LWEC Report Card

Urban Hydrology and Climate Change in the UK

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Summary

Urbanisation in the UK throughout the 18-20thC had resulted in a significant deterioration in urban water quality and increased risk of urban flooding, however more stringent environmental regulations and improved management in the latter part of the 20thC led to gradual improvements in urban water quality and better management of flooding. During this period the degree of change in the urban environment was much greater than possible effects of a changing climate. Despite improvements the contemporary urban water environment is still under significant pressure from urbanisation and the growing threat of climate change poses an additional challenge for the design of sustainable cities. Hydrological issues that continue to affect contemporary UK urban areas include urban flooding (pluvial, sewer, fluvial, and groundwater), altered channel geomorphology, and degraded water quality (point source, diffuse, and temperature). This review assesses the evidence concerning the impacts of urbanisation on flooding, channel geomorphology, and water quality and appraises this evidence in light of science concerning the impacts of climate change in the UK. Discussion is made of this material to consider the overall confidence in the direction and degree of change to urban flooding and water quality and for identifying key areas for ongoing research to address knowledge gaps.

Key findings of the review include:

- Pluvial flooding will continue to be a growing risk to urban centres where densification of housing stock takes place and suitable mitigation measures are not put in place. The evidence indicates an overall increased risk of pluvial flooding with climate change due to wetter winters and increased occurrence of intense storm events that would exceed existing design capacity.
- Urbanisation without suitable mitigation will increase the risk of fluvial flooding, especially where settlements are placed on existing floodplains. Climate change will increase the existing risk of fluvial flooding in urban areas through increased storm rainfall events and increased rainfall intensities driving more frequent and larger floods.
- There is only limited evidence to determine how urbanisation and climate change might affect urban groundwater flooding.
- Urbanisation has significantly altered channel morphology within UK urban centres. With future climate change it is likely that the impacts will be greater on downstream river morphology than in the locality of the urban area where channels are already so altered and managed for flood protection.
- This review has found limited evidence to define how water temperature will change as a result of climate change in UK urban watercourses and cannot make a firm statement regarding how temperature will change as a combined result of climate change and urbanisation. With higher temperatures there would be an increase in the degradation of pollutants, making them more ecologically harmful and lowering dissolved oxygen.

- Where no change in STW capacity or treatment level is improved we can have high confidence that point-source pollution will increase (in the absence of any climate –related confounding factors). Future climate shows signs of increased dry spells during summer, which would mean that any pollutant loading downstream of point discharges would have higher concentrations and higher residence times. No studies have however directly assessed this for urban areas of the UK.
- No specific research in the UK has assessed how urban diffuse pollution will alter with climate change but we anticipate this may get worse as dry spells become more prolonged allowing pollutants to accumulate for longer and then be entrained in more intense storm rainfall events.

Introduction

Since the industrial revolution of the 18-19th Century there has been a progressive movement of labour, production and commerce into urban areas. This shift from a largely rural agricultural society to one of industry and commerce has driven the rapid growth of urban areas and one common result has been the rapid deterioration of the urban water environment and an increased risk of flooding.

Pollution of air and water was totally unchecked for decades with the result being dangerously high levels of respiratory disease and morbidity resulting from infamous events such as London's lethal smog of 1952 (Bell & Davis, 2001) and the Great Stink of 1858 whereby the House of Commons had to be abandoned due to the persistent sewage problem which also led to common outbreaks of Cholera. It was not until the 1970s that water quality started improving beyond the Thames in London being considered an open sewer devoid of fish (Sumita Sinha-Jordan, 2005). Ever since the 1973 Water Act was passed there has been a generally positive change in how wastewater is regulated and managed as public authorities were given responsibilities for looking after sewage treatment leading to significant reductions in water pollution and overall improvements in water quality. There has also been a general decrease in pollutants being released from manufacturing in urban areas due to a combination of environmental regulation and export of manufacturing. However, a range of other pollutant sources have been more recently identified using modern scientific analytical techniques such as bioassays that are having more uncertain and complicated impacts upon receiving waters and human health (Matthiessen & Law, 2002).

Flooding of urban areas has been another key environmental concern impacting upon the lives of those living in proximity to large rivers and especially estuaries. While not always a result of urbanisation it is within the urban areas that most of the impacts are felt as this is where population is most dense and property most at risk. The Thames Flood of 1928 made thousands homeless in London but the flood itself was a result of heavy snow followed by thaw and heavy rain in the headwaters combined with a high spring tide, rather than urbanisation within the basin. Urbanisation has more of an effect on flooding in smaller catchments where the progressive loss of natural and rural areas and increase in impervious surfaces results in more rapid runoff generation, greater runoff volume, and more potential for flooding from sewers and storm drainage (Hollis & Luckett, 1976; Leopold, 1968; Braud et al., 2013; Miller et al., 2014; Kjeldsen et al., 2013).

Despite the significant improvements that have accompanied better regulation of environmental pollution, improved storm drainage and protection of urban property, there still remains in the contemporary urban centre a range of issues relating to both the quality and quantity of water. Particular issues relating to water quality include; the incidence of pollution events from point sources such as sewage treatment works (STW) or combined sewer overflows (CSO), diffuse pollution from urban pollutants being mobilised into river systems, and temperature changes as a result of power plants and other thermal emissions. Also there are forever more potential pollutants such as nanoparticles being released into urban rivers as a result of consumption of increasing numbers of products containing a wide variety of chemicals (Dumont et al., 2015) that are being shown to have detrimental impacts upon freshwater ecosystems (Sutherland et al., 2007). Regarding quantity, while there are a number of issues relating to low flows experienced in urban rivers that can affect water supply and pollution concentrations it is the issue of flooding at high flows that continues to have the most detrimental impacts on society and especially upon the areas surrounding the river. In association, the loss of natural pathways and gradual containment of urban rivers in artificial conduits to permit better flood regulation and protection has resulted in a change in river geomorphology with associated water quality and ecological implications (Gregory, 2006).

Over 80% of the population in Britain now live in urban areas and the population of the United Kingdom has risen from around 32 million in 1901 to 64.6 million in 2014 (ONS.gov.uk). The UK population is set to undergo a period of extensive growth and is projected by the Office of National Statistics (2012) to increase to 73.3 million in 2037, a growth of around 14%. Recent research by Holmans (2011) indicates that such growth results in an average annual demand of 240,000 – 245,000 new homes per year but that actual house-building is only slowly recovering from the lowest levels since the 1920s at approximately 100,000 per year. This projected increase in population may require more than simply expansion and intensification of existing urban areas and could be accommodated by the development of more new urban centres along the lines of post-war towns (TCPA, 2015) such as Bracknell or more recent developments such as Milton Keynes, built under the New Towns Act 1946. Clearly this projected growth will have environmental impacts and the expansion of urban areas will only confound existing problems, however there is no consensus on how this growth will be accommodated and distributed at present.

