

UK Climate Risk
Independent
Assessment (CCRA3)

Technical Report
Chapter 4:
Infrastructure

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Key Messages

- **Flooding remains a key risk to infrastructure with the latest climate projections indicating an increased likelihood of heavy precipitation.** There have been a large number of recent high-profile events (e.g. the floods of East Yorkshire in 2020, the Toddbrook Reservoir incident in 2019) which highlight, with increasing confidence, the high magnitude of such risks and their interacting risks and consequences (sections 4.2.1 and 4.3.1). There has been some limited progress across the infrastructure sector in both assessing and adapting to the risk via a suite of flood protection measures (section 4.3.2). However, increasing winter rains will ensure the risk needs sustained management, as will coastal flooding. Revised projections indicate a sustained rise in mean sea levels around the UK (section 4.4.1). The latter is one area in which adaptation pathways are being used extensively (e.g. management of flood risk in the Thames Estuary) and other shoreline management plans (section 4.4.2).
- **Water scarcity in summer remains a concern for supply.** Without adaptation and under a central population growth scenario, the water deficit across the UK by the late 21st Century is projected to be approximately 1220 and 2900 MI/day for pathways to 2°C and 4°C global warming respectively. This equates to the daily water usage of around 8.3 to 19.7 million people (HR Wallingford, 2020. See section 4.9.1). This increase in risk is a combination of population growth and climate change.

To maintain the current levels of risk (to the worst historic drought) in the face of rising population, environmental and climate pressures by the 2050s, would require additional capacity of about 2,700-3,000 MI/day in England. Further adaptation is likely to be needed; this will more likely be measures that actually reduce demand rather than improve supply (section 4.9.3). Actions to increase supply are also being explored.

- **While significant progress has been made, an adaptation shortfall appears to remain for storms, lightning and high winds in the energy sector.** An increasing dependency on the electricity network (section 4.2.1) means that energy supplies will need to become increasingly resilient to a range of increasing weather and climate risks across the sector (section 4.11.1). In particular, there is an adaptation shortfall to the effects of storms, lightning and high winds (linked to impacts on vegetation), although adaptation to heat and flooding is developing well. Water scarcity will also impact on the energy sector by limiting the cooling of thermal power plants (section 4.10.1) along with uncertain implications for hydroelectric generation (section 4.7.1). There are also considerable uncertainties regarding the effects of the changing future energy mix in the UK in line with Net Zero strategy (e.g. water requirements for the portfolio of Net Zero supply options). In particular, a notable further risk to energy generation is from an increasing reliance on generation of energy from offshore wind which is exposed to storms and high waves (section 4.12.1), although the exact impact of climate change on these phenomena remains uncertain.

- **A changing climate continues to be a problem for the transport sector.** Both Network Rail and national highways agencies have been proactive in implementing adaptation measures on national networks, but sustained action is still required. Significant risks are still posed to railways with respect to flooding (sections 4.3.1 & 4.4.1) and heat (section 4.13.1). On roads, problems are more likely to occur on local roads and smaller schemes (section 4.13.3) and indeed, there is an underlying need to assess the impact of single points of failure more broadly (e.g. bridges (section 4.5.1), earthworks (section 4.6.1) and subsidence (section 4.8.1)). Often a paucity of data is restricting progress in these areas.
- **The systems nature of infrastructure means that any unmitigated risk has the potential to have a propagating impact across the network or lead to cascading failures across multiple networks.** The consequences of cascading risks cause far-reaching social and economic disruption beyond the initial impact. Extensive research is still required into cascading and interacting risks with high profile case studies (e.g. flooding at Stansted Airport in 2013, the impacts of Storm Desmond in Lancaster in 2015) providing increasingly high confidence in the significant magnitude of the impacts (section 4.2.1). This is set to increase with climate change as the individual costs associated with impacts on each network become compounded. The increasing reliance on electricity (section 4.2.2) and Information and Communications Technology (ICT) (section 4.14.1) both represent key areas needing attention. For the latter, there remains a lack of publicly available information to ascertain the true scale of any vulnerabilities in the sector (section 4.14.2).
- **Current national planning policies for infrastructure differ in the extent to which climate impacts and adaptation are addressed.** For new major infrastructure the 2017 update to EIA regulations in England, Scotland, Wales and Northern Ireland, includes a requirement to assess the infrastructure's vulnerability to climate change, however it is not clear how comprehensive these assessments are in practice. Flood risks are also considered at the planning stage. There are fewer requirements for existing infrastructure to adapt to climate change. Some sectors have well-developed plans while other sectors are less well organised or have no coordinating body. Overall, there is a need for a coordinated, cross sectoral review of design codes and standards, climate risk guidance, inspections and maintenance guidance, and wider relevant industry guidance on risk management to incorporate the latest understanding of climate impacts.

Table 4.1 summarises the urgency scores for the 13 risks to UK infrastructure from climate change, using the urgency scoring system described in Chapter 2 (Watkiss and Betts, 2021). The CCRA3 list of risks and opportunities, developed in consultation with stakeholders, did not include any opportunities for UK infrastructure from climate change.

Table 4.1: Urgency scores for risks to Infrastructure

Risk number	Risk description	Urgency scores			
		England	Northern Ireland	Scotland	Wales
11	Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures	More action needed (Medium confidence)			
12	Risks to infrastructure services from river and surface water flooding	More action needed (Medium confidence)			
13	Risks to infrastructure services from coastal flooding and erosion	Further investigation (Medium confidence)			
14	Risks to bridges and pipelines from flooding and erosion	Further investigation (Low confidence)			
15	Risks to transport networks from slope and embankment failure	More action needed (Low confidence)			
16	Risks to hydroelectric generation from low or high river flows	Further investigation (Low confidence)	Watching brief (Low confidence)	Further investigation (Low confidence)	Further investigation (Low confidence)
17	Risks to subterranean and surface infrastructure from subsidence	Further investigation (Low confidence)			

I8	Risks to public water supplies from reduced water availability	More action needed (Medium confidence)	Sustain current action (Medium confidence)	Sustain current action (Medium confidence)	Sustain current action (Medium confidence)
I9	Risks to energy generation from reduced water availability	Further investigation (Medium confidence)	Watching brief (Medium confidence)	Watching brief (Medium confidence)	Watching brief (Medium confidence)
I10	Risks to energy from high and low temperatures, high winds and lightning	Further investigation (High confidence)			
I11	Risks to offshore infrastructure from storms and high waves	Sustain current action (Medium confidence)			
I12	Risks to transport from high and low temperatures, high winds and lightning	More action needed (Medium confidence)			
I13	Risks to digital from high and low temperatures, high winds and lightning	Further Investigation (Low confidence)			

4.1. Introduction

4.1.1 Scope of Chapter

This chapter assesses the climate-related risks and opportunities to infrastructure, primarily focussing on the ‘economic grey infrastructure’ that provides services such as heating, lighting, mobility, fresh water and sanitation to society, aligned with the remit of the National Infrastructure Commission (NIC). Green infrastructure is beyond the scope of this chapter but is included where appropriate as an adaptation measure. The chapter builds extensively on the equivalent chapter in the second Climate Change Risk Assessment (Dawson *et al.*, 2016) by using new evidence, including (where possible) the latest generation of climate scenarios, to update our understanding of previously identified climate risks and the role of current and future adaptation in the sector. The

Introduction Chapter to this report outlines the process and role of Government in choosing the list of risks and opportunities that have been considered here and in the other chapters. This list was provided to the authors by the CCRA Project Board (Customer).

Risks to current infrastructure have recently been systematically assessed through the NIC (2020). However, the scope of the NIC report covers all hazards, which meant that the specific impacts of climate were not considered in detail. The focus here is on the key risks to infrastructure previously identified from CCRA2, as well as the potential for the interaction of risks with other sectors. Following CCRA2, the descriptors to focus on have been combined and subsequently reviewed and approved by Central Government. The result is 13 indicators for infrastructure (Table 4.1) which will individually be covered in the chapter.

Our society and economies are heavily reliant on infrastructure to function effectively and it is a priority area of investment by the UK government (see Box 4.1). The *National Infrastructure Plan* underpins the co-ordinated delivery of major infrastructure in the UK (although with application for devolved administrations) but currently pays little consideration to climate change. However, recent developments in this area are significant. £640 billion of gross capital investment in infrastructure before 2024-25 was committed in the 2020 Spending Review with a new *National Infrastructure Strategy*. This follows the publication of the first *National Infrastructure Assessment* in 2018 (NIC, 2018a) which included a number of climate change related recommendations such as national flood resilience standards and a plan to enable the water sector to meet changing supply and demand in 2050. This has subsequently led to the recently published *Resilience Study by the National Infrastructure Commission* (2020).

Box 4.1: Socio-economic scenarios and infrastructure

Social, cultural and economic trends are highly relevant to the future risks of climate change, and strongly influence future magnitude through changes in exposure and vulnerability (see Chapter 2: Watkiss and Betts, 2021). They will also influence adaptation, including the capacity and resources of individuals, organisations and infrastructure operators to act. Cultural and socio-economic factors can act together as risk multipliers exacerbating the impacts associated with disruptions to infrastructure services caused by climate change, although for some cases, these factors can reduce vulnerability and thus dampen the overall impact.

The CCC commissioned a new consistent set of UK socioeconomic projections from Cambridge Econometrics (Cambridge Econometrics, 2019) as one of the CCRA3 research projects.

These include projections of population growth, population ageing, and migration (internal migration and immigration), presented in Chapter 5 (Kovats and Brisley, 2021). The central scenario assumes that the UK population grows at a steady pace, increasing by over 17 million (compared to 2016), to reach a total population of almost 83 million in 2100. This rising population will likely increase the demand for infrastructure services.

The Cambridge Econometrics (2019) projections provide central, low and high estimates for total GDP (£ millions, real) and percentage growth (from the previous year), based on estimates from the Office for Budget Responsibility (OBR). The Central scenario envisages a GDP annual growth rate for the UK of about 1.6% from 2018 to 2028 and an acceleration with GDP expected to grow by 2.2% per annum from 2029 onwards (through to 2100). The increase in economic growth will also increase infrastructure needs. This means there will be a large increase in the value at risk, in

terms of the infrastructure assets, service levels, etc., which increases the potential exposure to risk (though future economic growth could provide additional resources to address these risks). The socio-economic study also projected gross value added (GVA), employment and labour productivity, all of which are important for the infrastructure needs associated with different sectors. In the Central scenario all sectors experience a similar growth pattern based on the Central GDP growth rates.

There are a very large number of other socio-economic and cultural trends that could have a large influence on demand for services and thus infrastructure. Some of the more important will include the drive towards digitalisation, change to the work environment (noting the shift towards home working from COVID-19), changes in how leisure time is used (particularly regarding travel distances and mode) etc., as well as long-term policy shifts. COVID-19, in particular, has the potential to result in a significant policy change in terms of infrastructure. Although the UK government announced a £640bn investment in infrastructure in the March 2020 budget, additional investment in large infrastructure projects is likely as the UK and the devolved nations seek to rebuild their economies following the pandemic. This will provide opportunities to enhance adaptive capacity in both new and existing infrastructure.

All proposed investments will need to be critically evaluated through a Net Zero lens as the UK government has adopted a Net Zero target through a revision to the 2008 Climate Act (such that the net UK carbon account for the year 2050 is at least 100% lower than the 1990 baseline). The Scottish Government committed to a target of net-zero emissions of all greenhouse gases by 2045 (Scottish Government, 2019a), with the Infrastructure Commission for Scotland placing inclusive net-zero carbon economy at the core of its 30-year vision (Infrastructure Commission for Scotland, 2020). The Welsh Government has announced a 95% reduction in greenhouse gas emissions by 2050 with an ambition to reach Net Zero (Welsh Government, 2019a). This will impact upon the type of infrastructure the UK will be reliant upon in 2050 as well its role within the wider economy and society (see Box 4.2).

Box 4.2: Implications of Net Zero for Infrastructure

Following the Paris Agreement, the UK and the devolved nations have committed to achieving 'Net Zero'. However, Net Zero is only going to be achieved if clear policies are rapidly put into place to meet the ambitious targets set. Net Zero has implications across all sectors included in this risk assessment as rapid and significant changes will be required. The infrastructure sector is no different and as a significant contributor to UK greenhouse gas emissions, Net Zero will have major implications for the sector. However, at the time of writing, there is no detailed Government policy on how Net Zero will be achieved, and thus there is limited information on what exactly Net Zero will mean for infrastructure. The Climate Change Committee has published a detailed analysis that presents potential pathways to Net Zero for each sector of the economy (CCC, 2019a). It presents scenarios that illustrate the ways in which extensive decarbonisation of the UK economy could occur, by 2050, to demonstrate that a Net Zero emissions target by 2050 is achievable. However, this includes alternative approaches, and the actual pathways to achieve this are still in development and subsequently a long way from actual policy. Regardless of the route taken to achieve Net Zero, there will be implications for the infrastructure considered in this chapter, and interactions (potential positive or negative influences) with many of the climate risks detailed in this chapter. In particular, the anticipated infrastructure transformation in response to

delivering Net Zero goals will encompass significant changes in energy generation and transport, detailed in Box 4.2 Table 1.

Box 4.2 Table 1: Potential change associated with Net Zero and implications for UK infrastructure risk			
Sector	Risk affected	Examples of changes associated with Net Zero	Implications for UK infrastructure risk
Transport	I1, I2, I5, I12, I13	<ul style="list-style-type: none"> • Electrification of rail and road transport (electric vehicles) including smart charging infrastructure. • Use of alternative fuels. Hydrogen for Rail; low carbon alternatives such as biokerosene for Aviation. • Increased active travel (walking, cycling etc.) • Increased use of public transport. • Increased use of blue infrastructure (e.g., London Blue Ribbon Network) 	<ul style="list-style-type: none"> • Increased reliance on electricity and ICT with associated potential for cascading risks from weather-related damage and disruption to these infrastructures. • New flood risks to new infrastructure (e.g. electric vehicle charge points) • As yet unassessed risks associated with new infrastructure (e.g. hydrogen production, distribution and storage) • Health and safety risks to increased numbers of cyclists and pedestrians from extreme weather.
Land Use	I2	<ul style="list-style-type: none"> • Afforestation <p>Changes in farming practices (e.g. low carbon / restoring peatlands)</p>	<ul style="list-style-type: none"> • Potential to reduce infrastructure flood risk management and reduce extreme river flows and their impact on hydropower output (although afforestation is also vulnerable to droughts) • Conversely, flood risk could increase due to

			increased debris in rivers.
Energy and Water Supply	I1, I3, I8, I9, I10, I11, I13	<ul style="list-style-type: none"> ● Doubling or potential quadrupling of low carbon electricity needed to meet demand from other sectors incl. electrolysis (BEIS, 2020a). Rising from ~300 TWh/year in 2017 to 600 TWh/year under the CCC Further Ambition Scenario with potential for further electrification up to 1300 TWh/year (CCC, 2019a, Figure 2.3) ● Increased use of renewables: wind, solar, bioenergy with carbon capture and storage (BECCS) ● Development of a hydrogen industry. ● Increased development of bioenergy supply chains. ● Smarter control systems to improve efficiencies. ● Reductions in the demand for fossil fuels. ● Changes in water demand due to a changing energy mix. 	<ul style="list-style-type: none"> ● Increased reliance upon electricity supply increases the consequences of power outages. ● Uncertain projections for future wind generation. ● Increased significance of loss of offshore infrastructure to electricity supply. ● Increased requirements for water for Carbon Capture and Storage (CCS) and hydrogen (H₂) production increases vulnerability to water restrictions or coastal erosion and sea level rise if they are sited on the coast. ● Bioenergy crops can be impacted by drought, resulting in undersupply. ● Changes in the spatial distribution of supply to accommodate greater renewable generation. ● Increased dependencies (e.g. on ICT) makes cascade failures to other networks more probable. ● Changes in water quantity and distribution needs to accommodate a changing energy mix.

Overall, Net Zero will change the profile of risk. It will underpin the types of new infrastructure to be built, how and to what extent existing infrastructure is used in the future, decisions on adaptation solutions, and offer opportunities to build in resilience to climate impacts from the outset. It is also highlighted that the changing risks outlined in this report may affect the design of the Net Zero economy as it is important to plan the Net Zero transition so that it operates effectively and efficiently in the future climate, not the climate experienced in the recent past. In the context of this risk assessment, it is too early to provide an evidence-based analysis of how the risk profile will change. Instead implications of Net Zero are provided, where relevant, to provide an indication of whether the policy increases or decreases the risk and also whether climate change will make Net Zero harder or easier to achieve.

4.1.2 The challenges of assessing climate risks to infrastructure

The transport, energy, ICT and water sectors are all fundamental to day-to-day life, yet *all* regularly face weather-related challenges. The nature of the future risk remains similar to previous risk assessments, but the latest climate change scenarios (UKCP18) do indicate significant differences in climate extremes that need to be taken into account. These are summarised in Chapter 1 (Slingo, 2021) and underpin the evidence in this chapter wherever possible. It also highlights the need to increasingly consider low likelihood, high impact events for the infrastructure network (see Box 4.3)

Box 4.3: Low Likelihood, High Impact scenarios and Infrastructure

Chapter 1 (Slingo, 2021) has illustrated how there is now increasing evidence towards significant changes in future extremes of temperature and rainfall, as well as a changing evidence base in Earth system instabilities. Such changes could result in ‘tipping points’ being passed, leading to high impact outcomes across the risk indicators covered in this chapter. If scenarios or events which are unlikely but more extreme do occur, they would then be more likely to trigger cascade impacts (I1) via interacting risks (see Box 4.4).

The evidence base for such outcomes remains limited, although some examples have been explored. For example, Yesudian and Dawson (2021) assessed the risk to airports worldwide from scenarios of sea level rise from Jevrajeva *et al.* (2018), which are higher than those in UKCP18.

These scenarios considered much larger contributions of ice loss from Antarctica than in the UKC18 projections (De Conto and Pollard, 2016), which other work suggests may overestimate sea level rise risks this century (Edwards *et al.*, 2019). 1,238 airports were defined as being in the Low Elevation Coastal Zone (the area along the coast that is less than 10 m above sea level). Globally, the risk of disruption was projected to increase by a factor of 17–69 by 2100, depending on the rate of mean sea-level rise. A projected global mean sea level rise of 0.62 m by 2100 would place 100 airports around the world below mean sea level. While such a rise is almost the median projection for 2°C global warming by 2100 in that study, in UKCP18 it is at the upper end of the projected range for 2°C global warming by 2100 and the median for 4°C global warming by 2100 (see Chapter 1: Slingo, 2021). Yesudian and Dawson (2021) highlight that airports already benefit

from substantial flood protection that reduces present risk by a factor of 23 and to maintain risk in 2100 at current levels could cost up to \$57bn. Within the UK, London City airport ranked in the global top 20 by risk in 2100 for a 1.8 m global mean sea-level rise by 2100, which is the 95th percentile in the RCP8.5 scenarios considered by Yesudian and Dawson (2021) but substantially above the RCP8.5 95th percentile in UKCP18 (Palmer *et al.*, 2018).

