al*. 2013).

In addition, a long-term data management strategy is required. This should ensure data is consistently collected, quality assured, accompanied by good metadata, digitally archived and easily accessible (Arkell *et al*. 2013). There is a need for a more sophisticated approach using a more developed set of indicators to assess climate change impacts and the effectiveness of adaptation strategies.

Berggren (2008) developed a set of indicators to describe the impacts of climate change on urban drainage systems falling into three categories:

i) Indicators to describe system performance;
ii) Indicators to monitor the extent of the event once the system capacity has been reached; and
iii) Indicators to describe consequences in terms of technical, economical, socio-cultural, environmental, and health (see Table 11).

Table 11 – Indicators of climate change impacts on urban drainage systems (Berggren 2008)

Technical	Damage to pipes, facilities, pump stations, infrastructure, land (erosion and landslides), and property, which affects e.g. the system capacity, other parts of the technical infrastructure in the urban environment and inhabitants in the city.
Health	People become sick or are injured or killed by the damage and the polluted environment, and also in connection to drinking water quality.
Environmental	Spread of pollutants, nutrients, and hazardous substances in the water, soil, and/or air, affecting the ecosystems and species especially in the receiving waters.
Economical	Cost of damage, cost of treatment of a polluted environment, and secondary costs, e.g. if people are hindered from doing their job due to infrastructure failure (roads, railways, internet, etc.).
Socio-cultural	In the city/municipality/country, some areas might be more affected by damage and pollution than others, and if these are areas where poor people settle, then a class or social distinction will develop in the society.

[3] www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/6776.htm

These indicators can also be divided into how they are related to events occurring in the system, before any event (e.g. flooding) has occurred, during an event and after. The purpose of these indicators is to:

- Describe hydraulic performance in the system;
- Give indications about how close to a consequence the system is, i.e. safety margin;
- Make it possible to compare different catchment areas according to their sensitivity for climate change;
- Make it possible to compare different adaptation actions for the same catchment area, in order to decide what is best to do for this part of the system;
- Give indications about how adaptable, flexible and robust a system is.

8. Conclusions: research priorities and recommendations

Natural variability in the climate makes it difficult to attribute specific events to long-term climate change and to neatly differentiate between the effects of natural climate variability and long-term climate change.

This review has highlighted that some impacts of climate change are affecting wastewater infrastructure and this has implications on the wastewater companies' performance indicators. But it is also clear that some impacts are having greater impact on some regions more than others. The authors recommend that further work is undertaken to develop a set of indicators which can be applied at the catchment level to identify those catchments which are most prone to the adverse effects of climate change. In the absence of accurate and precise climate predictions, a risk-based approach can be used to explicitly accommodate a range of possible futures.

The performance of wastewater systems is inherently variable due to the stochastic nature of rainfall. Designers and operators of these systems have developed a good understanding of the variability but the onset of climate changes has increased the unpredictability of hazardous events in terms of their location of their occurrence, timing, and magnitude. This subsequently impacts upon the unpredictability in terms of the adverse impacts on communities which may create tension between utilities, local authorities and their respective customers and constituents.

Much of the reviewed literature describes the effects of climate changes mainly in terms of the impacts on the wastewater infrastructure. Although the consequential impacts on society and workers on sewer operations are mentioned, these are not well quantified. The authors recommend therefore that the development of risk and vulnerability assessments on potentially affected communities would help to understand better what these impacts are in a way that can inform decision making and adaptation strategies.

The authors suggest adoption of the recommendations of Arkell *et al*. (2013) regarding the development of monitoring programmes that will define climate-related thresholds, capture the impacts of a changing climate and relate these to service indicators. For example, a monitoring study should be conducted in coastal assets to identify the scale of the saline intrusion problem in wastewater systems. Monitoring programmes should be supported by long-term data management strategies.

In addition, the authors propose the development of an ‘adaptation strategies guide’ for water utilities with the adaptation options based on the projected climate impacts for different regions. The adaptation options do not need to be one-size-fits-all solution but wastewater companies could use the information included in the ‘guide’ to support them to develop plans that contain adaptation options suited to their specific needs, taking into consideration their location, climate impacts of concern, and available resources.

It is also recommend the development of studies to enhance the understanding of the drivers and challenges/barriers to uptake of adaptation and how these will influence the uptake of the proposed adaptation strategies. A focus should be given on social perception and acceptability, economic incentives and disincentives, inadequate policies and regulatory framework, and roles of different actors in uptake.

Although there is a need for wastewater companies to be able to develop and apply their own risk adaptation strategies, it is important that there is consistency for reporting purposes. A common reporting framework using a set of recommended parameters would help to overcome this which could be incorporated within wastewater companies’ business planning processes and related to serviceability indicators and customer level of service

Finally, very little information was found on cost-effectiveness of adaptation options but this could be in part due to commercial sensitivity. However, all the wastewater companies have to undertake cost-benefit assessment during business planning and it would be beneficial to analyse these data. In particular, a systematic/detailed assessment of the extent of benefits of SUDS to reduce sewage flooding related problems is recommended. Given the increasing emphasis on customer demands, it would also be beneficial to provide a summary of this analysis to inform stakeholder consultation.

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