Climate change presents an additional challenge for developers of modern urban areas in both the production of greenhouse gases and changes to climate. There are clear benefits in designing new developments to be carbon neutral or have more integrated transport so that humanity can minimise the local and global environmental impact of new development. However the impacts of climate change upon urban areas are perhaps more uncertain and potentially very serious. Headline climate change impacts such as raised sea levels will prove disastrous without mitigation given the location of many large urban areas along rivers, estuaries and the coast (EA, 2009), and increased temperatures pose interlinked issues relating to water quality (Hannah & Garner, 2013). There is also evidence that indicates the urban hear island effect will be impacted upon in UK cities and needs to be considered in future planning (Emmanuel & Kruger, 2012). Mitigation of impacts requires clear science and numbers that are not always available upon which to base solutions and very few cities across Europe have any dedicated mitigation or adaptation plans (Reckien et al., 2014).

This review will assess the evidence concerning the impacts of urbanisation on flooding and water quality and will seek to appraise this evidence in light of science concerning the impacts of climate change in the UK. It will also provide an objective assessment of the evidence concerning the relative and cumulative impacts that both urbanisation and climate change will have upon urban hydrology. Discussion will be made of this material to consider the overall confidence in the direction and degree of change to urban flooding and water quality and for identifying key areas for ongoing research to address knowledge gaps.

Hydrological impacts of urbanisation and climate change

Urban flooding

Urbanisation results in a number of changes to the local environment that can have wide ranging impacts upon hydrological processes. An increased proportion of area being made impervious has been identified as the primary driver of change to urban hydrological processes (Gibbons, 1996; Shuster et al., 2005). This results in decreased infiltration capacity and surface storage, thereby increasing concomitant runoff production at the plot scale. In urban areas this increase in impervious area is associated with a general replacement of natural flow pathways with artificial drainage structures that convey water more efficiently and act to reduce catchment response times (Kjeldsen et al. 2013). These hydrological changes can have a significant impact upon flooding from a variety of different sources and can affect changes in channel morphology. Such sources of flooding can be further altered by changes in the climate as the quantity and intensity of precipitation changes.

UK urban drainage – a brief introduction

Urban areas utilise a combination of surface drains and artificial drainage to route runoff as rapidly as possible away from densely built up impervious surfaces towards receiving water courses or temporary storage. Along with these systems are sewer systems that route waste from properties to sewage treatment works (STW) but that sometimes join storm drainage in combined sewer overflows (CSO) often in older cities. During high-intensity rain storms there is a risk that the drainage system capacity is overwhelmed, leading to flooding from rainfall (Shaw et al., 2011) or that surface runoff from adjacent land accumulates - termed pluvial or surface water flooding. Similarly sewers can surcharge due to linkages with storm drainage and CSOs become active or directly discharge to the surface via manholes - termed sewer flooding (Wheater, 2006). Drainage is designed to a specific capacity calculated by assessing the probable rainfall event of a certain return period or annual exceedance probability (AEP) under a range of rainfall durations to assess the critical duration (House, Listons, & Road, 2003). For example, drainage might be designed to a 1% AEP of 2 hour critical duration, which means that it is designed to meet the capacity for drainage required for a rainfall event of two hour duration that has a 1% probability of occurring in a given year (1 in 100 year event). The UK Flood and Water Management Act 2010 requires all new developments to have surface drainage plans and 2011 guidance (Defra, 2011) sets out that that drainage must be designed so that flooding does not occur in any building or local utility during a 1% AEP rainfall event. There is also the requirement that takes account for the likely impacts of climate change and increased impervious cover - with an extra 30% increase in the design storm to account for climate change and a further 10% to account for urban creep. UK legislation (PPS25) sets out that the discharge of this runoff into watercourses should not exceed the calculated 'greenfield run-off rate' or that of the discharge from the site in its 'natural' state (EA, 2013). This is achieved through the installation of attenuation features that slow down the movement of water - termed Sustainable urban Drainage Systems (SuDS) which are now requirements of the SuDS Standards.

Pluvial and sewer flooding

Across the UK pluvial (also known as surface water) flooding has become the single largest cause of property flooding in urban areas and is highly related to incidences of sewer flooding. An estimated 2.8 million properties are at risk from pluvial flooding alone (Environment Agency, 2009) and around 2 million people are exposed to a pluvial flood risk of 0.5% AEP, with an additional 1.2 million people at risk by 2050 from a combination of climate change (300,000) and population growth (900,000) (Houston, Werritty, & Bassett, 2011). Pluvial flooding accounts for around 40% of flood damage, and assorted economic losses, in the UK (Defra, 2014). National Audit Office (2004) data suggests nearly 12,000 properties are at risk of sewer flooding every ten years. During the 2007 UK floods - which were driven by two intense heavy rainfall events on 14-15 June and 19-20 July - Environment Agency figures suggest as many as two thirds of all flooding was attributed to inadequacies in surface water drainage systems (Pitt, 2004). In Northern Ireland much of the urban flooding experienced is due to rainfall overwhelming drainage systems and is an increasing problem as ageing infrastructure does not keep pace with development of new urban areas and is only designed to cope with a 3.3% AEP event at best, while many older areas operate to much lower standards (Rivers Agency, 2011).

Within the UK there has been insufficient evidence to link anthropogenic climate change to changes in observed precipitation records and such cause and effect may not become apparent until the 2050s (Fowler & Wilby, 2010). However our ability to provide projections of future UK climate under various emission scenarios benefits from a rich diversity of academic literature which has been refined significantly under the UK Climate Projections programme to provide probabilistic ensembles of future climate (UKCP09) (Watts, et al., 2015). UKCP09 projections for rainfall indicate the 21st C will have wetter, warmer winters (mainly to the north and west) and hotter, drier summers (mainly in the south and east) but with variable change predicted under emission scenarios (Murphy et al., 2009 - Figure 1).