Some changes, such as shifts in the Atlantic jet stream which underpins the UK's weather and storminess in general, can be sudden and cause unprecedented impacts. This was seen in 2020 when compound failures from two extreme storms in quick succession (Storms Ciara and Dennis) caused severe flood damage, with the impacts of the second storm felt even greater as it hindered clean-up operations from the first.

Weather and climate both impact on infrastructure performance and manifest in a variety of ways, but often lead to costly disruption or, in more severe cases, loss of service entirely. This has significant implications, not just for economic activity, but societal equity, health, and well-being more generally. However, there exists a continual trade-off between the cost of risk management versus the level of residual risk. Following NIC (2020), work is only just beginning on producing clear guidelines detailing the acceptability of loss of performance by the public, and indeed the willingness of the public to accept reduced levels of service when faced with an increasingly challenging operational environment (e.g. a climate emergency) in order to base such decisions. However, some sectors have begun this process. For example, as a starting point, water utility companies have surveyed the public to ascertain willingness to pay for investment in long-term adaptation measures.

A key consideration, particularly in light of the proposed investments, is the lifespan of infrastructure assets. Infrastructure is (mostly) designed for longevity and means that much of the infrastructure in existence today will be in place for the remainder of the century. Hence, there is a need to consider implications both for existing (potentially retrofitted) and new infrastructure. Climate change is actively considered when planning major new energy, transport, waste water and water projects under guidance from the UK Government's National Policy Statements, however guidance under the National Planning Policy Framework and Planning Guidance for smaller projects only considers flood risks and does not ensure other climate risks are considered (CCC, 2019b). For existing assets, adapting to climate change presents operators and owners with a challenge of coalescing and reconciling (where possible) actions across a range of aging assets, with differing design codes, environmental exposure, usage and maintenance regimes – all of which combine to determine how an asset may respond to a changing climate. Work is ongoing to introduce standards across Europe (see ISO 14090/14091) where the UK is represented by members of the Infrastructure Operators Adaptation Forum, but there is a sense that the inclusion of climate adaptation remains in its infancy. The CEN/CENELEC Coordination Group on Climate Change Adaptation (ACC-CG) has, as part of an EC mandate started in 2014, been steering the revision of 13 European standards to include adaptation to climate change. Translation of ISO 14090 into British Standards is also underway with a roadmap to be produced in due course. The British Standards Institution is currently developing BS 8631, due for publication by mid-2021, that provides guidance on developing and applying adaptation pathways to climate change adaptation planning and decision-making. However, it is highlighted that even when there is some guidance, designing climate-smart infrastructure in practice is extremely challenging. This is partly because of the high uncertainty around the future

climate (see Chapter 1: Slingo, 2021), and also because of the need to trade-off up-front costs versus long-term adaptation benefits (Watkiss *et al.*, 2019). For this reason, there has been a focus in the literature on decision making under uncertainty.

Additional complexity is added by the need to take a systems view (i.e. everything is interrelated and interdependent). No infrastructure network operates in isolation and a failure in one system can interact with others, and rapidly cascade into other sectors. Thus, system resilience to climate change goes beyond just the individual infrastructure networks. Indeed, interactions are not just limited to the infrastructure sector and can have far reaching consequences. As part of the 3rd Climate Change Risk Assessment, a project on Interacting Risks was commissioned to investigate this element (see Box 4.4).

4.1.3 Adaptation: Policy Considerations

The periodic CCRA is a requirement of the Climate Change Act 2008 and 2009 Climate Change (Scotland) Act. An additional key requirement in the Act was the production of climate change adaptation reports which can be requested by the Secretary of State. This process, known as *Adaptation Reporting Power* (ARP) in England, has been widely adopted across the infrastructure sector with a total of 91 assessments received during the first round of reporting. Although the process became voluntary in subsequent rounds, infrastructure related organisations / operators represent the vast majority of respondents (75/88) who have volunteered to report in the latest (third) round due in 2021. Although this is an excellent response rate, it is problematic for CCRA in two ways. Firstly, not all critical organisations are reporting and as such recommendations have since been made by the Climate Change Committee to reinstate compulsory reporting to ensure evidence is captured which is unable to be acquired easily by other ways. Secondly, the submission date for the third round of ARP is beyond the evidence capture phase of this CCRA and therefore is unavailable for inclusion and scrutiny. As such, there is a reliance on the second round of reporting, which demonstrated that whilst good consideration is being achieved in assessing risks and appropriate adaptation responses were underway, the reporting was too vague to provide any detailed assessment of progress (CCC, 2019b). Thus, steps 2 and 3 of the CCRA3 methodology which are focussed on adaptation consider reported progress on adaptation from the Climate Change Committee (Progress Reports), as well as input on policy developments from a range of industry representatives.

Policy continues to evolve in the infrastructure space, following on from the National Policy Statement (England & Wales) published in 2014, the Climate Change Adaptation Programme (Scotland) and the Northern Ireland Climate Change Adaptation plan. These have led to sector-level policy responses in the form of Sector Security & Resilience Plans (SSRPs), coordinated by the Cabinet Office Civil Contingencies Secretariat. Resilience of assets to relevant risks is detailed in the SSRPs, but as reported in CCRA2, there is no clear link between them and adaptation planning. Recent development in this area has been highlighted by the NIC (2020) which promotes a statutory requirement for regulators in the infrastructure sector to have resilience duties.

4.2. Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures (I1)

Infrastructure operates as a system of systems. It means that vulnerabilities on one network can cause problems on others, and therefore be far reaching beyond the infrastructure sector. Given the wide-ranging nature of the linkages, a full understanding of the impacts of cascading failures is difficult to ascertain. However, the vulnerability of interconnected systems may be significantly underestimated (Mao and Li, 2018). This is increasingly evidenced, albeit anecdotally, by high-profile case studies, but the limitation of this approach means that it is difficult to understand, with confidence, the full magnitude of future risks in this area.

Case studies (such as the August 2019 power cuts) and literature support an assessment of current risk being high magnitude, with high confidence, with disruption in urban areas potentially impacting hundreds of thousands of people annually. Future magnitude is given as high with medium confidence for all four nations.

Whilst there are many examples of best practice adaptation within individual infrastructure sectors, the practice of focusing efforts in this way means opportunities are being missed to improve resilience across the sector more generally. The lack of a systematic national assessment of interdependency risk, the poor assessment of progress on adaptation in this area, and the low likelihood that sufficient non-governmental action will be undertaken indicates that this risk is not currently being managed, and that only partial plans are in place to do so. Because of the high projected magnitude for this risk and the view that current and announced adaptation will not fully manage the risk, it has been scored as more action needed across the whole of the UK.

4.2.1 Current and future level of risk (I1)

4.2.1.1 Current risk (I1)

Note: it has not been possible to split the evidence by UK country for this risk.

4.2.1.1.1 Current risk - UK-wide (I1)

Infrastructure networks do not operate in isolation. They can be interdependent because (i) their services are reliant on other networks for power, fuel supplies and ICT; or (ii) they are co-located and experience the same hazard; or (iii) they are managed or used by the same organisations or people (Dawson, 2015). As such, failures can cascade from one infrastructure network to another, often caused by multi-hazards, cascade hazards and compound hazards (AghaKouchak *et al.*, 2018).

Infrastructure systems featured heavily in CCRA3 research on Interacting Risks (WSP, 2020) (see Box 4.4), which provides an understanding of how risks can cascade across, and interact beyond, the infrastructure sector. Indeed, the majority of risks studied described interactions within the infrastructure sector, such as coastal flooding causing power infrastructure inundation, or power

supply interruption leading to impacts on travel and freight operations. However, there are also clear links to other sectors, such as water supply interruptions leading to health and welfare impacts (see Chapter 5, Health, Communities and the Built Environment: Kovats and Brisley, 2021). Overall, WSP (2020) identified 7 interactions with a high impact magnitude score for the baseline period, with 13 scored as medium and 7 as low impact. System interdependencies are mapped in the National Infrastructure Commission's Resilience Study, which details how national-level decisions (such as policies, incentives, markets and other factors) influence UK infrastructure Levels of Service (ARUP, 2020).

CCRA2 (Dawson *et al.*, 2016) specifically reported on interruptions to the supply of biomass to power stations following flooding of the Port of Immingham in December 2013. Critical power and IT services were lost, causing the cessation of operations for a number of days. In the same month, flooding of the M23 motorway and railway station hampered the ability of staff to travel to Gatwick airport. Flooding of substations during the event at Gatwick resulted in disruption to 13,000 airline travellers (McMillan, 2014). In addition to these previously reported examples, a further notable event was the loss of electrical power at a major exchange in Birmingham in 2011 which led to the loss of broadband connection to hundreds of thousands of customers in the UK (BBC, 2011).

More recently, power outages in England and Wales on the 9th of August 2019 demonstrate the potential for cascading infrastructure failure (Ofgem, 2020a). The event was triggered by a lightning strike on the Eaton Socon-Wymondley circuit between Cambridgeshire and Hertfordshire, causing a routine fault on the national electricity transmission system and the disconnection of a number of small generators connected to the local distribution network. Simultaneously, two larger generators (Hornsea 1 Limited and Little Barford) experienced technical issues and were unable to provide power. The combined power losses exceeded the back-up power generation capacity of the Electricity System Operator (ESO), triggering a power outage. A total of 892 megawatts (MW) of net demand was disconnected from local distribution networks. The electricity supply of over 1 million consumers was interrupted. The outage had significant knock-on impacts for the rail sector, with the Train Operating Company (TOC) Govia Thameslink Railway experiencing stranded trains, triggered by on-board automatic safety systems. This in turn caused knock-on delays across the rail network (Ofgem, 2020a). Hornsea 1 Limited and RWE Generation UK plc (operators of Little Barford) each agreed to make voluntary payments of £4.5m to the Energy Industry Voluntary Redress Scheme.

Storms, heavy rainfall and flooding are often precursors to cascade events (e.g. Storm Desmond (see above) and Hurricane Katrina, (Leavitt and Kiefer, 2006)). Indeed, the Environment Agency's long-term investment scenarios show that over 40% of transport and utilities infrastructure are in areas at current risk of flooding, either directly or due to dependence on other sectors (Environment Agency, 2019a). Further examples of the current magnitude of the impact of cascading failures include the flooding of a substation in Lancaster following rainfall associated with Storm Desmond in December 2015, leaving the city without power for more than 30 hours. This had consequences for transportation (no traffic lights, no lighting at the train station, refuelling issues), telecommunications (no mobile network, internet or digital radio), and water supply in some areas (Kemp, 2016; Ferranti *et al.*, 2017). In this example, the failure was caused by a combination of hazards; (i) eight weeks of wet weather had left the Lune catchment saturated, and water levels high, the two-day rainfall was (at the time) a rainfall record for Lancaster; and (ii) an incoming high

tide (Ferranti *et al.*, 2017). Although an extreme case, winters in the most recent decade in the UK (2009-2018) are now 12% wetter than 1961-1990, with the total rainfall from heavy rainfall events increasing by 17% (2008-2017) (Met Office, 2019a).

Since CCRA2, there have been several new academic approaches to studying interdependencies. For example, Pescaroli and Alexander (2018) have developed a framework to describe risk, classifying it as: compound, interconnected, interacting, and cascading. In addition, Murdock *et al.* (2018) presents a method for quantifying disruption caused by different failures to visualise information using interdependency circle diagrams. Crucially, recent international research has indicated that the vulnerability of interconnected systems may be underestimated. Mao and Li (2018) modelled the resilience lifecycle of an electric power system, a telecommunication system, and a water supply system and noted that excluding interdependencies gave a misleading impression of total resilience.

Much of the recent UK-based research on cascading risks from infrastructure interdependencies is focused on the potential impact of flooding hazards. Many of these studies use a simulation approach, for instance, Thacker *et al.* (2017a) simulate the interdependencies between the electricity network and the domestic flight network, demonstrating the potential for large disruptions resulting from the failure of electricity assets. Ranking the top 500 electricity transmission and sub-transmission assets in the UK, the simulation indicates that the most critical assets are capable of disrupting over 4 million customers. A similar picture is seen for potential disruptions to airport customers, with an increasing criticality at the higher tiers of the transmission hierarchy, but with individual assets at all levels capable of similarly high impacts (i.e. each impacting in excess of 190,000 customers). It must be noted that this is a simulation and has not been validated against real data. It is not clear whether the level of redundancy (i.e. the ability to manage disruptions through the network) during outages of key assets is reflective of the situation during observed events.

Thacker *et al.* (2017b) studied the spatial distribution of risk from cascading failures between infrastructure systems. By testing 200,000 failure scenarios, the study identifies that hotspots tend to be located at the periphery of urban areas where high concentrations of users will be impacted (hence demand) and critical infrastructures are concentrated.

Thacker *et al.* (2018) utilised an approach where data on critical infrastructure asset networks (including electricity generation, transmission and distribution, airports, water towers, wastewater treatment and telecom masts) are given synthetic connections based on distance and intersected with probabilistic hazard maps (in this case the National Flood Risk Assessment (NaFRA) flood likelihood map data) to calculate expected annual damages from flooding of electricity substations. Although simulated, the results show the potential for large-scale knock-on costs. The largest indirect sector impacts correspond to the business services and real estate sectors as well as the mining sector.

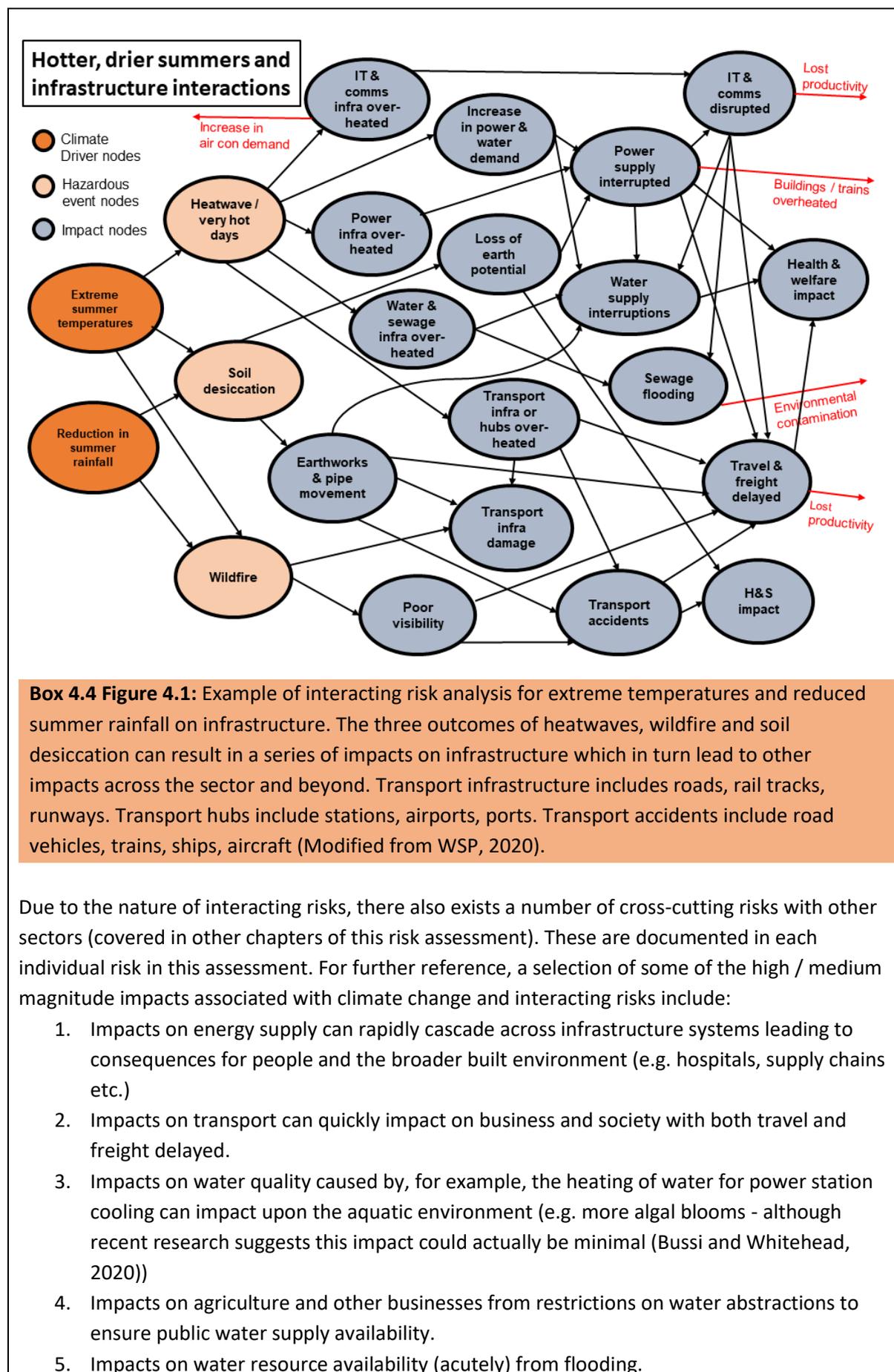
Pant *et al.* (2020) modelled a failure event initiated in the electricity network. The study estimated direct economic losses and total economic losses using an Input-Output (IO) model by assuming service disruptions lasted for 24 hours (with economic losses corresponding to losing demand from the equivalent of 24 hours of customers across sectors). Due to the forward and backward linkages

in the economic IO model, there are indirect economic losses to all sectors that use electricity, telecoms and railways outputs, and some of these losses feedback to these infrastructure sectors as well (Pant *et al.*, 2020).

Koks *et al.* (2019) used geospatial information on the location of electricity infrastructure assets and local industrial areas and employed a multiregional supply-use model of the UK economy to trace the impacts of floods of different return intervals across 37 subnational regions of the UK. The authors used the loss in labour productivity (temporary reduced employment) as the proxy for business disruption. The results show up to a 300% increase in total economic losses when power outages are included in the risk assessment, compared to analysis that just includes the economic impacts of business interruption due to flooded business premises (Koks *et al.*, 2019). The authors estimated that the total economic loss resulting from failure of five substations (worst case scenario) to be around £27 million per day.