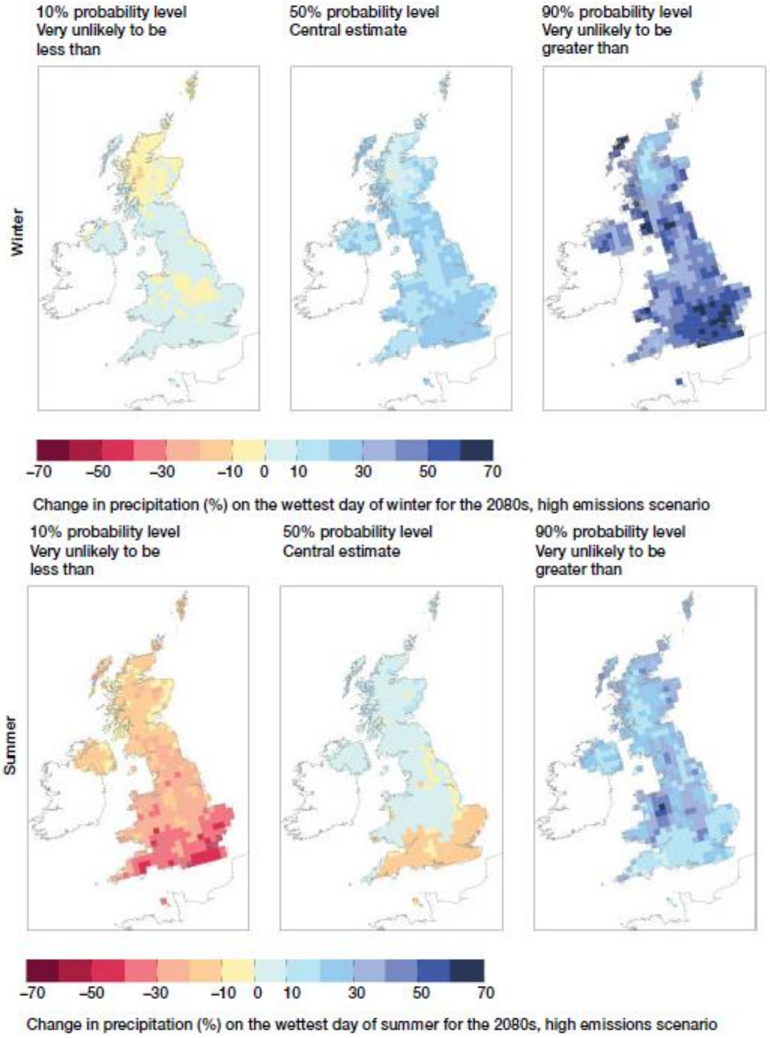

Figure 1- UKCP09 projections of future change in precipitation under high emisions scenario (Murphy, et al. 2009)

Assessing future changes to pluvial and sewer flooding in urban areas relies almost entirely upon analysing potential densification of existing developments, termed urban creep, and changes to future rainfall of the short-duration high-intensity variety that would cause rainfall to exceed drainage design capacity – being the most extreme events. While detailed analyses of an urban catchment would also require the development of detailed drainage network mapping and modelling, these are costly and not always available for research purposes, thus greater reliance is placed upon using qualitative studies, trend data, or urban creep and rainfall data. Douglas et al. (2010) undertake a comprehensive study of the causes of pluvial flooding in Heywood, Greater Manchester, and find that the observed densification of urban areas combined with UKCP09 projections for increases in the intensity and frequency of winter storm events will act to exacerbate the current pluvial flooding problem. They conclude that 'localised urban flooding is likely to increase and well-established urban areas unrelated to designated rivers and floodplains and with no previous history of flooding, are alarmingly at risk' (Douglas et al., 2010). Houston et al. (2011) used the UKCP09 Weather Generator to generate extreme rainfall for 44 urban areas using the medium emissions scenario, finding that extreme daily rainfall will increase rapidly in the South compared to other parts of the UK – being consistent with the UKCP09 prediction that convective storms and cells with frontal storms will likely become more intense and severe (UKCP09). However, it is noted that the Weather Generator 'cannot provide robust and reliable results for maximum 1-hour rainfall at high return periods' (Houston et al., 2011). Herein lies one of the current limits to providing robust estimates of how extreme short-duration precipitation might change in the future, that climate models do not produce robust future rainfall at durations under one day. Research into changes in extreme European rainfall using a range of Regional Climate Models (RCMs) found increases in winter, spring and autumn extreme precipitation by the 2080s (Fowler & Ekstrom, 2009). Summer changes have been shown to be more uncertain, with changes for events under one day duration remaining particularly unclear as models are unreliable at such time-steps (Fowler et al., 2007). Assessing the evidence of possible changes to UK precipitation Watts et al. (2015) find that medium confidence can be applied to increases in extreme rainfall except in summer.

More recent scientific developments led by the Met Office have involved applying a convection-permitting climate change model capable of simulating realistic hourly rainfall, including extreme rainfall. Kendon et al. (2014) find increases in hourly rainfall intensities in winter and an intensification of summer short-duration events, and in addition significantly more events that would cause flash flooding.

Fluvial flooding

Flooding that results from the overtopping of a surface watercourse is termed a fluvial flood and results in nature either from continuous rainfall over a long period of time or from a short-duration high-intensity storm event – or from a natural blockage that forms as a result of debris build up. These are entirely natural processes that are essential for a properly functioning river ecosystem and why it is potentially very risky to build new developments on what would naturally be floodplains close to river systems. Fluvial flooding can however also be driven by the process of urbanisation. The combined impact of increases in impervious area and replacement of natural flow pathways with artificial drainage systems has been shown by researchers to drive a more flashy response to storm events, whereby the catchment response is faster (Huang et al., 2008), river flows are greater (Hawley & Bledsoe, 2011), and a greater occurrence of small to medium floods occurs (Braud et al., 2013). This can lead to localised flooding in small catchments where the relative impervious area and artificial drainage area is high, and the greatest relative impact on high flows is often where land is converted from a rural to lower levels of urbanization (Miller et al., 2014). Urbanisation can also have a downstream impact in speeding up the conveyance and volume of water to other urban centres located further down the river system – especially when the natural storage of a floodplain is replaced by flood defences or the river is speeded-up in large scale artificial drainage or diversion (Shaw et al., 2011). The resultant flooding is assessed using an annual exceedance probability (AEP) whereby a given flood level of river flow is expressed as a percentage probability of occurring in any given year, such as the 1% AEP (1 in 100 year event).

The Environment Agency identified that there are 2.4 million properties at risk of flooding from rivers and the sea and that water related infrastructure is particularly at risk with over 55% of sewage and water pumping/treatment stations located in flood risk areas (EA, 2009). Flooding from sustained heavy rainfall over a long duration was experienced across the UK in the winter of 2013/14 causing increasingly saturated catchments and resulted in a record duration of daily flow above 250 cumecs for the Thames at Kingston and similar records across most Southern rivers (Huntingford et al., 2014). This sustained rainfall resulted in widespread flooding in areas such as Somerset and the Thames Basin – however it should be noted that a combination of river flood defence and coastal defence protected more than 800,000 properties (Hartwell-naguib et al., 2014) and that large urban areas were generally unaffected as a result. Widespread flash flooding resulted from the extreme rainfall events that occurred across the UK in June and July 2007 and resulted in the most devastating floods on record – affecting numerous large urban areas and flooding 55,000 properties at a cost of £3 billion (Pitt, 2004). Marsh et al. (2007) note that 'while localised downpours of a tropical intensity are a feature of English summers…a distinguishing characteristic of summer 2007 was the frequency and spatial extent of rainfall events'.