Box 4.4 Interacting risks and Infrastructure

Interacting risks pose one of the biggest challenges when assessing climate risks more generally. Disruption on one infrastructure network can quickly cascade onto other infrastructure networks, but it is also important to recognise that infrastructure is a key enabler of the UK economy and underpins many key activities. The CCRA3 Interacting Risks project (WSP, 2020) demonstrated that the consequences of impacts due to climate changes on individual parts of the infrastructure network have far wider repercussions for the natural and built environment. Considering these wider effects, the magnitude of the impact far exceeds the effects on the infrastructure itself. There are numerous examples of this phenomenon. Interruption to power supplies is frequently highlighted as a key example of a source of cascade failure, but there are many others. For example, flooding (or other significant disruption) of transport networks can prevent key workers from operating other pieces of critical infrastructure. Fundamentally, access routes to key assets (e.g. nuclear power plants) may not be protected to the same level as the asset itself. Reliance on IT and communications infrastructure as an example of a current and increasing risk. Modelling of knock-on (downstream) nodes from a particular risk enables a qualitative assessment of further impact. Indeed, the interruption of power supplies is the single risk with the highest impact across the entire risk assessment and would be a root cause of large-scale impact across the sector. Disruption of IT and communication services is the second highest impact risk with significant downstream impacts. Other impacts were shown to be affected by a high number of risks further up a chain of interactions. The project found that risks emanating from other sectors caused delays to travel and freight more so than other impacts. As an example, Box 4.4 Figure 4.1 illustrates how these two risks can manifest as a direct result of extreme heat and a reduction in summer rainfall.



Box 4.4 Figure 4.1: Example of interacting risk analysis for extreme temperatures and reduced summer rainfall on infrastructure. The three outcomes of heatwaves, wildfire and soil desiccation can result in a series of impacts on infrastructure which in turn lead to other impacts across the sector and beyond. Transport infrastructure includes roads, rail tracks, runways. Transport hubs include stations, airports, ports. Transport accidents include road vehicles, trains, ships, aircraft (Modified from WSP, 2020).

Due to the nature of interacting risks, there also exists a number of cross-cutting risks with other sectors (covered in other chapters of this risk assessment). These are documented in each individual risk in this assessment. For further reference, a selection of some of the high / medium magnitude impacts associated with climate change and interacting risks include:

1. Impacts on energy supply can rapidly cascade across infrastructure systems leading to consequences for people and the broader built environment (e.g. hospitals, supply chains etc.)
2. Impacts on transport can quickly impact on business and society with both travel and freight delayed.
3. Impacts on water quality caused by, for example, the heating of water for power station cooling can impact upon the aquatic environment (e.g. more algal blooms - although recent research suggests this impact could actually be minimal (Bussi and Whitehead, 2020))
4. Impacts on agriculture and other businesses from restrictions on water abstractions to ensure public water supply availability.
5. Impacts on water resource availability (acutely) from flooding.

6. Impacts from displaced risks caused by flood management schemes (both coastal and fluvial)
7. Impacts on the marine environment from increased coastal erosion exposing old landfill sites.

Policy makers can use this information to better target adaptation efforts to improve the resilience against key risks which have the potential to cause the most upstream and downstream interacting impacts (e.g. multi-party agreements to allow the management of resilience risks by exploiting differences between sectors / locations). This has implications for the urgency in which measures are implemented.

4.2.1.2. Future risk (I1)

Note: it has not been possible to split the evidence by UK country for this risk.

4.2.1.2.1. Future risk – UK-wide (I1)

WSP (2020) projected the change in impact magnitude of infrastructure interactions for scenarios of global warming reaching approximately 2°C and 4°C in the late 21st Century (2070-2099) with large uncertainty¹, scaled with macroeconomic growth (GDP and population growth projections) to account for future impacts being larger than today. This utilised the network maps showing principal interactions within and between the sectors (Box 4.4) with impacts being simulated based on knowledge of interactions between weather and the components in question. Projections for both the 2050s and the 2080s suggest that significant interactions in the infrastructure sector are more likely to occur and/or have greater impacts in the future, therefore with the current risk magnitude already high, the future risk magnitude can also be judged as high across the UK in scenarios of both 2°C and 4°C global warming at the end of the century (Table 4.2).

Impact ratings in the CCRA3 Interacting Risks magnitude framework are defined as follows for impacts on infrastructure:

High – Major annual damage and disruption or foregone opportunities (£hundreds of millions and/or hundreds of thousands of people affected)

Medium - Moderate annual damage and disruption or foregone opportunities (£tens of millions and/or tens of thousands of people affected)

Low - Minor annual damage and disruption or foregone opportunities (less than £10 million and/or thousands of people affected).

¹ UKCP18 probabilistic projections with RCP2.6 and RCP8.5 emissions, with 5th, 50th and 95th percentiles respectively reaching global warming of 1.1°C, 1.9°C and 2.8 °C (RCP2.6) and 3.0°C, 4.2°C and 5.8°C (RCP8.5) in 2070-2099. The RCP2.6 range approximately matches the lower CCRA3 scenario, and the RCP8.5 range includes the CCRA3 higher scenario but extends both slightly below and considerably above this (see Chapter 2: Watkiss and Betts, 2021).

Table 4.2 Summary of the most significant risk pathways modelled in the CCRA3 Interacting Risks project (WSP, 2020), along with the impact ratings (based on annual average impact and likelihood) in 2020 and 2080.

Climate drivers	Hazardous events	Main impact cascades		2020	2080
Increase in summer temperatures and reduction in summer mean rainfall	Heatwaves and very hot days	Transport infrastructure overheating, or disruption to IT and communications services	Travel and freight delays	Low	Medium
			Transport infrastructure damage	Medium	Medium
Extreme winter rainfall events and increase in winter mean rainfall	River, surface and groundwater flooding	Power infrastructure flooded	Power supply disrupted	Low	Low
		Water, sewerage infrastructure flooded, reduced water quality or power supply disrupted	Water supply disrupted	Low	Medium
			Sewer flooding	Low	Medium
		Transport hubs or infrastructure flooded, or power supply disrupted	Travel and freight delays	Medium	High
		Damaging water flows, slope or embankment failure	Transport infrastructure damage	Medium	High

The most significant interactions are those which result in travel and freight delay or damage to transport infrastructure. The most significant cross-sectoral interaction highlighted was linked to natural environment interactions (e.g. flooding leading to reduced water quality in the natural environment leading to water supply disruptions). However, drought leading to low reservoir levels and water supply disruptions was also found to be significant in the 2050s and 2080s in the higher warming scenario by 2100 (changes in drought frequency are uncertain and were modelled on a

‘what-if’ basis in the project).

4.2.1.3. Lock-in and thresholds (I1)

As highlighted in Box 2, the major cause of lock-in for this risk stems from high levels of infrastructure development planned for the near future (as per the National Infrastructure Plan). Infrastructure has a long lifetime and thus has an increased likelihood of facing future climate risks, while it could also be difficult or costly to retrofit adaptation later. In more specific terms, there is a concentration of lock-in risks because of an increasing reliance on electricity and ICT with all infrastructure sectors requiring power for some (if not all) of their assets. This situation is particularly acute in the transport sector due to the increasing electrification of transport systems and vehicles. The increasing dependence in utilities of telemetry/remote inspection means that the vulnerability to ICT failure is increasing very rapidly. Developments such as the likely introduction of autonomous transport technologies over the next 30-50 years will introduce new interdependencies and change the nature of cascading failure risks in the infrastructure system. Uptake of concepts such as digital twins, and the real-time management of assets management, will further increase reliance on power systems. CCRA2 noted there is insufficient information about the location of ICT and the criticality of its function. There are some modelling approaches that incorporate ICT systems, but these are not UK based.

Thresholds for cascade failure are difficult to define. When dealing with a system of systems, the network is effectively as strong as the weakest link. Although thresholds will exist for individual risks on individual assets, defining a clear threshold where a cascade failure will occur is an imprecise science given the range of compound hazards and interactions needing to be considered. This remains an important area for future research.

4.2.1.4. Cross-cutting risks and inter-dependencies (I1)

Owing to its nature, this risk has interactions with many other risks within the infrastructure sector and beyond. As well as the information on interdependencies, WSP (2020) identified the impacts which have the greatest number of downstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). In terms of infrastructure, power supply interruption has the highest number of connections (15, with 11 being in the infrastructure sector and 4 in the built environment), followed by IT and communications disruption (10, with 7 in the infrastructure sector and 3 in the built environment) and transport infrastructure/hub flooding (7, with 4 in the infrastructure sector and 3 in the built environment). Looking at impacts with large numbers of upstream connections (which can be affected from a number of different sources), those that are affected most by the infrastructure sector are travel and freight delays (13 connections with the infrastructure sector), water supply interruptions (9 connections), transport accidents, power supply interruptions, transport infrastructure damage and sewage flooding (all with 5 connections).

4.2.1.5 Implications of Net Zero (I1)

At present, no studies have assessed the extent to which future socio-economic scenarios or

planned developments to achieve Net Zero in the UK will affect the exposure and vulnerability of infrastructure systems to climate hazards. However, power supply interruption, and transport infrastructure/hub flooding are both identified in the literature as highly connected impacts with high potential for cascading failures. Both of these systems feature heavily in the CCC Net Zero Technical Report (CCC, 2019b) and the CCC's 2020 advice on the Sixth Carbon Budget (CCC, 2020a) as key areas for meeting emissions targets, hence future exposure and vulnerability will potentially be influenced by forthcoming recommendations / policy in this area. It is therefore possible that the Net Zero target could concentrate system risks. As an example, electrification of cars (as well as household energy supply, see risk H6) will increase the potential impact of power shortages brought on by weather related events. The increase in future climate change and the growing level of potential interacting and cascading risks could make the Net Zero target more difficult to achieve, in that it is likely to involve additional costs (for climate smart design) and might require greater margins for management in the system.

4.2.1.6 Inequalities (I1)

At present, no studies exist which specifically assess the observed inequality of risks to individuals/groups. The spatial hotspot analysis by Thacker *et al.* (2017a) demonstrates the importance of large urban areas of England and Wales for both demand for infrastructure services and their ability to accommodate these (especially in the periphery of urban areas). This analysis is based on simulation and also identifies important transport corridors between settlements. The CCRA3 interacting risks project (WSP, 2020) shows that of the 98 interactions (defined as a pair of connected hazardous event or impact nodes, excluding the climate driver nodes) taken into consideration in the infrastructure sector, 6 (2%) were defined as having coastal impacts only. For the remaining 92 interactions, the impacts are likely to be felt in multiple locations (i.e. both urban and rural areas, and the coastal zone). The study concludes that for the vast majority of interactions it is not possible to state that they are more important at one location over another. The consequences of this risk are high across England, Wales, Scotland and Northern Ireland.

4.2.1.7 Magnitude scores (I1)

The case studies and literature support an assessment of current high magnitude of risk with high confidence, with disruption in urban areas potentially impacting hundreds of thousands of people annually. WSP (2020) supports a continuation of high magnitude risk in the future, given that the size of the impact from cascading effects increases over time.

Although the existing literature on the potential impact of climate change on cascading failures in the infrastructure sector is limited, the evidence for future risk to the individual components of the infrastructure system contained in this chapter (for example, risks to energy, risks to infrastructure from river, surface, groundwater and coastal flooding) supports a medium level of confidence for a continued high magnitude risk of cascading infrastructure failure for all nations of the UK for the 2050s and 2080s under pathways to 2°C and 4°C global warming at the end of the 21st Century.

Table 4.3 Magnitude scores for risks to infrastructure networks (water, energy, transport, ICT) from cascading failures

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Northern Ireland	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Scotland	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Wales	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)

4.2.2 Extent to which current adaptation will manage the risk (I1)

4.2.2.1. Effects of current adaptation policy and commitments on current and future risks (I1)

4.2.2.1.1. UK-wide

The CCC (2019b) state there is no systematic national assessment of interdependency risk or a framework to improve resilience at the UK level, including addressing risks and opportunities from climate change. The general approach to manage cascade failure is by tackling individual risks on individual infrastructure networks. As a result, although the risks to individual components or systems are reduced, opportunities and efficiencies that could be gained by taking a whole-systems approach are often missed. As this work to build resilience is ongoing (at various levels), then the risk will be reduced somewhat by current adaptation efforts across specific sectors. The cumulative impact of these efforts on general cascade failures is unknown and as such expert judgement is required on the extent to which those efforts will manage the risk (as demonstrated in the CCRA3 Interacting Risks project).

A better understanding of cascade failures and improved efforts for data sharing could significantly reduce any adaptation shortfall. The OECD highlights the importance of specialist networking groups

such as the Infrastructure Operators Adaptation Forum in facilitating discussions between different infrastructure organisations and government, raising awareness, promoting collaboration and potentially increasing preparedness to reduce vulnerability (Vallejo and Mullan, 2017). In the UK, the 2004 Civil Contingencies Act provides a framework for cross-sectoral discussions on climate change adaptation within the broader context of disaster and crisis management. It created Local Resilience Forums (England and Wales, this is devolved for NI and Scotland), that bring together regional authorities and organisations, including category one responders, in order to create a risk profile for their region and produce localised regional plans and protocols to prepare for disaster management (Cabinet Office, 2013). Indeed, the Civil Contingencies Act places a duty on Category 1 and 2 responders to share information to enhance coordination, and the Green Book Guidance provides tools to identify and manage interdependencies that affect resilience in projects (HM Treasury, 2015), with supplementary information for policy makers and analysts (Defra, 2020a). There is ongoing work to share data with Local Resilience Forums across geographical and organisational boundaries via the Resilience Direct online platform. This is an online private 'network', which enables civil protection practitioners to share data during the preparation, response and recovery phases of an event or emergency. The platform is a secure site, and therefore requests to use evidence provided by other users have to be agreed by the user groups (Defra, 2018). In reality, the level of staffing, resources and materials varies between Local Resilience Forums (Quirk, 2019), potentially implying variability in local resilience (although this may be a rational response to lower vulnerability).

The devolved administrations are members of the Cabinet Office-led Infrastructure, Resilience and Security Working Group (IRSWG) and are working closely with the UK Government, each other and Local Resilience Forums on the existing risk to critical infrastructure. This includes work around the UK Sector Resilience Plans which set out risks to 13 sectors (including energy, transport and emergency services) and measures to improve resilience where necessary. It should be noted however that a review of LRF documents found little mention of managing cascading impacts.

The National Infrastructure Commission makes three recommendations to enable future resilient networks: firstly, that Government should introduce a statutory requirement by 2022 for Secretaries of State to publish five-yearly resilience standards, and an assessment of how infrastructure operators can deliver these standards; secondly, that by 2024, regulators should introduce a means to stress test infrastructure systems and decision-making to ensure that standards can be met; and thirdly, that infrastructure operators should develop and maintain strategies to ensure infrastructure services can continue to meet resilience standards in the long term (NIC, 2020)

While different aspects of infrastructure resilience are led at the UK level, the national adaptation programmes of each UK nation also include relevant information (with reserved matters included in the NAP2 document).

4.2.2.1.2 England

A CCC survey from 2014 (repeated in 2017) highlighted that Local Resilience Forums in England felt information was not being shared appropriately between them on infrastructure interdependencies (e.g. infrastructure operators and Category 1 and 2 responders). The second National Adaptation

Programme (NAP2) contains one action on dealing with cascading risks in infrastructure; 'help ensure local arrangements are in place to share data effectively on locally significant infrastructure sites with Local Resilience Forums'. The latest UK Government Response to the CCC's progress reports (HM Government, 2019a) pointed to the National Infrastructure Commission's report on resilience, the Adaptation Reporting Power, and the Infrastructure Operators Adaptation Forum as mechanisms to exchange information between providers but stated that further information was not available to the CCC as it is strictly confidential. The CCC is planning to update its survey of LRFs for its 2021 progress report to ascertain if progress has been made for these groups.

4.2.2.1.3 Northern Ireland

The latest Adaptation Programme for Northern Ireland (DAERA, 2019) contains an objective for transport and network services to be resilient to the impacts of flooding and extreme weather. The importance of interdependencies is mentioned throughout the document, though no specific actions are included to address cascading risks specifically.

4.2.2.1.4 Scotland

Scotland's most recent Climate Change Adaptation Programme (Scottish Government, 2019b) also mentions the importance of interdependencies between infrastructure sectors and includes a range of actions looking at supporting infrastructure systems to become more resilient in general. There are no specific actions that are included in response to this risk alone.

As an example of regional action, Glasgow has seen the creation of 'Climate Ready Clyde', bringing together a number of stakeholders including Local Authorities, SEPA, SGN, the NHS and Transport Scotland to develop Glasgow City Region's first Climate Adaptation Strategy. This strategy, which is currently in draft, outlines the processes and early interventions needed to manage climate risks, provides a strategic framework for adaptation, and sets out how the city will deepen and expand collaboration and collective impact between citizens and organisations (Climate Ready Clyde, 2020). Through the partnership, they have worked together on projects with wider infrastructure providers such as Scottish Water and Scottish Power Energy Networks to better understand regional interdependencies on infrastructure, producing new tools and assessments to deepen collective understanding. They have also produced a toolkit for assessing climate risk in built environment and infrastructure projects which includes a specific recommendation to consider cross-organisation risks and interdependencies.

4.2.2.1.5 Wales

In Wales, the Well-being of Future Generations (Wales) Act 2015 established Public Service Boards (PSBs) across the nation (Welsh Government, 2015). Each PSB must establish well-being plans, and in doing so, prepare well-being assessments which pay due regard to the latest UK Climate Change Risk Assessment. Alongside the well-being goals set out in the Act, the approach intends to support public services in Wales to achieve greater collaboration on cascading climate risks. Also, since the last CCRA, a National Infrastructure Commission for Wales was established. One of the key themes of the commissioner's 2019 report was resilience (National Infrastructure Commission for Wales,

2019). This recognition was reiterated in the 2020 report, where the commission has asked for evidence of risk management strategies (National Infrastructure Commission for Wales, 2020). This should prove an important tool in advising the Welsh Government on long term infrastructural needs.

The latest Welsh Climate Change Adaptation Programme (Welsh Government, 2019b) includes three specific actions aimed to address the cascading risks from climate change to infrastructure:

- Complete delivery of pilot exercise to improve emergency response to threats to infrastructure.
- Roll out new infrastructure emergency response processes across all Local Resilience Forums.
- Work with utility companies specifically to address the risk of a total failure of the UK's national electricity transmission network.