Detecting whether climate change has been affecting peak flows in the UK in observed flow records has proven as difficult and uncertain relating the impacts of urbanisation. Watts et al. (2015) summarise the available evidence and find only medium confidence in increases in winter flow, low confidence in changes to summer flows and insufficient evidence that climate change has been increasing flood magnitude, and Hannaford (2015) finds that observed changes cannot be directly attributed to climate change as records are limited and trends are affected by natural variability. This lack of long-term records also affects the ability to attribute changes in peak flows to urbanisation as such catchments are limited in good quality flow data and assessments of non-stationary trend in UK river flows have not revealed any differences between natural and non-natural catchments (Prosdocimi et al., 2013). Assessing the development of Bracknell town in the Thames basin from a previously rural state to that of a developed town, Crooks & Davies (2001) find some evidence of an upward trend in flood frequency and reduced time-to-peak with urbanisation. A comprehensive assessment of how urbanisation has altered the rainfall-runoff response of Thames catchments was undertaken by Crooks & Kay (2015) and evinces an increase in summer flows of around 15% during 2001-2010 as a result of increased urban cover since the early 20th century. However, it is data from other countries that have provided a more robust empirical assessment of this relationship, e.g Hollis (1975), who reveals, using US data, not only a relationship between increases in flood flows following urbanisation but that the relative effect of urbanisation on peak flows declines as flood recurrence intervals increase. Similarly, models provide a valuable tool for such analysis and assessments of small peri-urban catchments (e.g. Miller et al., 2014; Poelmans et al., 2011) and large urban catchments (Dams et al., 2013; Yan & Edwards, 2012) reveal a clear link between urbanisation and increases in peak flows and a more flashy response to storm events. The reality is however much more complicated and Wheater & Evans (2009) find 'while it may represent a significant increase in small catchments, at much larger scales the effects are highly complex and a result of sub-catchment responses and mitigation measures'.

Interestingly, for such a densely populated country facing significant population growth there is a striking disparity between the lack of research into the impacts of future urbanisation on river flooding compared to a wealth of studies on the predicted impacts of climate change. International research modelling the impacts of future urbanisation on peak flows and flooding in urban areas across a wide variety of climates and continents reveals a clear picture of how urbanisation can increase flood peaks and impact upon on future flood risk (e.g. Dams et al., 2013; Huang et al., 2008; Mejía & Moglen, 2010) but there are limited studies addressing this area of research in the UK. Taking a 16% population increase for the UK by 2031 Eigenbrod et al. (2011) demonstrate that under a densification scenario of urban areas there would be an increase of 1.7 million persons neighbouring rivers and a minimum 10% increase in peak flows, whereas under a sprawl scenario only 11,000 would be affected and peak flows would barely rise (0.3%). Miller et al. (2014) model how a change from rural to peri-urban land use can significantly impact upon the flood peak and catchment response – with an increase in impervious cover from 11% to 44% increasing peak flows by over 400%.

Greater attention has been paid to predicting the impact of climate change on river flooding through the application of RCM simulations in hydrological models at the national-regional scale. Taking a recent review of the evidence concerning river flooding in general there is a reported general low to medium confidence that fluvial flood risk will increase under climate change (Wilby, 2015). Modelling the Thames Basin, Bell et al. (2012) use the Grid-to-Grid (G2G) distributed model and UKCP09 A1B emissions scenario climate data and predict an average estimated changes in 20-year return period peak flow by the 2080s of 36% (range -11% to +68%). Assessing predicted changes to a smaller catchment under SRES-98 emission scenarios Prudhomme et al. (2003) shown an increase in magnitude and frequency of floods with climate change but large uncertainty attributed to the GCM used. Charlton & Arnell (2014) utilise the UKCP09 projections and find a greater proportion of high flows increase than average runoff, with significant variability between catchments and scenarios. Applying three UKCP09 products (Sample Data change, Weather Generator, RCM-derived change factors) to nine UK catchments to assess the impacts of climate change for the 2080s (A1B emissions) Kay & Jones (2012) determine it is important to not rely one product and that in general there is an agreement of an increase in the 2 and 20-year return period flood.

No specific studies could be found on climate change impacts on river flooding in a small UK urban catchment using more recent RCM outputs such as UKCP09 or convection permitting simulations. Smith et al. (2014) investigate the application of climate models for flood projection across the UK and reiterate the findings of Fowler et al. (2007) that climate model precipitation outputs are unsuitable for flood impact studies and that flood risk should be evaluated on a catchment by catchment approach, and contain significant uncertainties. Recent research by Kay et al. (2015) applies the CONVEX high resolution 1.5km RCM to project changes to future rainfall of the high-intensity short-duration type that would certainly impact urban flooding. This work has shown that at the scale of catchments greater than 50km2 the results are at present unclear and warrant further investigation. Results show a clear increase in future flood peaks in all seasons except summer, where despite increases in rainfall intensity over the 12km RCM the resultant runoff is insensitive. This is ascribed to scale, whereby smaller catchments would be better modelled by a finer scale hydrological model, particularly those small urban catchments. Also it was found that the higher resolution RCM actually performs worse than the 12km RCM at simulating flows across a number of UK catchments. Further research into the application of such products is recommended by the authors, particularly for smaller urban catchments where the impacts might be greatest.

The reality of future urban river flooding is that it will be a combination of factors relating to climate, planning and location that will interact and have relative and cumulative impacts but determining these impacts is difficult and has not fully been realised in a suitable study for the UK. Hall (2003) apply a quantified national flood risk analysis for England and Wales over 2030-2100 and predicted a potential 2000% increase in economic risks from flooding in the 2080s – attributable to a combination of climate change and socio-economic change. A broadly similar approach was followed by the 2004 Foresight Future Flooding project and Wheater & Evans (2009) highlight the complexity of considering climate change and urbanisation along with many other causal factors that could lead to changes in urban flooding – in particular local management interventions. To date no research has combined the type of national flood assessment of future urbanisation conducted by Eigenbrod et al. (2011) with a national climate change assessment. Miller et al. (2014) undertook an assessment of the relative and cumulative impacts of future urbanisation and climate change on a small peri-urban catchment in the UK and found using 11 ensemble outputs from UKCP09 A1B RCM that for winter events the cumulative impacts are highly significant but that the impact on peak flows are similar relative to change in either factor and climate precipitation data based on monthly changes was found unsuitable for modelling at such small spatial scales. Research from Belgium assessing such relative impacts under a range of climate scenarios found that under a 'wet' future scenario the combination of urban expansion and increased peak flows acts to amplify flood frequency and extent (Poelmans et al., 2011). However they also found that a consistent result of urban expansion is an increase in peak flows, while the various climate scenarios result in a 30% increase in peak flows under the wet scenario and an 18% decrease under the dry scenario. This illustrates a recurring limitation identified within the literature, that while the modelling of urbanisation is quite clear the uncertainty and format of existing climate model precipitation data limits any realistic assessment of how urban flooding might change in the future as a result of climate change.

Groundwater

Groundwater flooding occurs when the water table rises and is defined by Macdonald et al. (2008) as 'the emergence of groundwater at the ground surface away from perennial river channels or the rising of groundwater into man-made ground under conditions where the normal ranges are exceeded'. Estimates for England and Wales place over 1.6 million properties being at risk in the south and east of England alone but no national specific assessment of groundwater flooding has been made by the Environment Agency. Such flooding is driven by a number of different hydro-climatic scenarios. The UK floods of 2000-2001 encompassed widespread groundwater flooding from above average rainfall recharging aquifer levels in late 2000 at a rate with no modern parallel leading to especially protracted lowland flooding (Marsh & Dale, 2002). Other scenarios include flooding from shallow unconsolidated sedimentary aquifers that overlay non-aquifers, whereby intense rainfall can cause a rapid rise in levels, and also in urban locations where a reduction in abstraction allow depressed levels to rebound and flood subsurface infrastructure (Macdonald et al., 2008).

No systematic evidence is available to discern the impacts of historical climate change on UK groundwater levels (Watts et al., 2015) and so little to infer regarding changes in urban groundwater flooding on which also no specific literature was identified. Similarly there is a distinct lack of research into the impacts of urbanisation upon the risk of groundwater flooding but evidence suggests that even urban development's built on flood plains but protected by flood defences can be liable to groundwater flooding. In Oxford the raising of certain areas to reduce fluvial flood risk acts to create adjacent areas of groundwater flood risk at relatively low return periods of 10 to 25 years (Macdonald et al., 2012).

Limited literature assesses the potential impacts of future urbanisation and climate change on groundwater flooding and no specific literature on this subject was uncovered for this review. In a study of climate change on potential recharge of groundwater in Great Britain Herrera-Pantoja & Hiscock (2010) assess a number of urban areas and find the greatest threat is a decrease in levels as a result of drier conditions – which would indicate a reduced risk of flooding. In an assessment of chalk groundwater and climate change, Jackson et al. (2011) find that projections for the 2080s from an ensemble of GCMs under A2 emissions scenario indicate a slight (4.9%) of decrease in annual groundwater recharge in the future but with higher recharge rates in winter. In a comprehensive review of the literature on climate change and UK groundwater levels Jackson et al. (2013) find that there is some agreement that groundwater levels in most aquifers will decrease by the 2050s but that there is significant uncertainty regarding the magnitude of these changes and an overall low confidence in the response of groundwater to climate change (Watts et al., 2015). The findings from these studies would suggest that these overall drier conditions and lowered groundwater levels would thereby reduce the risk of future groundwater flooding in most years but that the threat of winter flooding could be increased as groundwater levels rebound rapidly during wetter winters. However the link between these projections and urban flooding has not been specifically assessed.

Channel morphology

It has long been widely recognised that urbanisation results in increases to peak flows, that the morphology of river channels is proportional to discharge, and that with urbanisation and increased high discharges the bed and banks will be eroded and enlarge the channel (Hollis & Luckett, 1976; Gregory, 2006). Such changes were illustrated in a study of the Monks Brook drainage basin by Gregory et al. (1992) with urbanisation being shown to increase channel capacity by up to 2-2.5 times, width up to 2.2 times and lowering of the bed by 0.4 times. Urbanisation has historically also altered channel morphology and resulted in channel straightening, realigning, culverting and installation of bank protection and flood defences. Assessing such changes within the Thames basin, Downs (1994) finds that urban catchments have experienced significant culverting and loss of natural river sinuosity and such channel management acts to reduce the chance of future channel. These channel adjustments also cause downstream changes in channel morphology as a result of higher stream velocities – driving increased erosion which then increases channel width and depth – as evinced by Brookes (1987) in a study of 46 channelization works in England and Wales. Modern environmental regulation (PPPG25) however means that developments should follow a more sustainable design that does not significantly alter channel morphology in such detrimental ways and there are also considerable efforts in place around the UK to restore urban rivers to a more natural state (Gilvear, Casas-mulet, & Spray, 2007) and rediscover the value of such restoration in ecosystem services such as natural flood defence and amenity value (Everard & Moggridge, 2012).

Anthropogenic climate change, as has been discussed, is projected to increase the peak discharge and alter the flow regime of river systems across the UK (Charlton & Arnell, 2014) and such changes will bring about an adjustment in river channel morphology (Gregory, 2006a). There is however limited specific research undertaken to assess how climate change will alter channel morphology in UK urban areas. In an assessment of climate changes influences on river discharge in five Danish rivers for the period 2071-2100 Thodsen (2007) finds that projected changes to higher mean annual and monthly flows, and higher peak flows, will all combine to increase the width and depth of watercourses according to regime theory but that such effects will be limited by the fact many Danish rivers have already been manipulated. In a modelling study of rivers in the Pacific Northwest on USA Praskievicz (2015) found changes in bedload transport and channel geometry on high-energy rivers as a result of climate change. Despite no specific studies of UK rivers being identified that assess changes to channel geo-morphology with projected urbanisation or climate change, we can infer, as Gregory (2006b) identifies, that the overwhelming evidence indicates that alterations of the incidence of hydrological events will act to disrupt the fluvial system and alter channel geomorphology.

Urban water quality

Urbanisation degrades water quality through three primary mechanisms: i) through generation and discharge of pollutants at point sources, ii) increased mobilisation of pollutants from diffuse sources across a catchment – particularly during storms, and iii) changes to the temperature of receiving watercourses (e.g. Kaushal et al., 2010), raising temperatures in watercourses downstream of STW outlets and power plants and even warming resulting from runoff over paved surfaces (Herb et al., 2008).

Point sources include untreated excess effluent being diverted from STWs and sewage mains and into overflow structures during extreme rainfall leading to serious short and long-term impacts (Ellis, 1991). Summarising water quality data collected for eastern UK rivers draining to the North Sea, Neal & Robson (2000) find major, minor, nutrient and trace elements in urban and industrial rivers that reflects the importance of point source pollutants and for more soluble chemical species urban and industrial concentrations are higher in summer months due to reduced dilution in lower flows. Regulation and treatment technology is proving increasingly effective at limiting such point sources and the EA report that the General Quality Assessment (GQA) scheme used to monitor rivers across the UK has shown an improvement in river water quality from 55% being designated as good or excellent in 1990 to 80% in 2009, and an improvement in biological quality from 63% to 73% over the same period (EA, 2013). In contrast, the impact of combined sewer overflows (CSOs) is at high flows and it is recognised that the environmental consequences should be minimised as far as is feasible above and beyond the natural mitigation provided by dilution from the high runoff in the driving rainfall event itself (CIWEM, 2004). Such discharges can impair receiving waters contributing high loads of a wide range of pollutants most notably microbial pathogens BOD and suspended solids (Abdellatif et al., 2014). There is evidence that conditions in terms of other water quality indicators such as total N, total P (Bi et al., 2015), DO and ammonium (Fu and Butler, 2012) will also deteriorate as a result of overflows.