Prosperity for All: A Climate Conscious Wales (Welsh Government, 2019b) references a pilot being undertaken in the Dyfed-Powys region which brings together responder agencies and utility companies to strengthen preparedness around the various risks to infrastructure. Nevertheless, it is not clear to what extent climate risks are considered.

4.2.2.2 Effects of non-government adaptation (I1)

Infrastructure operators are becoming increasingly aware of interdependencies and cascade failures and including them in their in-house research and longer-term strategic planning. A project funded by the International Union of Railways developed (with stakeholder consultation) a two-sided framework for use by any organisation to develop climate-change-ready transport infrastructure, regardless of their current level of knowledge or preparedness for climate change (Quinn *et al.*, 2018). The framework is composed of an adaptation strategy and an implementation plan, in order to embed climate change adaptation within organisational procedures so it becomes a normal function of business. However, there is little evidence to suggest that strategic actions to reduce exposure or vulnerability to climate change are happening (CCC, 2019b). Following Storm Desmond and Storm Eva (both December 2015), the electricity network companies have been reviewing and updating Engineering Technical Report (ETR) 138 – Resilience to Flooding of Grid and Primary Substations to consider enhancing the protection provided to primary substations supplying >10,000 ('key local infrastructure'), and identifying 'locally significant infrastructure (e.g. supply to rural communities) within the broader remit of considering interdependencies (Booth *et al.*, 2017).

4.2.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I1)

Despite the actions described above there is judged by the authors to be an adaptation shortfall for this risk given the lack of evidence on how far proposed actions listed above are reducing the current and future risk of cascading impacts. This assessment is similar to that in the most recent CCC Progress Report (2019) for England (and reserved matters at the UK level) which scored progress in this area as 1/10, with existing plans given a low assessment, stating that they do not clearly address the risks identified in CCRA2.

Fundamentally, this is an area where non-governmental action will not manage the risk in the absence of government intervention. Public bodies and private organisations that manage, operate and maintain infrastructure have to meet statutory requirements and performance standards for the services they provide, and climate change is one of the risk factors that they should account for in their decision making in order to fulfil their obligations. In the specific case of infrastructure networks, the presence of complex interdependencies coupled with uncertainty around climate change makes it challenging to fully understand and thus address the risks posed (information failures). Further, in dealing with cascading failures, which require some degree of system thinking, significant governance barriers exist, which affect not only the level of preparedness of the infrastructure network, but also the type of response to failures and disruptions. In fact, the interconnectivity between the infrastructure assets means that any poorly defined responsibilities, or lack of coordination between various operators, could undermine the ability to anticipate, react and recover from cascading failures. Government can play a key role in adopting a system-based approach to planning for resilience by providing the information to enable this, and providing infrastructure operators with a regulatory framework that supports adaptation at network level rather than at the level of individual assets.

The lack of a systematic national assessment of interdependency risk, the poor assessment of progress on adaptation in this area, and the low likelihood that sufficient non-governmental action will be undertaken indicates to the authors that this risk is not currently being managed, and that only partial plans are in place to do so. Although cascading failure and interdependencies are increasingly being acknowledged in policies, strategies and plans in place, these lack clear objectives following SMART principles (Specific, Measurable, Achievable, Realistic and Timebound, see National Audit Office, 2019) to reduce risk to a low magnitude, across the likely range of future climate scenarios. As there is no evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

4.2.2.4 Adaptation Scores (I1)

Table 4.4 Adaptation scores for risks to infrastructure networks (water, energy, transport, ICT) from cascading failures			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

4.2.3 Benefits of further adaptation action in the next five years (I1)

4.2.3.1 Additional adaptation that would address the adaptation shortfall (I1)

There are beneficial adaptation actions which could be enacted during the next five years. However, the benefits of these actions are often primarily aimed at a particular infrastructure system, and

hence also relate to other risks within this report. For instance, Thacker *et al.* (2018) demonstrate the benefits of bringing forward adaptation work in the protection of electricity substations. The study concentrates on the ETR 138 recommendations that major electricity assets be made resilient to a 1:1000-year flood. By simulating the potential costs involved in cascading impacts of flood-related substation failure it is found that (i) building a wall is cost beneficial for all substations; (ii) relocating the substation is not cost beneficial in most cases; and (iii) in approximately 50% of cases, raising the substation would be cost beneficial.

CCC (2017) argue that common standards of resilience (such as ISO 14091) would help with investment planning and help emergency planners better understand the potential for service disruption arising from assets in their area. ETR 138 ‘Resilience to Flooding’ is given as a good example that has been adopted within the electricity transmission and distribution sector. It is stated that enhanced arrangements for information sharing on critical risks of interdependence are required to assist in creating the appropriate institutional conditions for adaptation.

4.2.3.2. Indicative costs and benefits of additional adaptation (I1)

There is some evidence on the potential costs and benefits of adaptation for infrastructure investment (OECD, 2015) and in general positive benefit-to-cost ratios are reported for making infrastructure resilient (GCA, 2019). However, there is little evidence on the economic benefits for addressing cascading risks or moving to a systems-based approach. The studies that do exist tend to assess the additional benefits in considering indirect costs from adaptation (rather than just the avoided costs of damage to the infrastructure asset and operation itself), e.g. Thacker *et al.* (2018) for electricity substations, and Pant *et al.* (2020) for multiple networks. The consideration of indirect risks increases benefit streams and thus leads to higher economic benefits (and NPVs/BCR ratios). Evidence from other countries highlights that a systems-approach can also highlight the key vulnerability pinch points in networks, and thus help to direct adaptation, e.g. over-designing some key nodes or elements of the network.

4.2.3.3. Overall urgency scores (I1)

Table 4.5: Urgency scores for risks to infrastructure networks (water, energy, transport, ICT) from cascading failures				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	Medium	Medium	Medium	Medium

Due to the high projected magnitude for this risk and the lack of a systematic national assessment of interdependency risk, this risk has been scored as more action needed. Although the risk is recognised in the National Adaptation Programmes for each UK nation, there is presently limited evidenced progress on adaptation in this area, combined with little evidence to suggest that sufficient non-governmental action will be undertaken to keep the risk constant at today’s level, or

reduce it in future. Policies, strategies and plans require clear SMART objectives to reduce risk to a low magnitude across the likely range of future climate scenarios. This score is given with medium confidence, noting the lack of specific evidence on benefits of future adaptation for cascading failure, but acknowledging a high level of agreement between experts.

4.2.4 Looking ahead (I1)

In terms of considerations beyond CCRA3, including information that would be useful to inform CCRA4 and NAP4, it can be argued that the potentially beneficial measures identified above would be considered transformational, given the CCC's (2019b) low assessment of progress in this area. Much of the literature actually highlights that transformational adaptation requires a shift towards system thinking (e.g. Lonsdale *et al.*, 2015).

Practitioners have highlighted the need for more research into compound hazards, and that it would be useful to record and monitor impacts caused by cascading failures from weather and climate related disruptions (e.g. Storm Dennis). The CCC (2019b) similarly argue that a useful indicator would be to record and monitor impacts caused by cascading failures from weather and climate related disruptions.

4.3. Risks to infrastructure services from river and surface water flooding (I2)

Identified as a key risk with an adaptation shortfall in previous UK CCRA3s, river and surface flooding is a perennial risk to UK infrastructure, with each season adding new case studies and evidence to underpin the significant magnitude of the threat. The latest research indicates that all infrastructure continues to face an increased risk from surface water flooding with a continuation of the current level of adaptation ambition, and even in the most ambitious adaptation scenarios modelled for CCRA3. Projections of risk from river flooding are more mixed. Railway lines and stations continue to look increasingly exposed to fluvial flooding, but taking into account adaptation, the risk of fluvial flooding appears to now be reducing for energy and clean water infrastructure assets. The risk to landfill sites from both sources of flooding is low. The current magnitude of the risk is scored as high across the whole of the UK with high confidence. Future magnitude without additional adaptation is scored as high with medium confidence.

The evidence also highlights that despite progress, particularly through investment in flood defences, there exists an adaptation shortfall across the UK which will require further government intervention to overcome in the next five years. Taken together, this leads to an urgency score of more action needed.

4.3.1 Current and future level of risk (I2)

4.3.1.1. Current risk (I2)

4.3.1.1.1. UK wide

Since the previous CCRA, the UK has seen a number of high-profile flood events that have impacted infrastructure services. 2019 was a particularly significant year with winter flooding making the headlines in South Yorkshire, quickly followed by the impacts of Storm Ciara and Dennis in 2020. October 2018 saw significant flooding from Storm Callum impacting on infrastructure in Wales whereas 2016 and 2019 saw intense summer and autumn rainfall producing flash floods notably impacting several stations on the London Underground.

For infrastructure, Sayers *et al.* (2020) quantify the current number or length of assets at 'significant' risk (denoted as an annual probability exceedance of 1:75 or higher for river flooding and 1:30 or higher for surface water flooding). The infrastructure types assessed are rail line length and number of rail stations, clean water sites, sewage treatment works, power stations' electricity substations, and landfill sites. Flooding of health and emergency services infrastructure is covered under risk H12. Across the UK, hundreds of individual assets and hundreds of kilometres of train lines are exposed to significant levels of river and surface water flooding in each UK nation, though it has not been possible in the research to determine what percentage of the total numbers of assets is at risk. The figures exclude roads, ports, airports and digital infrastructure assets such as data centres and telephone exchanges. It should also be noted that the assessment does not take into account local measures implemented to reduce the risk of flooding such as placing assets on higher ground. The effects of flooding on road networks, in addition to damage to the roads themselves, are to service users. This is particularly significant when considering delays to emergency services. Pregolato *et al.* (2016) assessed urban strategies for reducing the impacts of extreme weather including flooding on infrastructure networks. In this study, person delays experienced during transport on the road network in Newcastle were modelled to be 63 minutes and 119 minutes during a 1 in 10 and 1 in 200-year surface water flood respectively.

On the railways of Great Britain, Network Rail (2017a) reported that between 2006 and 2016 flooding caused an annual average of approximately £15 million in Schedule 8 compensation payments (paid to passenger and freight train operators for network disruption) between Network Rail and Train Operating Companies. It must be noted that the reported figures do not distinguish between river, surface and groundwater flooding and coastal flooding. Additionally, this figure does not include repair and remediation work following flood events. An analysis of different climate risks (flooding, landslide, extreme weather, high winds, precipitation change and sea level rise) on the UK rail network identified flooding as the greatest risk (Wang *et al.*, 2020).

In their review of drivers of urban flood risk, O'Donnell and Thorne (2020) point to the problems associated with ageing infrastructure, requiring replacement or upgrading at significant costs. It argued that rehabilitation of intra-urban assets is taking place at an insufficient pace to keep up with deterioration, representing an increasing driver of UK flood risk.

4.3.1.1.2. England

In England, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.6 below (from Sayers *et al.*, 2020).

Table 4.6. Number or length of infrastructure assets currently exposed to 'significant' risk of surface water or river flooding in England		
Infrastructure Asset	Exposure to surface water flooding (1:30 or greater)	Exposure to river flooding (1:75 or greater)
Water sites (no.)	43	19
Sewage treatment works (no.)	601	478
Power stations (no.)	170	53
Electricity substations (no)	463	143
Rail length (km)	1,691	444
Rail stations (no.)	450	44
Landfill sites	0	0

The Environment Agency (2018) assessed the costs of the widespread flooding in December 2015 and January 2016 following Storms Desmond, Eva and Frank. The storms were associated with record-breaking monthly rainfall for parts of the UK and led to extensive flooding in the North of England. The Environment Agency analysis produced high-level economic estimates of the costs following an approach utilised for estimates of the 2007 summer floods and the 2013 to 2014 winter floods. The best estimate for the impact on rail transport was £121 million at 2015 prices (with a range of £103 million to £129 million). This figure is based on Network Rail assessments of infrastructure damages and disruption payments. It must be noted that this figure includes capital and welfare damages associated with the collapse of a sea wall in the Dover Folkestone area which is related to Risk I3 (the report does not disaggregate these figures). It was also noted by Network Rail that it is sometimes difficult to distinguish between flood and storm damage.

Further evidence from the Environment Agency (2018) assessment of the 2015-16 storms gives a best estimate for the costs to road transport as £220 million (with a range of £165 million to £275 million) based on Department for Communities and Local Government and Highways Authority data. It must be noted that this figure includes capital and welfare damages associated with impacts not covered in this risk, such as the collapse of the Tadcaster Bridge (Risks I1 and I4) and a landslip on the A591 (Risk I5). The Environment Agency also assessed the costs to electricity infrastructure, utilising DECC estimates for operational and infrastructure costs of £11 million. This included 100,000 people who endured power cuts over three days following the flooding of a substation in Lancaster. It was deemed not possible to assess the economic impact on ICT associated with the flooding of a BT exchange in York and a Vodafone data centre in Leeds as data were not provided by the respective companies.

Booth *et al.*, (2017) assessed the impact of severe flooding of the River Lune during Storm Desmond in 2015. This caused defences to be overtopped at a 132 kV grid substation, and on Saturday 5th December the decision was taken to switch off supplies to 60,987 customers (which equates to a medium magnitude impact). At Kirkstall, in North Leeds, the defences were overtopped during

Storm Eva, in 2015) when the River Aire burst its banks - electricity supplies to over 27,000 customers in the nearby Leeds Central Business District were lost (medium magnitude).

Network Rail’s most recent Weather Resilience and Climate Change Adaptation Plans for the English Routes of Anglia, London North East and East Midlands, North West and Central, South East, Wessex and Western report a combined annual average of £11.1 million of flood-related Schedule 8 payments (the compensation payments to passenger and freight train operators for network disruption) between 2006/07 and 2018/19. Note that this does not include costs of repair and remediation work, or Schedule 4 payments (compensation payments to passenger and freight train operators for Network Rail’s possession of the network).

Pant *et al.* (2018) quantified infrastructure flood impacts in terms of disrupted customers linked directly to flood assets and customers disrupted indirectly due to network effects in the Thames catchment area. The likelihood of flooding to areas of land within the flood plain of 1 in 1000 year fluvial and tidal flooding scenario was considered. Wastewater treatment works were found to have the largest risks because large numbers of such assets are located directly in flood areas. Water storage assets were found to have relatively lower flooding risks being located away from flood zones or at elevation, as expected due to function. Likewise, telecom assets are also found to be located away from flood zones or at elevation. There are potentially high magnitude disruptions resulting from aggregated electricity failures.

4.3.1.1.3. Northern Ireland

In Northern Ireland, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.7 below (from Sayers *et al.*, 2020).

Table 4.7. Number or length of infrastructure assets currently exposed to ‘significant’ risk of surface water or river flooding in Northern Ireland		
Infrastructure Asset	Exposure to surface water flooding (1:30 or greater)	Exposure to river flooding (1:75 or greater)
Water sites (no.)	382	91
Sewage treatment works (no.)	0	0
Power stations (no.)	3	0
Electricity substations (no)	6	1
Rail length (km)	183	87
Rail stations (no.)	3	0
Landfill sites	0	0

The Department for Infrastructure NI has produced a technical assessment of future flood risks in ‘The Northern Ireland Flood Risk Assessment’ (DfI, 2018) it identifies areas of potential significant flood risk. Their mapping analysis highlights an additional 248 key service and transport infrastructure assets are at risk from climate change. The latest risk assessments and corresponding management plans are currently out for consultation (see 4.3.2).

4.3.1.1.4. Scotland

In Scotland, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.8 below (from Sayers *et al.*, 2020).

Table 4.8. Number or length of infrastructure assets currently exposed to 'significant' risk of surface water or river flooding in Scotland		
Infrastructure Asset	Exposure to surface water flooding (1:30 or greater)	Exposure to river flooding (1:75 or greater)
Water sites (no.)	0	2
Sewage treatment works (no.)	20	63
Power stations (no.)	5	14
Electricity substations (no)	34	33
Rail length (km)	861	268
Rail stations (no.)	64	7
Landfill sites	5	1

Network Rail's Scotland Route reported in their most recent Weather Resilience and Climate Change Adaptation Plan (2020a) that flooding accounted for 20.3% of delay minutes between 2006/07 and 2018/19. The annual cost of flooding through Schedule 8 payments averaged £1.32 million, with the highest year totalling £3.31 million. Note that this does not include costs of repair and remediation work, or Schedule 4 payments (compensation payments to passenger and freight train operators for Network Rail's possession of the network).

4.3.1.1.5. Wales

In Wales, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.9 below (from Sayers *et al.*, 2020).

Table 4.9. Number or length of infrastructure assets currently exposed to 'significant' risk of surface water or river flooding in Wales		
Infrastructure Asset	Exposure to surface water flooding (1:30 or greater)	Exposure to river flooding (1:75 or greater)
Water sites (no.)	62	35
Sewage treatment works (no.)	126	60
Power stations (no.)	0	0
Electricity substations (no)	72	57
Rail length (km)	809	345
Rail stations (no.)	79	30
Landfill sites	0	0

Network Rail's Wales Route's latest Weather Resilience and Climate Change Adaptation plan (2020b) reported that flooding was the most significant weather-related cause of delay between 2006/07 and 2018/19, costing a total of £5 million in Schedule 8 payments with an annual average cost of

£0.38 million and recording a maximum of £0.68million.

4.3.1.2. Future risk (12)

4.3.1.2.1. UK-wide

Extensive modelling of future risk has been completed in Sayers *et al.* (2020). The CCRA3 Future Flooding project (Sayers *et al.*, 2020) provides bespoke flood risk projections for the whole of the UK, including information on how the outputs have been validated and similarities with other flood data used by the UK Government and devolved administrations. This work documents both the future exposure of infrastructure assets to climate change as well as the impact of adaptation measures with a range of results available via a future flood explorer tool. To assess this baseline level of risk, the 'reduced whole system' adaptation scenario has been used. The projections form the basis of the analysis for this risk, but other evidence sources are included where these have been identified.

4.3.1.2.1.1 Surface Water Flooding

Sayers *et al.* (2020) project that all infrastructure assets across the four countries will face increased exposure to surface water risk in the absence of further adaptation action. In a scenario of 4°C global warming in 2100² ("4°C in 2100") and a scenario of low population growth, a potential doubling of risk is projected by the 2080s for power stations and electricity substations in England and railways in England, Wales and Northern Ireland. Only 5 landfill sites are currently deemed at risk from surface water flooding (all in Scotland) and this does not change in the future. Dozens of different scenarios are modelled and available through the Sayers results database (web link: [CCRA research - UK Climate Risk.](#))

Separate analysis from Dale *et al.* (2017) present results from the UKWIR rainfall intensity project. This assessed changes in 1 in 30-year storm rainfall quantities for use in sewer modelling and design. Large increases in storm rainfall were projected with a Convective Permitting Model and a scenario of 5.5°C global warming at 2100³. With no adaptation, estimated changes to storms show similar or higher changes to those currently used by the water industry - this could have significant impacts on the resilience of sewer networks in the future.