Aside from the point pollution sources associated with urban areas, diffuse pollution has significant impacts that continue to grow with urbanisation and continue to be difficult to regulate and control, plus are more affected by climate and extreme events. Nearly one third of pollution incidences within the Thames Region reported by the EA are attributed to urban diffuse pollution and include pollutants such as oil and hydrocarbons, pesticides, solvents, sediment, metals and organic pollution among others coming from a range of sources including residential runoff, commercial/industrial runoff, construction, vehicle emissions, and sewer leaks among others (Ellis & Mitchell, 2006). During storm conditions accumulated sediments that contain pollutants can be mobilised in what is termed the ‘first-flush’ event (Sansalone et al., 1997) whereby storm rainfall acts to mobilise and entrain these sediments and deliver significant quantities of pollutants to receiving water during a storm event. A particular source is the mobilisation of sediments contained in drainage gulley’s which can act as sinks for diffuse pollutants and subsequently become a source of pollution during a storm – as illustrated in a study undertaken by Fulcher (1994) on stormwater flows from a residential area of Nottingham, UK. The ultimate delivery of these pollutants to receiving watercourses however is directly influenced by the presence of stormwater management infrastructure such as retention ponds which have been shown to decrease nutrient and DOC delivery (Hale et al., 2014).

While the focus has historically been around sediments and organic matter, heavy metals and nutrients, more recently interest has grown concerning pathogens and emerging priority pollutants such as industrially derived components of the type listed under the WFD (Fletcher, Andrieu, & Hamel, 2013). Similarly there is a growing body of research into the potential levels of nanoparticle pollution and the impacts these might have on the water environment (Dumont et al. 2015).

Water quality impacts can also be assessed using macro-invertebrates in conjunction with pollutant analysis. Assessing stream quality using the EA General Quality Assessment (GQA) methods on a small urban catchment in Sheffield Robson et al. (2006) found that benthic invertebrates are adversely affected by inputs from stormwater into the receiving watercourse. Against a backdrop of substantial improvement in water quality in the last 50 years when many UK rivers were devoid of fish, at a national scale macroinvertebrate recovery since early 1990s has been particularly pronounced in urban rivers due to the steep decline in primary industry and marked improvement in wastewater treatment (Vaughan and Ormerod, 2012). However these improvements, measured in terms of increase in biodiversity and pollution sensitive taxa, are not uniform geographically, being less apparent in parts of the south-east notably the Thames basin.

Evidence for elevated nutrient concentrations in UK rivers is widespread and action to reduce inputs is highly concerted. For example, much of the country is designated as a Nitrate Vulnerable Zone (over 65% of English farmland) and the curbing of phosphorus loads is invariably amongst the most common measures for meeting WFD targets for specific waterbodies under river basin management planning. Despite high inputs of pollutants these are not always reflected in undesirable ecological status of waterbodies or of other unwanted consequences of eutrophication, even in urban rivers (Halliday et al., 2015). This is often because residence time is insufficient in short urban rivers for phytoplankton. However, respiration by an enhanced body of benthic algae and heterotroph biomass may give rise to transiently low oxygen levels. If these are then coupled with increased organic loading from polluting urban activities, these systems are vulnerable to anoxia, particularly as there is evidence of organic matter being more readily degraded and bioavailable in urban streams (Hosen et al., 2014).

Future urbanisation

There is little specific literature on evidence (be it from observations or modelling inferences) on how future urbanisation in the UK will affect water quality. In principle however, an increase in population will put strain on the capacity of existing infrastructure, increasing the dry weather flows reaching treatment plants and thereby the loads of pollutants to receiving waters, Consequently river concentrations of all pollutants, in particular those not undergoing specific treatment, will be higher in dry periods in a future of increased urbanisation due to the effective lessening in dilution (Keller et al., 2015). While a range of future populations projections exist (ONS 2013) these have not been translated into spatially explicit maps of distribution or development of new towns – thus limiting the ability to determine impacts. A study of future urbanisation in the USA by Hughes et al. (2014) indicates it is likely to have a moderate to severe impacts upon aquatic ecosystems but that the degree of impact will depend on existing land use and the type of urbanisation. The authors also highlight there is also a significant future threat posed by toxic chemicals that are not removed or neutralised by water treatments and of which the impact upon receiving ecosystems remain uncertain – particularly endocrine disruptors and cumulative chemical mixes. These are similar to the concerns in the UK where there is certainly a growing threat from those substances currently not controlled and treated for such as nano-particles (Dumont et al., 2015) or steroid oestrogens (Keller et al., 2015) but that for more conventional pollutants greater controls and more effective treatment in waste water will generally increase the quality of the water through reduced loading.

Despite the lack of specific targeted research on modelling the impacts of future urban growth in the UK on water quality the clear evidence on the impacts of urbanisation on water quality would indicate that there will be a degradation of water quality in the urban areas of the UK if suitable controls and treatment are not put in place. With the high levels of projected population growth in the near future it thus becomes more important than ever to improve treatment controls and minimise further impacts.

General changes in water quality due to climate change

Comprehensive reviews on the observed and potential impacts of climate change on river temperature and water quality over the 20th and 21st Century have been covered in LWEC Water Source Papers on these subjects (Hannah & Garner, 2013; Whitehead, et al. 2013a). In a summary of these reviews by Watts et al. (2015) the authors found that for recent history there is a medium confidence of increases in river temperatures as a result of a warming climate – with a physically based expectation that with increased solar radiation river temperature rise as a result. Changes in water quality that could have resulted from a warming climate and elevated river temperatures are much more complicated to identify and isolate as the direction of response is not fully understood and any climate signals can be masked by numerous other changes to the bio-phiyical condition of the watercourse. There are no specific studies assessing changes in urban water quality or temperature as a result of climate change – mainly as the degree of change in urban areas regarding development and management of pollution is such that any signal from a changing climate would be near impossible to isolate.

For future water temperature in the UK, Hannah & Garner (2013) indicate there are few predictive studies of river temperature under climate change to evaluate how temperature will change. They find a medium level of agreement that river temperatures will increase with climate change but that current knowledge limits any assessment of the rate of this change. Such changes will result from direct alterations to the energy exchanges of radiation and heat in river systems and shifts in hydrological processes along with indirect alterations in how humans manage riparian land and utilise water resources in response to climate change.