4.3.1.2.1.2 River flooding

Sayers *et al.* (2020) reports more variable changes in flood risk to infrastructure assets from river flooding. Across the UK, in the reduced whole system scenario (which assumes adaptation to flood risk continues but implementation is in-line with a lower level of ambition, also described as 'no additional action') the level of risk decreases for clean water sites, power stations and electricity substations by between 0 and 70% by the 2080s in a scenario of +4°C in 2100 and low population.

² For the scenario of 4°C global warming in 2100, Sayers *et al.* (2020) used a subset of the UKCP18 probabilistic projections that reached 3.9°C to 4.1°C global warming in 2090-2100, relative to the 1850-1900 average.

³ Met Office regional climate model at 1.5km resolution (Kendon *et al.*, 2014) with boundary conditions from the HadGEM2-ES global climate model driven by the RCP8.5 concentration scenario, reaching global warming of approximately 5.5°C at 2100 (Betts *et al.*, 2015).

For sewage treatment works, rail lines and stations, there is generally either no change or an increase in risk of up to 80%. Only one landfill site is classed as being at risk from river flooding and this does not change in the future.

Climate change also impacts the standard of protection afforded by flood defences that help to protect sites from river flooding (Sayers *et al.*, 2020). In the absence of any further adaptation the reduction in the standard of protection provided by fluvial defences is mixed with some areas experiencing an effective increase in the standard of protection as peak flood flows reduce (reflecting the complex spatial pattern of future changes in peaks flows).

Bell *et al.* (2016) assessed the possible impacts of climate change on snow and peak river flows across Britain. The results indicate that in a scenario of +4°C at the end of the century⁴, the seasonality of peak river flows will be affected in some parts of the country by 2069-2099, with northerly regions tending to experience annual maxima earlier in the water year in future, with changes in southerly regions being less clear-cut.

Other evidence looking at the waste sector does suggest some risk. Some studies have looked at the risks to solid waste infrastructure indirectly through disruption to other infrastructure (e.g. failure of the electricity, gas or water supplies or disruption of transportation routes) (Ramsbottom *et al.*, 2012). Other sources of evidence suggest differently to Sayers *et al.* (2020) that flood risk will be the biggest threat to the sector, with increases in temperature also likely to require some changes to operations and management. Flooding of landfill sites usually results in an associated pollution event (Laner *et al.*, 2009; Neuhold and Nachtnabel, 2011).

Flood incidents can produce large amounts of waste within the flooded area; a minimum of 250 kg of additional waste per household is likely from a single flood (Watson and Powrie, 2015). However, the flooded area would need to include a significant (> 1,000,000) number of dwellings before this would have an impact on overall UK waste arisings.

4.3.1.2.2. England

Sayers *et al.* (2020) project that in England, under a low population and no additional adaptation scenario, the risk of river flooding to sewage treatment works, railway line and railway stations increases at both the 2050s and 2080s. In a +4°C in 2100 scenario, there is a projected 32% increase in sewage works and length of rail at risk by the 2080s, with a 45% increase in railway stations at risk. The number of clean water sites, power stations and electricity substations are all projected to decrease in risk by at least 56% in the same period. For surface flooding, risk increases for all infrastructure assets at both the 2050s and 2080s. By the 2080s in a +4°C in 2100 scenario, the increase in risk ranges from 57% for railway stations to 114% for electricity substations.

⁴ UKCP09 11-member perturbed-parameter ensemble of the HadRM3 regional climate model driven by the SRES A1B scenario.

4.3.1.2.3. Northern Ireland

Railway lines are the only infrastructure type in Northern Ireland that Sayers *et al.* (2020) project to increase in risk from river flooding (under a low population and no additional adaptation ('reduced whole system' scenario). Risk increases by 50% by the 2080s in a +4°C in 2100 scenario. All other infrastructure types are projected to decrease in risk. For surface water flooding, increased risk is projected for freshwater sites, electricity substations, railway lines and railway stations. By the 2080s in the +4°C in 2100 scenario, this increase in risk ranges from 49% for freshwater sites to 137% for railway lines. The risk to power stations is projected to decrease under all scenarios.

4.3.1.2.4. Scotland

In Scotland, Sayers *et al.* (2020) project that sewage treatment works, railway lines and railway stations will have an increased risk of river flooding. By the 2080s in a +4°C in 2100 scenario, this increase ranges from 5% for sewage treatment works to 70% for railway stations. All other infrastructure types are projected to decrease in risk. For surface water flooding all infrastructure types are projected to increase in risk, ranging between 27% for sewage treatment works and 64% for railway lines by the 2080s in a +4°C in 2100 scenario.

4.3.1.2.5. Wales

Sewage treatment sites, railway lines and railway stations are projected to see an increase in risk of river flooding (Sayers *et al.*, 2020). By the 2080s in a +4°C in 2100 scenario, this increase in risk ranges between 16% for sewage treatment works and 79% for railway lines (all other infrastructure types are projected to decrease in risk). All infrastructure types are projected to be at a higher risk of surface water flooding, ranging from 26% for sewage treatment works to 110% for railway lines (by the 2080s in a +4°C in 2100 scenario).

In Wales, River Basin Management Plans (RBMPs) have been produced for Western Wales; Severn and Dee River and 11 catchment summaries focus on climate risks; soils, water, trees, biodiversity, water demand, and supply and character. Natural Resources Wales (2018) assessed that the following numbers of infrastructure sites in specific River Basin Districts are at increased risk from being affected by flooding with climate change: Dee, 445; Severn, 1658; Western Wales, 1658. The reports also assess the number of railway properties at risk from flooding with climate change: Dee, 3; Severn, 34; Western Wales, 11.

4.3.1.3. Lock-in and thresholds (I2)

The major cause of lock-in is from 'business as usual' planning and infrastructure being added in the near future if resilience measures are not being added, the long operational life of assets and thus the likelihood of facing future climate risks, and because it could be difficult or costly to retrofit later. There is potential for lock-in if flood defences / stormwater systems are under-engineered to cope with projected changes in climate ('lack of action' lock-in). The latter is particularly difficult to fix in urban environments once installed. There are also implications for maladaptation with flood defences which effectively pass the flooding problem downstream.

Key thresholds exist as assets will be engineered to resist floods of a specified return period. For example, reservoir dams are engineered to withstand a 1:10,000-year flood (see case study), but other structures are only built to withstand 1:100-year or lower floods. However, given likely increases to flood risk, there is scope for an upward inflation in engineering codes. The Cabinet Office now recommends that any Critical National Infrastructure should be able to withstand a 1:200-year event, but there is a major difference whether this is a 1 in 200-year risk today, or one with future climate change (i.e. in the 2050s). This can have important cost implications, from the trade-off between higher standards of protection and costs today versus future resilience and has led to a greater focus on decision making under uncertainty.

4.3.1.4. Cross-cutting risks and inter-dependencies (I2)

The CCRA3 Interacting Risk project (WSP, 2020) assessed the impact of river, surface and groundwater flooding on infrastructure to have a number of significant cascading impacts in the 2020s, 2050s and 2080s in scenarios of approximately 2°C and 4°C global warming in the late 21st Century⁵, both to infrastructure and other sectors. The direct impact of extreme rainfall events causes flooding of power infrastructure, transport infrastructure and hubs and water sewage infrastructure. WSP (2020) also identified indirect impacts of cascades from flooding causing slope and embankment failures leading to transport damage and subsequent travel delays, and cascades from power disruptions from flooding affecting transport, water supplies and building productivity.

Table 4.2 shows that the two most significant cascading risks are caused by flooding of transport infrastructure resulting in travel and freight delays, and slope and embankment failures which in turn lead to transport infrastructure damage. These were determined to have a 'high' score for impacts by 2080.

4.3.1.5 Implications of Net Zero (I2)

Natural flood management is intertwined with Net Zero policy (see 4.4.2). Many hard protection measures have high embodied carbon, and thus there is more interest in nature-based solutions (ecosystem-based adaptation) as an alternative or as part of flood management portfolios. The Net Zero target is likely to increase the interest in these schemes. Flood risk can be reduced by slowing run-off implementing a range of natural flood risk management interventions and the use of sustainable urban drainage systems. Increased tree planting rates, primarily for carbon capture, in both rural and urban areas could have some impact on localised fluvial flooding. However, there is a limit to the effectiveness of natural flood management (Dadson *et al.*, 2017), and perversely the Net Zero target may make it more challenging to manage the risk, though the Environment Agency has developed a Carbon Planning Tool to assess carbon over the whole life of built assets. Also relevant is PAS 2080, a global standard for managing infrastructure carbon. At the same time, the increase in flood related risks to infrastructure services, might make Net Zero more difficult to achieve, in that it

⁵ UKCP18 probabilistic projections with RCP2.6 and RCP8.5 emissions, with 5th and 95th percentiles reaching global warming of 1.1°C to 2.8 °C (RCP2.6) and 3°C to 5.8°C (RCP8.5) in 2070-2099. The RCP2.6 range approximately matches the lower CCRA3 scenario, and the RCP8.5 range includes the CCRA3 higher scenario but extends both slightly below and considerably above this (see Chapter 2: Watkiss and Betts, 2021).

is likely to involve additional costs (for climate smart design) due to the greater margins or uplifts than currently required.

4.3.1.6 Inequalities (I2)

Decisions on where investment is targeted towards flood defences remain a challenge. There is a need to identify critical single points of failure in networks which have the biggest impacts for the largest groups of people. However, protecting these may move the problem elsewhere due to the available funding reallocated to other areas which may have lower populations but a higher proportion of socially vulnerable groups. The type of spatial location will also determine the extent to which disruption can be overcome, with potential inequalities for populations in rural locations with options for different service providers. For instance, cities may have multiple broadband providers, whereas this may not be the case in the country.

4.3.1.7 Magnitude scores (I2)

Table 4.10 Magnitude scores for risks to infrastructure services from river and surface water flooding					
Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Northern Ireland	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Scotland	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Wales	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)

Evidence on the impact of flooding events on infrastructure in the UK supports a current high magnitude with high confidence. Evidence from the Environment Agency (2018) on the 2015-2016 storms in England demonstrates costs to the infrastructure sector in the £100s of millions with hundreds of thousands of people affected. Best estimate figures include £121 million to rail, £220 million costs to roads and £11 million to electricity (although damages associated with other risks in

this assessment, such as landslips, should be noted). Annual figures on impact across the infrastructure sector are partial, but also indicate that magnitude is high on an annualised basis.

Network Rail reported an annual average of approximately £15 million in compensation payments to passengers related with flooding on their network, which does not include remediation and repair work. The stock of assets exposed to current hazard identified by Sayers *et al.*, (2020) and the vulnerability demonstrated in cost assessments of previous events supports high magnitude with high confidence across the four nations of the UK for infrastructure as a whole. It must be noted that the evidence (particularly annualised data) is uneven in quality and availability between infrastructure types.

Projections by Sayers *et al.* (2020) using UKCP18 indicate that all four UK countries will face increased exposure to surface water risk for all infrastructure types in the absence of further adaptation, with some scenarios seeing a potential doubling of risk by the 2080s in a +4°C in 2100 scenario and a low population growth scenario. Projections for risk from river flooding are more mixed, but sewage treatment works, rail lines and stations see either a maintained or increased risk. It is the judgement of the authors that without further adaptation, the risk will remain high for all four countries under all assessed climate scenarios.

4.3.2 The extent to which current adaptation will manage the risk (I2)

4.3.2.1. Effects of current adaptation policy and commitments on current and future risks (Risk I2)

4.3.2.1.1 UK-wide

CCRA2 determined with medium confidence that there is likely to be a significant adaptation shortfall in the future for this risk across the UK. The rationale centred around the fact that although resilience initiatives such as the Cabinet Office Critical Infrastructure Resilience programme and Sector Security and Resilience Plans have been established in the late 2000s, there had, at that point, been no published account of achievements in improving resilience of infrastructure systems to flood risk. It was stated that few sectors systematically report on the resilience of their assets and disruption caused by flooding (particularly non-regulated sectors such as ports and digital networks, as well as local infrastructure).

A UK Coordination Group (comprising representatives of the 4 nations – Environment Agency, SEPA, NRW, DfI NI) share information about allowances for Climate Change in Flood Risk Management and for Development Planning. The Group is reviewing the latest UKCP18 information and developing adaptive policies for their respective jurisdictions (primarily allowances for increased sea level rise, river flows and rainfall intensities along with associated planning advice). The implementation of the resulting guidance on allowances will provide a sound basis for ongoing adaptation activities to manage flood risk across the UK.

Sayers *et al.* (2020) argue that flood risk is best managed through a portfolio of measures implemented through a continuous process of adjustment. This portfolio approach has been adopted in recent policy such as the Scottish Government's 'Delivering Sustainable Flood Risk

Management' (2019c), the Well-being of Future Generations Act in Wales (2015), the 25 Year Environment Plan (HM Government, 2018) and Defra's second National Adaptation Programme 2018-2023 (Defra, 2018). Recent flood policy updates (Defra's Policy Statement (2020b), the Environment Agency's National Flood and Coastal Erosion Risk Management Strategy (2020a), and the Welsh Government's National FCERM Strategy for Wales (2020a)) are calling for higher levels of ambition on managing flood risk, which could, if implemented, move adaptation towards the 'enhanced whole system' scenario modelled in Sayers *et al.* (2020) as a maximum reasonable adaptation scenario. The flood and coastal erosion risk management policy statement published in July 2020 (HM Government, 2020a) notes the importance of securing multiple benefits and how local plans will link with wider plans for an area, such as water resource plans, as well as with local nature recovery strategies. The National Strategy for Flood and Coastal Erosion Risk Management in Wales also takes a systemic approach, strengthening policies on communication, catchment approaches, collaborative working and forward planning. It complements new legislation to not only reduce present risk but also prevent issues for future generations through informed, place-based decisions. The recent improvements to asset data and mapping, alongside new guidance on natural flood management and investment, aim to make a strategic approach possible and more widely understood by the public and those responsible for delivery.

Sayers *et al.* (2020) point to Natural Flood Management (NFM) (also known as Working with Natural Processes (WwNP)), as a supporting measure in flood risk management (capable of delivering multiple outcomes). They include measures such as upland storage, the management of run-off from agriculture, floodplain/river restoration and tree planting, and are promoted in guidance by the Environment Agency and DfI Rivers, the EU Floods Directive 2007, Scotland's Flood Risk Management Act, the Welsh Government's FCERM Strategy (which aligns with the National Resources Policy) and England's 25 Year Environment Plan. Planning is assisted by NFM opportunity maps which have been produced for England and Wales, Scotland, and Northern Ireland. In Wales, implementation of Schedule 3 of the FWMA commenced in January 2019, with all new development at or above 100 square metres needing to obtain approval for their drainage measures (using SUDs hierarchy) before work can commence on site. Similarly, Blue-Green infrastructure and Blue-Green Cities utilising 'Green Infrastructure' or SuDS (Sustainable Drainage Systems), are also promoted in guidance, e.g. the Core Strategy and Urban Core Plan for Gateshead and Newcastle upon Tyne 2010-2030, the Newcastle Local Flood Risk Management Strategy (Newcastle City Council, 2016), and the Ebbsfleet Implementation Framework (Ebbsfleet Development Framework, 2017).

4.3.2.1.2 England

Under the Current Levels of Adaptation (CLA) scenario, which assumes a present day level of ambition in flood policy to be continued into the future, Sayers *et al.* (2020) project that risk of river flooding still increases compared to the present day for all those infrastructure types identified as increasing in risk under the Reduced Whole System (RWS) scenario, though the increase is less than in the baseline scenario. These are sewage treatment works, railway lines and railway stations. This is also the case for surface flooding, with freshwater sites, sewage treatment works, power stations, electricity substations, railway lines and railway stations all increasing in risk compared to the present day (with modest decreases compared to the projections for RWS).

The Environment Agency provides guidance on adaptation schemes and strategies for infrastructure from river flooding for England (Environment Agency, 2020a; Reynard and Kay, 2017), which includes projections of the anticipated change for peak river flows (referred to as 'climate change allowances'). They vary by river basin district, and with the period of time into the future. This information provides asset owners with a basis upon which to develop their own flood risk assessments as well as to underpin assessments for new developments.

O'Donnell *et al* (2017) argue that the implementation of innovative urban flood risk management approaches and infrastructure is hampered by socio-political, biophysical and governance barriers, particularly the failure in England to enact Schedule 3 of the 2010 Flood and Water Management Act. This would mandate surface water drainage for new developments to comply with mandatory National Standards for SuDS. The authors conclude that the intensity of the urbanisation driver of flood risk has not changed. O'Donnell and Thorne (2020) argue that strong business cases, supported by monetised evidence of benefits, and collaborative, inter-agency working could advance implementation of Blue-Green infrastructure within current flood risk management legislation.

Conversely, a 2018 government review by the Ministry of Housing, Communities and Local Government on the application and effectiveness of planning policy for sustainable urban drainage (SuDS) found that the majority (80%) of adopted local plans (and just over 90% of emerging plans) contained policies that clearly reflect the requirements of the National Planning Policy Framework (NPPF). Although the requirement in the NPPF refers only to major developments (see Risk H3).

4.3.2.1.3 Northern Ireland

As with England, all infrastructure projected to be at increased risk of river and surface water flooding under the RWS scenario in Sayers *et al.* (2020) is also projected to increase in risk under the CLA (Current Levels of Adaptation) scenario. For river flooding, only railway lines are projected to increase in risk from river flooding, whereas freshwater sites, electricity substations and railway stations (as well as railway lines) are projected to see an increase in risk from surface water flooding. The draft Flood Risk Management Plan (FRMP) for the period 2021 – 2027, aimed at managing and mitigating the risk of flooding in Northern Ireland, has been published for a six-month public consultation (December 2020 until June 2021); the FRMP will be finalised by December 2021. The Plan focuses on 12 Areas of Potential Significant Flood Risk (APSFR) which were previously identified in the 2018 NI Flood Risk Assessment (DfI 2018). In addition, 9 'Transitional Areas of Potential Significant Flood Risk' (TAPSFR), identified as APSFR in the 2011 PFRA, have been determined to ensure continuity between FRMPs and facilitate implementation of any outstanding commitments arising from delivery of objectives and measures within the 2015–2021 FRMPs. For Northern Ireland, 'medium probability' scenarios have been considered in assessing the impacts of Climate Change on flood risk for the 2080s epoch.