For future water quality in UK rivers Whitehead et al. (2013a) find a medium/low confidence for future changes as a result of climate change due to uncertainties on how future climate will alter physical, chemical and biological systems combined with further uncertainty arising from climate models. The authors find that the predicted lower flows will result in higher residence times which will support greater algal and cyanobacteria blooms and thereby reduce dissolved oxygen. Lower flows also provide less dilution of discharges such as STWs and resultant higher concentration loads. This reduced dilution impacts upon organic pollutant concentrations raising biochemical oxygen demand (BOD) and lowers dissolved oxygen (DO). Water quality will also be affected by the increased temperatures, which acts to cause chemical and bacteriological process at faster rates.

Future climate change and water quality in urban areas

Increases in temperature as a result of climate change will most likely raise water temperatures and bring about a reduced oxygen carrying capacity, and such effects will be especially pronounced in future in large densely populated rivers in southern England such as the Thames (Cox and Whitehead 2009). Oxygen levels will be further impaired under higher temperatures by faster rates of microbial oxygen-consuming processes such as the nitrification of already enhanced loads of ammonium. As urban streams tend to exhibit raised average temperatures and increased seasonal diurnal variations (LeBlanc, Brown, & FitzGibbon, 1997) the effects of raised temperatures might not be the same as for more rural streams and research on more natural watercourses might not be readily translatable to urban streams (Wilby et al., 2006).

A combination of rapid population growth and climate change certainly poses a number of threats for the UK and modelling of potential impacts reveals some serious concerns for water quality and the water environment. Results from Astaraie-Imani et al. (2012) demonstrate that climate change combined with increasing urbanisation will lead to a lowering of river quality in the UK through an increased frequency and magnitude of events exceeding threshold dissolved oxygen and ammonium concentrations. The authors find that this is primarily a result of increases in rainfall depth rather than intensity and that changes resulting from urbanisation are driven mainly by projected increases in per capita water consumption. In a review of water quality changes with climate change, Whitehead et al. (2013b) identify the combined threat of urbanisation and climate change in causing more frequent uncontrolled discharges from urban areas. This is a result of more frequent droughts and increased high-intensity short-duration storm events – whereby rainfall will overwhelm drainage system capacity and flush nutrients from urban areas that have accumulated during dry periods. Evidence from other countries backs up such assessments. In an assessment of rainfall variables on urban effluent concentrations and fluxes undertaken in Canada (Gooré, Monette, & Gasperi, 2015) reveals that given the large volumes of effluent in urban receiving watercourses any change in climate towards more frequent shorter and intense rainfall events will significantly worsen water quality. Such findings were echoed by Mahbub et al. (2011) in a study or wash-off of volatile organic compounds from roads in a study in the Gold Coast, Australia, with changes to rainfall affecting the wash-off of a number of such compounds.

As previously discussed one of the main threats to urban water quality will come from those substances not currently controlled as pollutants. An analysis of endocrine disruption in fish due to steroid estrogen pollutants contaminating urban watercourses from STW effluent has shown that in England and Wales there is an increased future risk of disruption, primarily through increased population and under drier scenarios (Keller et al., 2015). The lack of specific targeted research on a wide range of un-controlled pollutants limits our understanding of how such substances might be affecting water courses in urban locations and downstream receiving areas.

There is an inherent complexity in attributing future water quality to climate change alone, especially in urban areas, as the source management of pollutants plays a particular role in the potential impacts of climatic changes. For example despite evidence of recent increased warming in the UK observed changes in invertebrate communities were found to be driven by improvements to water quality rather than any climatic shifts (Vaughan & Ormerod, 2014). Much of the actual changes that occur will be affected by how point and diffuse pollution is managed in urban areas in the future and the relative impacts of climate change on future water quality in urbanising basins may be small (Cox & Whitehead, 2009). Henriques et al. (2015) utilise water management scenarios to explore the impacts of future changes to 2050 and highlight that a future dominated by short-term economic growth and competiveness will act to exacerbate the potentially negative impacts of climate change on water quality. They show the importance of considering future water management – with a significant deterioration of urban water quality under an 'uncontrolled demand' scenario whereby new developments do not incorporate SuDS features resulting in elevated runoff levels, whereas under an 'innovation' scenario it is the inverse. Whereas it would be hoped that future developments will be designed to successfully minimise risk of pollution, older urban areas with combined sewer systems and existing treatment infrastructure of limited capacity are vulnerable to more extreme future rainfall patterns. In these cases point source pollution from combined sewer overflows and bypass tanks at sewage treatment plants are liable to generate pollutant incidents in downstream water bodies. It is accepted that the severity of this particular set of threats to UK water quality will increase under climate change (CIWEM, 2004; Abdellatif et al., 2014). Nevertheless, areas of more recent urban growth with separate foul and storm systems will not be immune to problems, such as those posed by the occurrence of misconnections.

The uncertainties on how future climate will alter physical, chemical and biological systems combined with further uncertainty arising from climate models and future water management significantly limits our ability to provide robust predations of how water quality will change with urbanisation and climate change (Whitehead et al., 2013a). Much of this uncertainty is attributed by Arnell et al. (2015) to the high uncertainty and lack of ability in being able to predict the type of hydrological changes, such as duration of dry spells and frequency of first flush events that would mobilise pollutants, how future catchment management will be undertaken, the effectiveness of policy interventions such as the WFD, and an overall lack of scientific understanding on how the components of the water environment interact.

Confidence in the science

The scale of confidence used in this review of the literature ascribes an overall indication of confidence based upon a consideration of the amount of evidence that includes the type and quality, along with the level of agreement between the available literature. The matrix developed for use in the LWEC report cards reflects the degree of agreement of scientific studies and the level of information available (Figure 2).

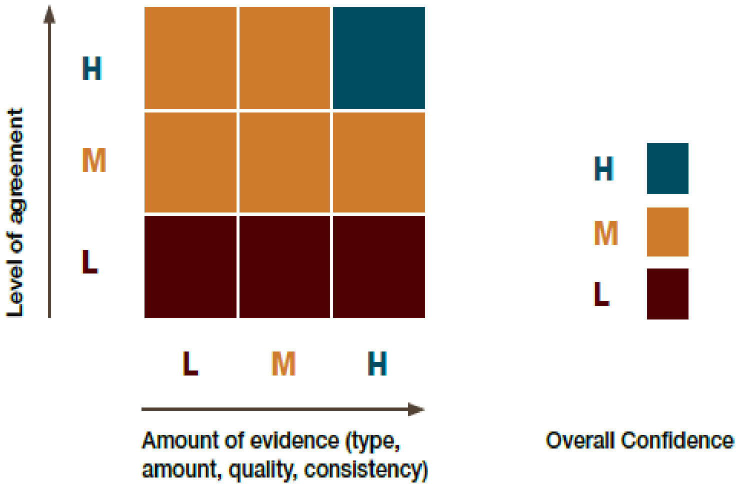

Figure 2: LWEC Report Card confidence scale.