DfI sits on the UK Coordination Group (chaired by DEFRA) as competent authority for the implementation of the EU Floods Directive in Northern Ireland. As a requirement of the EU Floods Directive, DfI Water and Drainage Policy Division along with its stakeholders is currently preparing the 2nd cycle of Flood Risk Management Plans for Northern Ireland (mentioned above). Climate change is an aspect which must be considered in this planning cycle. The new Flood Risk

Management Plan will highlight the flood hazards and risks in the Areas of Potential Significant Flood Risk in Northern Ireland from rivers, the sea and surface water. The plan identifies the objectives and measures that will be undertaken to manage the risk of flooding and sets out how the relevant authorities will work together with communities to manage flood risks. Currently NI allowances for flood risk management and development planning (primarily allowances for increased sea level rise, river flows and rainfall intensities along with associated planning advice) are based on UKCP09 information but the desire for NI is to move to new allowances based on UKCP18 information, which will be supported through the UK Coordination Group.

NI Water (2020) recently published 'Our Strategy 2021-2046' which recognises the climate emergency as one of six strategic risks for the next 25 years. Most of the urban areas in Northern Ireland are served by combined sewers that carry both sewerage and surface water which is inefficient and results in pollution and flood. NI Water plans to gradually transform the sewerage network by taking every economically viable opportunity to disconnect surface areas from existing combined sewers, for example when laying a new storm sewer to service a new development. In many locations this will help free up capacity in combined sewers for new connections without having to lay new or combined sewers. NI Water will actively promote the use of green infrastructure such as sustainable drainage systems (SuDS) in new developments by providing clear guidance to developers. NI Water will retrofit SuDS where it helps to reduce the risk of flooding and facilitates storm separation.

4.3.2.1.4 Scotland

Sayers *et al.* (2020) project that all infrastructure types that are projected to increase in risk from flooding under the RWS scenario are also projected to increase in risk under the CLA scenario, though to a lesser degree. For river flooding these are sewage treatment works, railway lines and railway stations. For surface water flooding power stations and electricity substations, sewage treatment works, railway lines and railway stations are projected to increase in risk compared to the present day.

The SCCAP2 (Scottish Government, 2019b) describes current and planned flood risk management actions in Scotland. Scotland's Flood Risk Management Act (2009) encourages a sustainable catchment-based approach. This incorporates coordination between 'responsible authorities' (stakeholders) and the creation of plans for local districts and potentially vulnerable areas, and SEPA's subsequent Flood Risk Management Strategies, covering 2015-2021. These plans include the actions to be taken over a six-year flood risk management cycle (2016-2022). These are aided through SEPA flood maps and the Mapping Flood Disadvantage Tool, which are used in identifying priority areas for emergency services and to communicate flood risk issues to local communities. SEPA is creating a new Flooding Strategy "One Planet Prosperity" which aims to embed adaptation as a key principle to ensure flood risk management plans and actions tackle future flood risk through support to individual and community resilience to flooding.

A working group on surface water management has been established under the Scottish Advisory and Implementation Forum for Flooding (SAIFF). It includes representatives of Scottish Water, local authorities, SEPA and the Scottish Government. Surface water management planning guidance was

published in 2018, to support responsible authorities in preparation of Surface Water Management Plans (SWMPs) to help with the management of surface water flooding. The Flood Risk Management Strategies and Plans include actions in the first six-year cycle to prepare Surface Water Management Plans.

The Flood Risk Management (Scotland) Act 2009 places a duty on local authorities to map SuDS in their area, although there is no statutory timescale for doing this. Any SuDS (or other actions to reduce the risk of surface water flooding) that are retrofitted for the purposes of flood risk management will be in the Flood Risk Management Strategies and Local Flood Risk Management Plans. If SuDS are retrofitted for other purposes (e.g. water quality) then they may not be in the Flood Risk Management Plans. In Scotland, there is also a requirement for SuDS for all developments other than single dwellings. Surface water drainage in Scotland falls under Scottish Water and the road authority who are responsible for sewers and roads respectively.

4.3.2.1.5 Wales

Sayers *et al.* (2020) project that all infrastructure types that are projected to increase in risk from flooding under the RWS scenario are also projected to increase in risk under the CLA scenario, though to a lesser degree. For river flooding these are sewage treatment works, railway lines and railway stations. For surface water flooding electricity substations, sewage treatment works, freshwater sites, railway lines and railway stations are projected to increase in risk compared to the present day.

In Wales, the Future Wales: National Plan 2040 (Welsh Government, 2021a) along with the Flood and Coastal Erosion Risk Management Strategy (Welsh Government, 2020a) provides a distinct approach from the rest of the UK, driven through the Environment Act (Wales) 2016 and Natural Resources Policy. These place a major emphasis on the role of resilient ecological networks, green infrastructure and nature-based flood risk management in managing climate risks to infrastructure over the long term.

The National Strategy for Flood and Coastal Erosion Management in Wales sets the overall policy framework for Local Flood Management Strategies delivered through Natural Resources Wales and local authorities. For climate change, one key point states that risk management authorities (RMAs) should use UKCP figures in their local and regional responses. In addition, the National Strategy commits to respond to the increasing risk from climate change by building a stronger pipeline of FCERM projects and updating long-term investment requirements using the latest climate change risk data. A national Flood & Coastal Erosion Committee was established in 2019 alongside the Wales Coastal Monitoring Centre. The Welsh Government's adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b), sets out further measures to adapt infrastructure to these risks. The government has committed to a review of transport case studies to share best practice in transport adaptation and research is planned to review risks to bridges and pipelines at risk from river flooding and bridge scour in order to target intervention (see risk I5).

River Basement Management Plans have been established across Wales and recognise the risks posed from climate change and increased likelihood of flooding. Commitments are made throughout

with regards to various infrastructure, such as sewerage systems, drainage, and the use of sustainable blue and green infrastructure where possible (including SuDS).

4.3.2.2 Effects of non-government adaptation (I2)

The electricity transmission and distribution network industry was deemed to have made the most progress in systematically assessing flood risk (CCC, 2019b). It has developed cross-industry technical standards for managing current and future flood risk and applies a consistent approach in identifying critical assets at high levels of risk. This is reflected in the future flood risk project (Sayers *et al.*, 2020). This information is used to make business cases to the relevant regulator to fund cost-beneficial resilience measures through the price control process. Substations serving one million customers were assessed to have benefitted from flood protection measures from investment planned between 2011 and 2023, with £172 million being allocated. The standard (ETR 138) may be reviewed in light of the National Flood Resilience Review and improved climate modelling.

Planned actions by electricity supply, transmission and distribution companies are expected to see over 90% of substations deemed at risk of flooding become resilient to 1 in 1000-year flood events by 2021. This is in line with standard ETR 138, which applies this requirement to primary substations with over 10,000 connections. This standard includes an assessment of the risks from flooding to all new and existing sites. It is not clear what actions are being taken for non-primary substations. It was reported that plans to manage risks to nuclear infrastructure include consideration of all relevant hazards. However, although the Cabinet Office set a benchmark that essential services provided by Critical National Infrastructure (CNI) should not be disrupted by a flood event with an annual likelihood of 1 in 200 (0.5% annual probability), it was not explicitly clear how this benchmark was being interpreted by sector, or the extent to which this standard was now in place. This makes it difficult to assess how risk is being managed autonomously. It was stated that more consideration of the resilience of systems as well as individual assets needs to be made.

The rail network benefits from specific actions targeted on flood risk, as noted for example in the Network Rail NW&C Region Weather Resilience and Climate Change Adaptation (WRCCA) Plan (Network Rail, 2020b) and more broadly in the Network Rail Weather Resilience and Climate Change Adaptation Strategy (Network Rail, 2017a). For example, In Scotland, flooding has been allocated over £13 million in funding between 2019-2024 to alleviate or reduce risk at 32 known flooding sites (Climate Ready Scotland action references NRCRS3 and NRCRS5). Network Rail Regions are tasked with providing updates on implementation of their WRCCA Plans to ORR and the central to the WRCCA Team twice a year, with the WRCCA Working Group reviewing progress and identifying improvements.

In telecommunications, the CCC (2019a) report there has been a push by the industry to improve resilience following the National Flood Resilience Review (NFRR). Ofcom published revised security guidance in 2017, including requirements to meet NFRR obligations and to ensure all sites (not just those in scope of NFRR) are protected from flooding. The NFRR accounts for climate change, however the review is limited to the next 10 years and it is not known if sanctions are applied by Ofcom for non-compliance.

With respect to waste, much of the existing infrastructure is likely to have been upgraded or

replaced by 2050. Any new waste facility whether entirely new or constructed for replacement or upgrade and the development of new waste facilities would be required to follow the latest planning rules in the National Planning Policy Framework (MHCLG, 2019). This explicitly requires that developments in flood risk areas should be avoided and if unavoidable, “the development should be made safe from flooding for its lifetime”. Any additional requirements to increase resilience should be included in the permitting process (the Environment Agency permit allows the operation of waste facilities) allowing the mitigation of some of the effects of climate change.

Landfill sites have a much longer lifetime than other waste facilities and it is likely that most modern landfills (those with engineered liners) will retain the ability to pollute the surrounding environment for perhaps as long as a millennium (Bebb and Kersey, 2003; Hall *et al.*, 2007). This pollution potential could be reduced by changing landfill management practices to accelerate degradation or by removing the waste through landfill mining (Watson and Powrie, 2015). This would suggest that of all solid waste management infrastructure, landfill sites are the most vulnerable to long term climate change.

4.3.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I2)

For risks which are currently medium or high magnitude today, the CCRA3 framework considers risk to be managed if the drivers of vulnerability and exposure are being well managed (today and in the future), and recent climate trends are well accounted for in the policies. The score of ‘partially’ managed reflects the evidence indicating that progress on flood defences has been made, though not enough to fully manage the risk. Evidence of SMART (Specific, Measurable, Achievable, Realistic and Timebound) objectives such as ETR 138 is available, but not widespread. In the CLA scenario in the Sayers *et al.* (2020) analysis, which represents planned and announced adaptation, future exposure is reduced compared with the RWS scenario (representing a scenario with no additional adaptation), but does not reduce exposure compared with the present day. It is noted that recent flood policy updates are calling for higher levels of ambition on managing flood risk, which could if implemented move adaptation towards the ‘enhanced whole system’ scenario modelled in Sayers *et al.* (2020) as a maximum reasonable adaptation scenario. It must be noted that even in this scenario, exposure would not be brought back to current levels for infrastructure projected to see an increase in exposure under the less ambitious RWS and CLA scenarios.

4.3.2.4 Adaptation Scores (I2)

Table 4.11 Adaptation scores for risks to infrastructure services from river and surface water flooding			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

4.3.3 Benefits of further adaptation action in the next five years (I2)

4.3.3.1. Additional planned adaptation that would address the adaptation shortfall (I2)

As recommended in CCRA2 (Dawson *et al.*, 2016), there remains a need for the development of consistent indicators of network resilience to flood risk across all critical national infrastructure sectors and networks. Such indicators would help to create the institutional conditions for adaptation and would allow for improvements to be measured over time. This could build on improvement in local hazard information, such as the Cabinet Office's Resilience Direct platform which provides street-level surface water flood forecasts to authorities and category 1 and 2 responders.

In response to modelled impacts on emergency services due to observed surface and fluvial flooding in York, Coles *et al.* 2017 argued that an appropriate adaptation strategy should identify areas on the road network that are most vulnerable to flooding, as well as parts of the road network that are crucial for emergency services, e.g. access to hospitals. Green *et al.* (2017) recommended that the ambulance service should ensure that they are situated at strategic stand-by points during flood conditions to minimise the impact of a blocked road network on delaying emergency response to vulnerable locations.

For urban road transport, Pregolato *et al.* (2016) suggest both green infrastructure and conventional engineering measures to improve resilience. Spatial distribution of green roofs reduced person delays during a 1 in 10-year flood by 26%, compared with 12% from hard engineering measures for a single junction (both are compared with the effects of a 1 in 10-year flood with no adaptation), which highlights the potential benefits of blue-green infrastructure for urban flood resilience. The economic feasibility of this measure has not been assessed.

As covered in Risk I1, Thacker *et al.* (2018) demonstrate the benefits of bringing forward adaptation work in the protection of electricity substations. It is estimated that if National Grid brought forward the entirety of planned works scheduled for 2022, this would result in additional savings of £133,260,000 in avoided expected annual losses (although this would be constrained by planning and time scale). It must be noted that this research is based on simulation work.

4.3.3.2. Indicative costs and benefits of additional adaptation (I2)

There is evidence on the potential costs and benefits of further adaptation. Much of this indicates high economic benefits from investing in flood adaptation for infrastructure (OECD, 2015: GCA, 2019). However, some care should be taken in interpreting this evidence, as much is based on 'predict and optimise' studies (where future risk levels are known), rather than an analysis taking account of uncertainty (and thus the potential for under or over investment).

The effects of different adaptation strategies on the annual expected damages from river flooding in the UK can be estimated from a recent EU+UK-wide regional climate change impact assessment (Dottori *et al.*, 2020), which used a regional-scale hydrological model with country-specific flood depth-damage functions to simulate economic damages under different global warming and

adaptation scenarios. Without adaptation, annual expected damages increase from 0.03% of UK GDP nowadays, to 0.04 and 0.06% of GDP with 2°C and 3°C global warming respectively (assuming the population and economy of 2100). However, the impacts are significantly reduced with adaptation. With 3°C global warming by 2100, the reduction in expected annual damage compared with no adaptation, in 2100, is 87% for raising of dykes, 94% for retention areas, 39% for relocation of built-up areas and 50% for building damage reduction measures.

More generally, there are a range of low-regret measures that have been identified in this area (Vallejo and Mullan, 2017; Watkiss *et al.*, 2019), which include:

- Supporting decision-making by providing tools and information,
- Screening climate risks (climate risk management) in public investments,
- Screening climate risks (climate risk management) in private sector investments,
- Enabling infrastructure resilience through policy and regulation,
- Encouraging the disclosure of climate risks/uptake in commercial finance,
- Supporting innovative risk spreading (insurance).

There are also estimates of the economic benefits and costs of some green infrastructure (McVittie *et al.*, 2017), though these are often site-specific. It is highlighted that there are important governance challenges, as well as opportunity and transaction costs associated with green infrastructure (Watkiss *et al.*, 2019). The benefit to cost ratios of SuDS have been studied (e.g., Ossa-Moreno *et al.*, 2017), and guidance exists for estimation (Benefit of SuDS Tool (BeST) (UKCIRIA)), although the financial case alone does not appear to incentivise adaptation.

4.3.3.3. Overall urgency scores (I2)

Because of the high projected magnitude for this risk and the view that current and announced adaptation will not fully manage the risk, it has been scored as more action needed across the whole of the UK. Low-regret actions identified include supporting decision-making by providing tools and information and screening climate risks (climate risk management) in public and private sector investments.

Table 4.12 Urgency scores for risks to infrastructure services from river and surface water flooding				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	Medium	Medium	Medium	Medium

4.3.4 Looking ahead (I2)

Flooding remains a key priority given the high impact and high-profile nature of its impacts. The evidence base for improved flood defences is mature and the electricity sector has demonstrated

that adaptation measures can be readily implemented. Despite the high costs involved, further action is needed to improve flood defences across the infrastructure sector.

4.4. Risks to infrastructure services from coastal flooding and erosion (I3)

Global mean sea levels are currently rising at an accelerating rate. Coastal erosion and coastal flooding, which have always occurred around the UK, will become worse as sea levels rise. Other socioeconomic changes could also increase vulnerability (mainly increased development and population in low-lying coastal areas and decline in salt marshes, shingle and sand dunes which provide an important buffering against coastal flooding and erosion). There is evidence that the consequences of coastal flooding in the recent past have been tempered due to improvements in flood defences, together with advances in flood forecasting, warning and emergency response and spatial planning. However, notable instances of coastal flooding (e.g. in the winter of 2013/14) have still occurred and significantly impacted infrastructure along the coast.

Across the UK, rail networks tend to be exposed to significant coastal flooding, as well as a number of sewage treatment works. Other infrastructure assets tend to have low current and future risk. In the case of nuclear power stations, this is due to their very high standard of protection. Data for levels of risk from coastal erosion are less available, though the CCC has developed projections of risk for England.

There is high confidence that mean sea-level will continue to rise around the UK for at least the next three centuries, even with low climate change scenarios (Palmer *et al.*, 2018). Larger rises are considered possible due to potential marine ice sheet instabilities. Extreme water levels are therefore projected to increase during the 21st century and beyond, and without further adaptation (e.g. raising flood defences, managed retreat), the projected increases in extreme water levels will significantly increase coastal flood and erosion risk for railways and some sewage treatments works according to the projections produced for CCRA3. Although shoreline management plans are in place, adaptation responses are currently considered inadequate to fully manage the increasing risk, with further investigation needed. Beneficial actions could include achieving a better understanding of current and future risk, monitoring and evaluation of the projected impact of current policies and actions and the creation of ‘what if’ scenarios of high rates of change.

4.4.1. Current and future level of risk (I3)

4.4.1.1 Current risk (I3)

4.4.1.1.1 UK-wide

Coastal flooding and erosion are driven by a combination of the sea level and extreme water levels, which arise as combinations of four main factors: (i) waves (especially setup and runup); (ii) astronomical tides; (iii) storm surges; and (iv) relative mean sea level (Pugh and Woodworth, 2014).

The scale of flooding and erosion is dependent on the characteristics of the land, e.g. underlying coastal morphology (topography, rock type, slope of beach, etc.) and the additional influence of rainfall and river discharge may also be significant in some estuaries (Hendry *et al.*, 2019). These four components exhibit considerable natural year-to-year variability and it is the interaction between the components that combine to result in extreme water levels. Longer-term changes in any, or all, of the four components can also lead to variations in the frequency and magnitude of extreme sea levels. It should be noted that individual components can cause problems on their own, such as flooding caused solely by extreme waves even in places where sea level is not rising.

Global mean sea level (GMSL) increased by 0.16 m from 1902 to 2016 (IPCC, 2019). Relative mean sea levels rose during this period more in the south than north of the UK due to post-glacial rebound (Scotland is rising whereas southern England is sinking), whereas the east coast is more prone to damaging storm surges. This is because of the shallow water depths and funnelling shape of the North Sea, with notable events on 31st January and 1st February 1953, and 5th and 6th December 2013 (Spencer *et al.*, 2015; Wadey *et al.*, 2015). However, storm surge risk is also prevalent along the west and south coasts, with noteworthy events on the 26th February 1990 and 14th February 2014 (Haigh *et al.*, 2017a).

Horsburgh *et al.* (2020) highlight that a growing number of studies, at both global and national scales, have found evidence for increases in extreme still water levels over the late 19th, 20th and early part of the 21st century. The overwhelming scientific consensus is that these observed changes in extreme still water levels around the UK and worldwide have been driven primarily by the observed rise in relative mean sea level. As a result, extreme sea levels that previously had a long return period (>100 years) near the beginning of the 20th century now have much lower (~10 year) return periods. There is little evidence for long-term systematic changes in storminess or storm surge magnitude over the last 100 years above natural variability. Several studies have looked at historical changes in the nature of coastal hazards and erosion. Wolf *et al.* (2020) highlighted that it has proved difficult to accurately assess current and historic changes in the wave climate due to the lack of long-term wave measurements and due to the fact that trends are obscured by large natural variability). However, positive regional trends in extreme wave heights have been reported at several locations in the north-east Atlantic since the late 1970s. Haigh *et al.* (2020) reviews studies that have assessed changes in tide. These studies suggest that changes in tidal range will typically be in the order of plus or minus 10% of any changes in mean sea level, which could slightly enhance or lessen coastal flooding at some locations.

Taking a long-term view, Haigh *et al.* (2017b) suggest that the number and consequences of coastal floods appears to have declined since 1915 in the UK, reflecting better defences and improvements in flood forecasting, warning and emergency response and planning. Wider efforts at improved adaptation should also be noted, particularly in recent decades, which has also resulted in a reduction in flood risk. Hendry *et al.* (2019) showed the importance of considering compound events (i.e. flooding from both marine and fluvial/pluvial sources occurring concurrently or in close succession), and that the previous lack of consideration of this has likely led to underestimation of flood risk around UK coasts. The CCC (2018a) highlighted that it is increasingly recognized that natural systems, such as saltmarshes, shingle and sand dunes, provide important buffering against floods and are in decline, which has increased flood risk. These act alongside other natural

infrastructure such as rivers and floodplains to manage flood risk.

As highlighted by Masselink *et al.* (2020), the natural response of coastal systems to mean sea-level rise is to migrate landwards, through erosion of the lower part of the nearshore profile and deposition on the upper part. They highlight that 17% of the UK coast and 19.9% of the Irish coast is currently suffering from erosion. Approximately 3,700 km (around 25%) of the English and Welsh coast is currently experiencing erosion of greater than 10 cm per year.

Sayers *et al.* (2020) quantified the current number of assets or length of infrastructure exposed to a 1:75 chance of annual coastal flooding for major receptors including clean and wastewater sites, electricity generation sites and transport networks (see Table 4.13 below). The assets facing the largest risks from coastal flooding are rail lines, railway stations and sewage treatment works.

Table 4.13 Number or length of infrastructure assets currently exposed to 'significant' risk of coastal flooding across the UK (Sayers *et al.* 2020)

Infrastructure Asset at 1:75 or greater risk of coastal flooding (present day)	England	Northern Ireland	Scotland	Wales	Total (UK wide)
Water sites (no.)	3	11	0	8	22
Sewage treatment works (no.)	53	0	20	18	91
Power stations (no.)	34	0	1	0	35
Electricity substations (no)	23	0	4	7	34
Rail length (km)	114	20	65	312	511
Rail stations (no.)	5	3	5	12	25
Landfill sites	0	0	0	0	0

Some further risk information by country is given below.

4.4.1.1.2. England

The railway line at Dawlish provides the highest profile example of infrastructure at risk of coastal flooding and erosion. Dawson *et al.* (2016) provide a comprehensive review into the impacts of coastal flooding and erosion at this location. Work is currently underway to further protect this section (see section 4.4.2.1). Yorkshire Water relocating a wastewater treatment works at Withernsea further inland due to coastal erosion. As mentioned in I1, CCRA2 (Dawson *et al.*, 2016) specifically reported on interruptions to the supply of biomass to power stations following flooding of the Port of Immingham in December 2013. Critical power and IT services were lost causing the cessation of operations for a number of days. Tides exceeded the dock gate height by half a metre. Work has been approved to improve flood protection at the Port.

4.4.1.1.3. Northern Ireland

19.5% of the Northern Ireland coastline is suffering from erosion (McKibbin, 2016). DAERA and DfI commissioned a baseline study and gap analysis of coastal erosion risk management in Northern

Ireland. The report identifies areas that may be vulnerable to coastal erosion in Northern Ireland.

4.4.1.1.4. Scotland

CCC (2019c) stated that Scotland has significant infrastructure assets located in coastal areas and hence potentially exposed to flooding from the sea. Key infrastructure assets located in the coastal zone include power stations, ports, roads, and rail networks. According to the Dynamic Coast (National Coastal Change Assessment) project, soft coastline (coasts with the potential to erode) make up 19% (3,800 km) of the Scottish coast. Between a half and a third of all coastal buildings, roads, rail and water networks lie in these erodible sections. Since the 1970s, 870 km of the soft coastline has moved position: 420 km has advanced, 440 km has eroded, and the remaining 2,940 km has remained approximately stable.

4.4.1.1.5. Wales

Welsh railways are particularly exposed with 312 km of rail considered to be at risk (Sayers *et al.*, 2020).

4.4.1.2. Future risk (I3)

4.4.1.2.1. UK-wide

In the UKCP18 marine projections (Palmer *et al.*, 2018), sea levels at the four UK capital cities are projected to rise by between 0.08 m and 1.15 m by 2100, relative to the levels in 1981-2000, depending on location, scenario and level of climate response, excluding vertical land motions. Projected rises are generally higher in the south of the country than the north. In a projection consistent with approximately 4°C global warming by 2100⁶, local sea level rise at the UK capitals ranges from 0.54 m for Edinburgh to 0.78 m for London. Larger rises are possible with higher warming and/or if the sea level responds more rapidly, for example if marine ice sheets were to collapse. The low-likelihood high-impact scenarios have been identified by recent global expert elicitations (Garner *et al.*, 2018; Bamber *et al.*, 2019), which raise the possibility of high global sea level rise under high-emission scenarios, with conceivably reaching 2 m by 2100. There is low confidence in regional projections of storminess and associated changes in storm surges and waves (Palmer *et al.*, 2018).

Brown *et al.*, (2018), drawing on a vulnerability-led and decision-centric framework, developed a Decision Support Tool which combined observations and modelling to explore the future vulnerability to mean sea-level rise and storms for nuclear energy sites in Britain.

4.4.1.2.2. England

Sayers *et al.*, (2020) indicate that the number of rail stations and length of rail exposed to high risk of coastal flooding will increase significantly with climate change in the absence of adaptation. In a

⁶ Based on 50th percentile of UKCP18 marine projections, using RCP8.5 concentration pathway.

scenario of 4°C global warming at 2100 (+4°C at 2100) with low population growth, the length of railway track exposed to coastal flooding could potentially increase five-fold in England (400% increase). Sewage treatment works at risk could also increase three-fold (200%), and there is a ~55% increase in risk for electricity substations. Water sites and power stations are projected to have lower risks compared to today in the baseline scenario.

CCC (2018a) estimated the number of infrastructure assets at current and future risk from coastal erosion, as shown below. According to Brand and Spencer (2018), there are 1200 landfill sites in England that are in low-lying coastal areas and almost 80 are likely to start eroding within the next 40 years without intervention.

Table 4.14 Present day estimates of coastal erosion risk for infrastructure assets in England, taken from CCC (2018c) using values derived from Jacobs (2018). These values do not include erosion rates from complex cliffs.

Infrastructure asset	Present day coastal erosion risk (range from 'mid-estimate' to 'high-estimate')	End century coastal erosion risk (range from 'mid-estimate' to 'high-estimate')
Motorways and A-roads (km)	5 – 6	68 – 93
Other public roads (km)	30 – 49	440 – 602
Railway lines (km)	8 – 12	60 - 76
Railway stations (no.)	0	12 – 15
Historic landfill sites (ha)	21 - 31	181 - 239

4.4.1.2.3. Northern Ireland

Sayers *et al.* (2020) indicates that in the absence of further adaptation and in a +4°C at 2100 scenario with low population growth, the length of railway track exposed to coastal flooding could potentially double in Northern Ireland by the 2080s. The report also notes that rising sea levels pose a significant threat for the coast of NI and climate change could also contribute to beach erosion because of the predicted increase in storm activity and intensity. Projections for other infrastructure assets either do not change in the future or show a decrease in risk.

4.4.1.2.4. Scotland

Sayers *et al.* (2020) indicates that in a +4°C at 2100 with low population growth, the length of railway track (and associated stations) exposed to coastal flooding could increase by around 75% by the 2080s, and rail stations by nearly 30%. Other infrastructure asset types show no change or small decreases in risk in the baseline scenario.

If recent erosion rates were to continue in the future, the National Coastal Change Assessment (Dynamic Coast 1) estimates that by 2050 at least 1.6 km of railway, 5.2 km of road and 2.4 km of clean water network as well as significant areas of runways, would be affected by coastal erosion (Hansom *et al.*, 2017). These numbers are likely to be underestimated. If erosion rates increase in the future, as expected with climate change, Dynamic Coast 1 and National Flood Risk Assessment are likely to underestimate the extent of assets at risk from future coastal erosion. Large numbers of

assets are sited close to potentially erodible coasts (including 1,300 km of roads and 100 km of railway lines). There are assets worth £13.3 billion within 50 metres of the soft coast of which £340 million worth is expected to be threatened by erosion by 2050 (these figures include non-infrastructure assets such as residential and non-residential buildings (CCC, 2019c)). Dynamic Coast 2 will be published in 2021 and will consider how future sea level rise projections will further increase erosion rates and the impacts this could have on assets near the coastline.

4.4.1.2.5. Wales

Sayers *et al.* (2020) indicates that under a +4°C at 2100 scenario, accompanied by a low population growth scenario, the length of railway track (and associated stations) exposed to coastal flooding could increase by around 60% by the 2080s, and rail stations by 10%. Like England, sewage treatment works also show a significant increase in risk of around 50%. Other infrastructure asset types show no change or small decreases in risk in the baseline scenario.

4.4.1.3 Lock-in and thresholds (I3)

Society will experience mean sea-level rise for many centuries even if global temperature is stabilized and so therefore is locked into an increased risk of coastal flooding and erosion if flood defences, for example, are not upgraded. This also creates the potential for lock-in risk for any development in coastal areas, and a particular issue is highlighted for coastal infrastructure, because of the long life-times involved (and the fact it may be costly to retrofit or move later). For instance, new nuclear build is amongst the most extreme type of lock-in (if adaptation were not to be included) with still water return level projections being considered for year 2190 (Horizon Nuclear Power, 2019). High confidence in the projections ensures that sea defences can be engineered to withstand projected rises in mean sea levels, but the high uncertainty makes such decisions difficult, and has led to the greater focus on adaptive management.

There are likely to be certain thresholds in the level and rate of mean sea-level rise that dramatically shift the way coastal flooding and erosion is managed and a point at which infrastructure and properties will be relocated away from the coast (and for current infrastructure, difficult decisions are needed on whether to protect or abandon). However, these thresholds are not well understood for the majority of the coastline. For London, an adaptive management (pathways) approach has been adopted for managing increasing flood risk in the Thames Estuary 2100 Plan (Environment Agency, 2012; Ranger *et al.*, 2013). For sea-level rise below about 2.5 m, with respect to a 2005 baseline, London can be protected via the existing Thames Barrier, along with raising of downstream and upstream defences. However, with a mean sea-level rise of more than 2.5 m, a new barrier with locks would need to be built further downstream to protect London. Hall *et al.* (2019) carried out a sensitivity analysis of the costs and benefits of alternative adaptation pathways to a wide range of mean sea-level rise trajectories for London. They show that the adaptation pathway that most cost-effectively and robustly maintains risk at a tolerable level involves moving the Thames Barrier 17 km towards the sea if mean sea level rises 2 m above present levels. The adaptive flood management approach has been developed into a tool for wider application and is being used elsewhere around the world (Haasnoot *et al.*, 2013, 2019). Frampton *et al.* (2020) considered how adaptation pathways could help strategic coastal management decision-making and adaptation, building on the current

Shoreline Management Planning approach. These iterative adaptive management frameworks use thresholds to determine future management strategies, with additional management strategies, measures or policies aligned to future thresholds levels (adaptation tipping points).

4.4.1.4. Cross-cutting risks and inter-dependencies (I3)

The CCRA3 interacting risks project (WSP, 2020) created a number of systems maps of key interactions between infrastructure, the built environment and natural environment. The maps highlighted a number of interdependencies between coastal flooding and erosion impacts to power, transport and sewage infrastructure leading to knock on impacts to power supply disruptions, transport damage, travel accidents and travel delays.

4.4.1.5 Implications of Net Zero (I3)

There is the potential that some new low / zero carbon energy infrastructure, e.g. carbon capture and storage technology, could be sited in coastal areas. This might require consideration to ensure appropriate siting and climate resilient design.

4.4.1.6 Inequalities (I3)

Sayers *et al.* (2017) showed that compared to the national average, more socially vulnerable communities at the coast are disproportionately at risk and will see their risk increase more rapidly with climate change than elsewhere. As with all flood defences, there are issues with determining what is protected and the associated downside of simply moving the risk elsewhere, and this applies to the services provided by infrastructure as well as direct risks to people from coastal flooding.

4.4.1.7 Magnitude scores (I3)

Present day risk is medium (Table 4.15), as studies since CCRA2 have provided further evidence of the nature and magnitude of observed changes in mean sea-level rise, storms and waves, and associated risks. Quantified evidence on the monetary impact of coastal flooding and erosion on infrastructure is sparse. Although notable events such as the collapse of the Dawlish Sea Wall can cause impacts running into the £10s to £100s of millions, current evidence does not support present day 'high' magnitude at an annual level. The lack of systematic reporting of costs indicates low confidence in this rating, with the possibility that costs are currently underestimated. Sayers *et al.* (2020) and the UKCP18 marine projections (Palmer *et al.*, 2018) indicate that there is high confidence that regional mean sea-level will continue to rise around the UK. Sayers *et al.* (2020) indicate that the number of rail stations and rail length exposed to high risk of coastal flooding will increase significantly with climate change in the absence of adaptation. Coastal erosion is projected to increase the risk to road, rail and landfill infrastructure without further adaptation. Future risk is projected to increase by an order of magnitude in most cases in England. However, despite evidence that risk will rise throughout the UK, as annualised baseline information on the current impact of coastal erosion on infrastructure is not available, it is not possible to determine whether this would be classified as 'high' magnitude. Medium magnitude with low confidence is given for future scenarios (Table 4.15).

Table 4.15 Magnitude scores for risks to infrastructure services from coastal flooding and erosion					
Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Northern Ireland	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Scotland	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Wales	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)

4.4.2 The extent to which current adaptation will manage the risk (I3)

4.4.2.1 Effects of current adaptation policy and commitments on current and future risks (I3)

Many of the policies outlined in risk I2 that relate to all sources of flooding are relevant to this risk also. Additional policies that only apply to coastal flood or erosion risk are provided below.

4.4.2.1.1 England

Shoreline Management Plans (SMP) are in place for the full length of the English coastline. CCC (2018a) noted that while the SMPs provide long-term considerations for all parts of the English coast, they cannot be relied upon as committed adaptation plans as they are non-statutory and unfunded. The Government's July 2020 Policy Statement (HM Government, 2020a) set out the ambition to review national policy for Shoreline Management Plans to ensure local plans are transparent, to continuously review outcomes and to enable local authorities to make robust decisions for their areas (but without further detail on to what extent the SMP aspirations will be funded in the future, which leaves the remaining uncertainty on how far they may be implemented).

To create a more resilient future the Government's July 2020 Policy Statement (HM Government, 2020) set out five policy areas:

1. Upgrading and expanding our national flood defences and infrastructure,
2. Managing the flow of water more effectively,
3. Harnessing the power of nature to reduce flood and coastal erosion risk and achieve multiple benefits,
4. Better preparing our communities,
5. Enabling more resilient places through a catchment-based approach.

4.4.2.1.2 Northern Ireland

The Northern Ireland Climate Change Adaptation Programme 2019-24 mentions plans by Translink to complete a study on the effects of expected mean sea-level rise on coastal assets using UKCP18 to inform long term decisions on its management of track assets (DAERA, 2019).

4.4.2.1.3 Scotland

SMPs are in place in some parts of Scotland that have coastlines that are vulnerable to coastal flooding or erosion. SEPA have not yet met their requirement under S19 of the FRM Scotland Act to map artificial features and natural structures which could impact flood risk if removed. These plans are currently being reviewed.

The Scottish Government have also commissioned the Dynamic Coast project to deliver an up-to date assessment of coastal changes and provide a robust evidence base from which to plan strategically. Dynamic Coast 2 will be published in 2021 and will consider how future sea level rise projections will further increase erosion rates and the impacts this could have on assets near the coastline. The project supports existing strategic planning, such as SMPs, Flood Risk Management Planning, Strategic and Local Plans, and National and Regional Marine Planning, and identifies those areas which may remain, or may become, susceptible to erosion in the coming decades and require supplementary support. The identification of such susceptible areas and assets will enable the development of future management policies and adaptation plans that are robustly based on a strategic and objective evidence base.

4.4.2.1.4 Wales

SMPs are in place for the full length of the Welsh coastline. The Welsh climate change adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b) notes that Coastal Alert System which forecasts coastal flooding, wave overtopping, and toe scour up to 36 hours in advance. A number of other projects are also underway with Network Rail to improve the resilience of the rail network in Wales. Much of these works are being undertaken to respond to a number of impacts including flood risk and risks from slope and embankment failure. Network Rail has also invested £50 million along the north Wales coast under their railway upgrade programme. The Welsh Adaptation Programme highlights this as one of the key actions to help address coastal risks, including that innovative technologies are being used to help reduce the risks to rail lines on soft coastal ground.

In the National Strategy, the Welsh Government prioritises FCERM funding to schemes which primarily reduce risk of flooding or coastal erosion to existing homes. While it states infrastructure

(and businesses) may also benefit, especially in larger schemes, additional costs or protection to third party assets must be subject to a partnership contribution proportionate to those assets benefitting. A number of significant projects have been completed since CCRA2. For example, the £3m Town Beach scheme in Porthcawl, completed in 2019, upgrades the original defence and was designed to reduce risk from flooding and erosion to 260 properties including multiple businesses and key infrastructure along the promenade.