Urban flooding

Pluvial and sewer flooding

While the evidence indicates a high confidence can be applied to urbanisation increasing the risk of pluvial and sewer flooding, determining the actual impact of future population growth and associated urbanisation is uncertain, especially as more surface water warning systems are being developed and SuDS are put in place. However, a high confidence can be applied to the increasing risk of pluvial flooding of urbanisation into areas in which densification of housing stock takes place, such as in the south and south-east (Houston et al., 2011).

For future projections on the impacts of climate change the science is only recently starting to provide the right tools for providing robust assessments of how pluvial flooding might change in the future. Taking the evidence as provided under UKCP09 scenarios a medium confidence can be applied to projections of an increased risk of pluvial flooding in urban areas as result of climate change, except in summer. While there is a high degree of agreement in the types of change predicted there is an associated acknowledgement that the underlying datasets are not fit for modelling the short-duration high-intensity rainfall events that drive pluvial flooding.

More suitable projections of how climate change might alter future rainfall (CONVEX) have recently shown more robust evidence of climate change causing a future intensification of summer and winter rainfall events which would drive increased pluvial flooding. However, as there is at present limited application of such data in modelling flooding using such products, and no application within small urban catchments, we can only ascribe a medium confidence.

Fluvial

Overall the evidence indicates a high confidence can be applied to the science concerning the impacts of urbanisation on increasing fluvial flooding – caused by an increase in impervious surfaces driving a faster catchment response and increased runoff. There is evidence of such impacts at the localised urban scale and collectively in basins subject to significant urban growth. However, the actual impacts of future developments in the UK might not be so evident if runoff is managed using appropriate mitigation measures to reduce runoff generation and store storm runoff locally using attenuation measures. As more stringent regulation for more sustainable drainage becomes enacted in the UK such mitigation will play a growing role in minimising the impact of future urban development.

Medium confidence can be ascribed to the impacts of future climate change on increasing urban fluvial flooding – through increased storm rainfall events and increased rainfall intensities. Certainty is mainly limited by the lack of suitable climate projection data but current and ongoing use of the CONVEX datasets in modelling urban fluvial flooding should improve the overall confidence.

Groundwater flooding

Given the limited evidence only a very low confidence can be ascribed concerning the impacts of historical and future climate change on groundwater flooding and only limited evidence to determine how urbanisation has played a role in affecting such flooding.

Geomorphology

As a result of climate change and given the strength of evidence in future changes to peak flows and river regime in combination with evidence from studies in other countries it would seem a medium confidence can be applied to climate change resulting in changes to river morphology in urban areas. As discussed however, many of these rivers are already heavily modified and stabilised so it may be that the effect of climate change on runoff from urban areas will have a greater impact upon downstream river morphology than in the locality of the urban area.

Urban water quality

Temperature

There is a high level of confidence that urbanisation has increased urban watercourse temperatures where there exists either outlets from treatment works, industrial outfalls or power stations but low confidence of historical climate change causing elevated levels of temperature of rivers in general. Considering the future impacts of urbanisation on river water quality is complicated but a high confidence can be ascribed to future urbanisation increasing river temperatures.

Existing reviews indicate a medium level of confidence can be ascribed to future increases in river temperatures in the UK but predicted changes for specific sites are beyond current knowledge (Hannah & Garner, 2013). This review has found limited evidence to define how temperature will change as a result of climate change in urban watercourses and cannot make a firm statement regarding how temperature will change as a combined result of climate change and urbanisation. Higher temperatures will increase the degradation of pollutants, making them more ecologically harmful, in turn further lowering DO.

Point source and diffuse pollution

In terms of point source pollution as a result of increased urbanisation, where no change in STW capacity or treatment level is improved we can have high confidence that pollution will increase (in the absence of any climate –related confounding factors). Future climate shows signs of increased dry spells during summer which would mean that any pollutant loading downstream of point discharges would have higher concentrations and in higher residence times. No studies have however directly assessed this for the UK and thus we have only low confidence of climate change causing increased degradation of water quality as a result of climate change.

Diffuse urban inputs are largely connected with wash off of accumulated pollutants following dry spells. No specific research has assessed how urban diffuse pollution will alter with climate change in the UK but the evidence from other countries and of increased dry spells in UK summers we anticipate this may get worse as pollutants would accumulate and then be washed off during storms – however this can only be said with low confidence at present.

As for any change in water quality in urban areas as a result of a change in climate, any confidence is entirely dependent on the level of confidence in the change in hydrological response. More extreme high flows will cause more severe fluxes via overflow events, higher loadings to receiving waters which even if they don’t bring about higher concentrations in the short term will increase pollutant load to riverbed sediments and thereby increase the concentrations later by indirect in-river transformation mechanisms. More extreme low flows will mean treated effluents will undergo less dilution in the receiving waterbody, this will in particular be an issue for contaminants not specifically targeted for treatment at STWs.

Conclusions

Houston et al. (2011) state that ‘climate change is only part of the story of vulnerability to flooding, and that in the short and medium term other economic, demographic and social forces may have greater impacts’ and that ‘national population growth has the potential to put around three times more people at risk from pluvial flooding by 2050 than climate change’. These are important statements that highlight the fact that the relative change in the urban fabric is potentially much greater than that of climate change in the medium term. A general lack of research on the impacts of climate change on urban catchments within the UK limits our ability to fully understand how climate change will impact upon urban hydrology and to design and implement effective mitigation measures. Determining the impacts of climate change in UK urban areas requires the integration of state-of-the-art climate science with robust projections of future urbanisation.

Key knowledge gaps that limit our ability to determine confidence in the science concerning the impacts of climate change on future urban flooding and pollution in the UK include the following (current research programmes that partially fill this gap but have not produced outputs for use in this review are listed):

1. Suitable climate change projections of sub-daily changes in precipitation that can model how short-duration high-intensity storms will change across seasons. This limits our ability to model how storm rainfall will change in urban areas and how this will affect both pluvial and fluvial flooding. Current collaborative work between the Met Office and the Centre for Ecology and Hydrology is utilising significantly downscaled RCM data (CONVEX) to model how sub-daily changes to rainfall will impact upon river flooding in urban areas.
2. Projected scenarios for future urbanisation in the United Kingdom – using projected population statistics to model urban growth.
3. Detailed empirical observations of how urbanisation has impacted upon urban flooding and pollution in UK catchments – at a range of scales and types of development.
4. Modelling of climate change impacts on water quality in the UK to identify how a range of water quality parameters will change as a result of combined urbanisation and climate change. The POLLCURB project being led by the Centre for Ecology and Hydrology is currently undertaking a Thames scale research programme to assess the possible future impacts of combined climate change and population growth on water quantity and quality.
5. Research on a wide range of un-controlled substances produced in urban centres that could cause pollution of urban watercourses.
6. Monitoring and modelling of how climate change impacts upon urban groundwater levels and groundwater flooding.

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