4.4.2.2 Effects of non-government adaptation (I3)

The CCC (2019b) reported that the electricity sector has a well-developed understanding of risks faced by flooding including coastal flooding. Planned actions by electricity supply, transmission and distribution companies are expected to see over 90% of substations deemed at risk of flooding become resilient to 1 in 1000-year flood events by 2021. This is in line with standard ETR 138, which applies this requirement to primary substations with over 10,000 connections. This standard includes an assessment of the risks from flooding to all new and existing sites. It is not clear what actions are being taken for non-primary substations. It was reported that plans to manage risks to nuclear infrastructure include consideration of all relevant hazards. The entire nuclear fleet of power stations is located in the coastal zone, with the Office for Nuclear Regulation expecting nuclear licensees to provide flood protection to a return period of 10,000 years. Nuclear sites thus have very high standards of protection.

Resilience standards for ports are left to individual asset owners. It was reported that ports have been proactive in raising quay heights and assessing interdependencies. It is stated that there is no overarching plan to adapt ports to manage climate risks (CCC, 2019a). Internationally, there is non-mandatory guidance from the World Association for Waterborne Transport Infrastructure or PIANC (Working Group 178) regarding climate change adaptation for ports and inland waterways.

The CCC (2019b) states that there is no clear plan or process by the industry or Government with actions to manage climate risks – including coastal flood risk – to telecoms, digital and ICT infrastructure.

Some adaptation is underway to protect vulnerable coastal rail infrastructure. Dawson *et al.* (2016) assessed the extent to which projected sea-level rise would have been likely to impact upon the functioning of the Dawlish to Teignmouth stretch of the London to Penzance railway line, in England, in the absence of improvements to the sea wall. The critical Dawlish line was projected to suffer serious reliability issues due to flooding by 2040 on the basis of no additional action, with line restrictions increasing from 10 days per year to 30–40, and maintenance costs tripling or quadrupling (£6.9–£8.7m per year, including over £1m compensation). A higher and more resilient sea wall is currently under construction.

4.4.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I3)

The available evidence indicates that the risk is beginning to be managed through the various policy frameworks (e.g. SMPs, FCERM) and that understanding of the risk has improved through projects such as Dynamic Coasts (Hansom *et al.*, 2017). Infrastructure owners with the most risk have also

been proactive in protecting their assets. However, it is difficult to ascertain with any confidence whether, despite the investment in the area, the level of risk is being maintained to today’s level.

Although policy frameworks exist, further work is needed to translate these into delivery. This applies to all nations of the UK. Several barriers exist, which prevent both private and public operators from undertaking the appropriate level of adaptation to coastal risk and therefore typically require government intervention, either through information, incentives, regulations or in some cases directly providing adaptation (see discussion for previous risk). Another barrier can occur where there is disagreement over responsibility when adaptation is needed, for example where different infrastructure operators, such as road, rail and water, are at risk at potentially different time horizons as reported in Old Colwyn, Wales (BBC, 2019).

4.4.2.4 Adaptation Scores (I3)

Table 4.16 Adaptation scores to risks to infrastructure services from coastal flooding and erosion			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

4.4.3. Benefits of further adaptation action in the next five years (I3)

4.4.3.1 Additional planned adaptation that would address the adaptation shortfall (I3)

There is increased realisation that it is unrealistic to promote a ‘hold the line’ policy for much of the coastline. The CCC (2018a) highlighted that 1,460 km of coastline in England designated as 'hold the line' to the end of the century, achieves a much lower benefit-cost-ratio than the flood and coastal erosion risk management interventions that are government-funded today. On this basis therefore, funding for these locations is unlikely and realistic plans to adapt to the inevitability of change are needed now. This raises the fundamental questions of how to: (i) plan our future shoreline on the open coast and along estuaries; and (ii) deliver practical portfolios of adaptation options that are technically feasible, balance costs and benefits, can attract appropriate finance, and are socially acceptable.

Recent research commissioned by the CCC (Jacobs, 2018) has explored the application of adaptation pathways to help explore alternative sequences of adaptation responses to climate change at a sample of coastal sites. The process of developing and evaluating alternative adaptation pathways allows potentially flexible responses to be explored in the face of uncertainty. As noted earlier, there are significant uncertainties inherent in estimating the rate of mean sea-level rise and the future frequency and severity of extreme coastal events that drive coastal erosion and flooding. The use of adaptation pathways for the long-term planning of flood risk management, first used in developing the Thames Estuary 2100 flood risk management strategy (Environment Agency, 2012), has been shown to be a promising technique that is being applied more widely (e.g. in developing the Humber 2100+ flood risk management strategy). The Environment Agency committed to increase use of

adaptive management in flood and coastal risk management (Environment Agency, 2020a). As mentioned earlier, Hall *et al.* (2019) quantify sequences of adaptations that would be needed to protect London from flooding by the sea to the year 2300. The approach is transferable to other vulnerable coastal cities of high strategic, economic and political importance.

Much of the work required in this area revolves around better understanding risk. Firstly, comprehensive data on the scale of risk from coastal erosion and flood risk for roads, ports and airports are required for future climates. Secondly, better monitoring and evaluation of existing policies would be beneficial to determine to what extent these are managing the risk down (such as with the risk of flooding to rail). Given the uncertainties around sea level rise, ‘what if’ planning for high coastal risk scenarios would be beneficial for understanding what could be done in the event of very high rates of change.

4.4.3.2 Indicative costs and benefits of additional adaptation (I3)

In general terms, the literature reports that coastal adaptation is an extremely cost-effective response, significantly reducing residual damage costs down to very low levels (Hinkel *et al.*, 2014). The National Infrastructure Commission (2018c) analysed the investment that would be required to provide a range of resilience standards for coastal flooding. The benefits of achieving a resilient infrastructure sector were estimated as the value of the ‘avoided’ or ‘mitigated’ damage and disruption caused by climate-induced events. Similar analysis was undertaken by the Environment Agency (2014), updated in Environment Agency (2019b), who estimated that the net present value of the optimised long-term investment in flood and coastal erosion risk protection, including the economic damages avoided by making the investment, including the benefits of protecting infrastructure.

4.4.3.3 Overall urgency score (I3)

As a result of the medium projected magnitude for this risk, and the view that current and announced adaptation is partially managing risk, it has been scored as further investigation needed. Beneficial actions could include achieving a better understanding of current and future risk, monitoring and evaluation of the projected impact of current policies and actions and the creation of ‘what if’ scenarios of high rates of change. Further investigation is needed to identify the locations where more action would be beneficial to infrastructure and the equivalent built environment.

Table 4.17 Urgency scores for risks to infrastructure services from coastal flooding and erosion				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further Investigation	Further Investigation	Further Investigation	Further Investigation
Confidence	Medium	Medium	Medium	Medium

4.4.4. Looking ahead (I3)

Further work would be beneficial on interacting risks, particularly to infrastructure services from coastal, river (fluvial), surface water (pluvial) and groundwater flooding. As stated, Hendry *et al.* (2019) showed the importance of considering compound events (i.e. flooding from both marine and fluvial/pluvial sources occurring concurrently or in close succession). The previous lack of consideration of compound flooding means that flood risk has likely been underestimated around UK coasts, particularly along the south-western and western coasts. Further work could also assess more fully the interaction between flood and erosion risk (Dawson *et al.*, 2009; Pollard *et al.*, 2019) and consider multi-hazard risk more widely (i.e. account for interaction between flooding, and other hazards, such as wind damage or landslides (Zscheischler *et al.*, 2018; Hillier *et al.*, 2020)). It is crucial that this be addressed in future assessments of flood risk and flood management approaches.

4.5 Risks to bridges and pipelines from flooding and erosion (I4)

Since CCRA2, limited new evidence has been published on the risk to bridges and pipelines from flooding and erosion. The lack of significant evidence for bridges indicates no overall change in the magnitude of impacts for this descriptor. Currently, there are no quantitative projections for climate change impacts on these assets with results limited to the identification of weather events and environmental hazards which underlie the risk (e.g. rainfall, temperature, erosion for pipelines, increased hydrostatic pressure, scour for bridges).

Overall, the current risk to bridges and pipelines from flooding and erosion is identified as medium, with medium confidence; for future scenarios, the risk remains medium but with low confidence. Although, there have been positive developments in all UK nations to improve understanding of the risks to bridges and pipelines from scour, flooding and erosion, more work is still needed to understand the extent of assets at risk, the amount of adaptation underway and how the risk is being reduced through those actions. Further research is needed to define links between the forecasts and the actual projected impact at the local, regional and national environment level; i.e. the level of rainfall, frequency of severe events, changes in wind climate, the degree, extent and depth of flooding, increased rates of erosion and the exacerbation of land movement. A greater understanding and analysis of ground movement and associated impacts is another area requiring further investigation.

The Urgency Score highlights the need for further investigation for the whole UK, given the low quality of available evidence. This should concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the likely range of future climate scenarios (2 – 4°C, and across the 10-90th percentile uncertainty range within each scenario).

4.5.1 Current and future level of risk (I4)

4.5.1.1. Current risk (I4)

Note: it has not been possible to split the evidence by UK country for this risk.

4.5.1.1.1. UK-wide

The main categories of weather events and environmental hazards for pipelines include flooding and heavy rainfall (including saturated ground conditions), snow and ice, increases in temperature, coastal and river erosion, storm events, and high winds. Since the last CCRA, specific publications addressing risks to pipelines from climate change have been scarce.

The literature for bridges is more established than pipelines. Ettema *et al.* (2018) report that in 2016 (post Storm Desmond), 452 critical transportation assets were remediated, including 278 bridge repairs at an estimated cost of £123.6m over four years in Cumbria County Council. This adds to evidence of the impact of floods on bridges reported in CCRA2, such as the 2009 Cumbria floods, where several bridges were lost, and the 2015 winter floods where a major bridge connecting the town of Tadcaster collapsed, causing major transport disruption and the rupturing of gas pipelines and loss of fibre optics communications. It appears there has been a trend of increased frequency of extreme rainfall causing increased failure incidence of old masonry arch bridges.

In recent times the failure incidence of such short-span bridges has been noticeably increasing (e.g. in November 2009, three 19th century UK bridges failed) and could be suggestive of insufficient hydraulic capacity or alternative failure mechanism not envisaged at the time of design, such as foundation scour or undermining (Ryan *et al.* 2015).

Sayers *et al.* (2015) stated that factors contributing to collapse of bridges include high river flows due to rainfall and debris stuck against piers, and more frequent high in-river water levels. Scour of the bridge foundations is well-known to be the first factor for bridge failure. Warmer temperatures may lead to drying out of embankments and accelerated weathering-related deterioration. Although work has been conducted for resilience assessment on the UK Gas Distribution Network (ENA, 2015), the lack of significant evidence in changes to the current risk for bridges would indicate no overall change in magnitude for this descriptor.

Lamb *et al.* (2019) developed a combined scour fragility and statistical bridge failure to quantify the risk of disruption due to scour over the British rail network (using 1830-2003 data). Models are used to estimate the probability of single or multiple bridge failures on the rail network of Great Britain. These are combined with a model for passenger journey disruption to calculate a system-wide estimate for the risk of scour failures incorporating passenger journey disruptions and economic costs. Without considering climate change, this estimate can be translated into an expected annual utility cost to passengers of between £6 million and £60 million. However, the model may be adjusted to consider climate change scenarios, by reflecting changes in the hydrological regime.

This magnitude of risk to bridges and pipelines from flooding and erosion may vary between

different types of places (e.g. urban, rural, upland, and coastal according to the exposure and vulnerability of the bridge, encompassing bridge design and material). For example, rural bridges tend to be smaller than urban bridges (due to the minor demand), however they are likely to have less redundancy, i.e. no alternative way is available to cross the obstacle.

4.5.1.2. Future risk (I4)

4.5.1.2.1 UK- wide

CCRA2 (Dawson *et al.*, 2016) stated that increased winter precipitation and river flows will increase scour at bridges, potentially increasing the rate of failure to an average of one bridge per year in the UK. At the time, there had not been any national-level modelling of how risk may increase in the future. It was also reported that significant uncertainties about the structural integrity of road and rail bridges existed (many of which were built over a century ago). It was not known at a national level which bridges were used for gas pipelines/electricity cables (although it was stated that service providers have this mapped at the local level).

The availability of data is currently a missed opportunity, since bridge data are scarce or not well-organised, particularly at national level (Pregolato *et al.*, 2019). Regarding strategic crossings and pipelines in general, data are protected due to security.

Currently, there are no quantitative projections for climate change impacts for pipelines. Further research is needed to define links between the forecasts and the actual projected impact at the local, regional and national environment level, i.e. the level of rainfall, frequency of severe events, change in wind levels, the degree, extent and depth of flooding, increased rates of erosion, and the exacerbation of land movement. A greater understanding and analysis of ground movement and associate impacts is another area also requiring further investigation.

Bridges have considerably long service lives and are usually built to a design life of 50-100 years. However, existing bridges were built with past climate as their basis, with no consideration of climate change. Nasr *et al.*, (2019) present the most comprehensive work on the potential risks on bridges as a result of climate change. Utilising more than 200 research articles, a total of 31 individual risks are identified and discussed, including durability, serviceability, geotechnical, increased demand, accidental loads, extreme natural events, and operational risks. Most of these risks may act in combination to cause bridge failures. For instance, the increased hydrostatic pressure behind bridge abutments can combine with the risk of accelerated scour rates and the durability risks to cause failure.

The Rail Safety and Standards Board (RSSB, 2016a) describe the potential impact of future climate change on the GB railway. Excess precipitation and flooding can potentially lead to earthworks failure and scour of bridges. UK transport agencies (e.g. Highways England, Network Rail) are in the process of reviewing current standards, as an input to the design process (e.g. the on-going Network Rail climate change adaptation plan). Bridge scour is controlled based on the design, using a 1 in 200-year return period rainfall event for new construction, with a 20% allowance for climate change. Similarly, new drainage systems are designed based on a return period storm event of 10 to 50

years, with a 20% allowance for climate change (Network Rail, 2015b; Highways England, 2016). However, guidelines address the peak river flow allowances by river basin district with much higher values (from 20% up to 105% for 2080s). Thus, the design in respect of bridge scour being based on a 20% single national allowance for climate change does not seem appropriate (i.e. +20% likely to be readily exceeded in future scenarios) (Reynard *et al.*, 2009) nor in keeping with current climate evidence (e.g. the Environment Agency is in the process of updating peak river flow allowances by river basin district, based on UKCP18) (Environment Agency, 2020b). Overall, there is much debate about the 20% uniform adjustment in estimated peak flood flows (Kuklicke and Demeritt, 2016; Pregolato *et al.*, 2017), since on one hand it is considered 'simplistic' (catchment type variability or regional variations ignored) (Reynard *et al.*, 2009; Defra, 2006), but on the other hand it is a pragmatic approach which allows management decisions to be made (Lane *et al.*, 2011).

Ongoing urbanisation of the watershed is indicated as a cause of increased levels of flooding, which has been cited by multiple studies as a potential factor that could exacerbate risk, especially of short-span bridges over relatively small waterways (e.g. small rivers, streams and canals), which were usually designed for relatively minor values compared to the standard return-period floods.

No systematic quantitative assessment of climate risks to bridges for the UK exists, unlike for the United States (e.g. Wright *et al.* (2012) and Khelifa *et al.* (2013)), hence it is not possible to adequately assess the differences in risk between devolved administrations in detail. Updated climate projections can support risk judgements regarding the weather and climate variables that underpin risks to bridges, i.e. heat-induced damage to pavements and railways, as well as thermally-induced stresses in the structure, melting permafrost that generates additional runoff and sea level rise, thus higher flow speeds and faster scour at piers, rainfall events that trigger slope failure, foundation settlement and landslides, seasonal contrasts of rainfall to generate shrinkage and swelling of clays, and winds that generate wave impact to piers and abutments (Amro Nasr *et al.* 2019). Overall, there is no evidence to suggest that the magnitude of the risk has changed for this descriptor since CCRA2.

4.5.1.3 Lock-in and thresholds (I4)

Bridges are critical components of transportation networks and have clear potential for lock-in risks, with design lives of 50-100 years. They are also extremely expensive to retrofit, so correct specification is essential. There are a large range of specific thresholds associated with bridge design, notably with the engineering to cope with floods or windstorms of specific return periods. Given likely increases to extremes, this will require increases in engineering codes. However, this is challenging for new bridges because of uncertainty, and the balance between the level of climate uplift to factor in versus the additional costs of doing so.

4.5.1.4 Cross-cutting risks and inter-dependencies (I4)

In terms of interacting risks, bridges often co-locate various types of infrastructure (e.g. pipes, electric cables) that cross a river at the same point. Also, both bridges and pipelines are affected by road transportation. Extreme weather impacts on the ability of the workforce to access and carry out their roles, particularly field-based engineers. The CCRA3 interacting risks project (WSP, 2020)

identified the impacts which have the greatest number of upstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). Transport infrastructure damage is in the top 20 impacts with 3 connections.

WSP (2020) noted that the impact of flooding on transport infrastructure can have a number of significant cascading impacts in the 2020s, 2050s and the 2080s.

- The direct impact of extreme rainfall events causes flooding of transport infrastructure and hubs.
- Indirect impacts of cascades from flooding of infrastructure leading to transport damage and subsequent travel accidents and travel delays. The latter cascade was rated as having a medium risk in 2020 and a high risk (based on likelihood and impact) in 2080 under a 4°C scenario.
- Cross- sectoral, increased drought stress in the natural environment can lead to soil desiccation, impacting soil condition and quality. This can lead to structural stability issues and pipeline movement.

It is important to note that transport networks (especially roads) are critical during emergency management and recovery, allowing accessibility to hospitals and to sites for repairs and replacements (e.g. Arrighi *et al.*, 2019).

Bridges also represent an important connection between infrastructure and cultural heritage and provide examples of interactions with risks discussed in Chapter 5 (Kovats and Brisley, 2021). There are implications to the need for maintenance, and potentially poor maintenance for historic bridges, which then suffer during severe weather. For example, the collapse of parts of the Grade-II listed Tadcaster Bridge caused by the swollen River following Storm Eva in December 2015 (Historic England, 2016).

4.5.1.5 Implications of Net Zero (I4)

There is no clear evidence that the UK's Net Zero target will significantly affect this risk. It is stated in the CCC Net Zero Technical Report (CCC, 2019a) that the UK's gas distribution networks are currently undergoing a programme of refurbishment that is replacing existing iron gas distribution pipes with plastic ones that will potentially make the networks 'hydrogen ready'. This replacement programme will need to consider future climate risks. The CCC's Sixth Carbon Budget advice suggested that parts of the gas grid may need to be decommissioned as part of a transition to Net Zero, meaning the future gas grid may not be as extensive as the one we have today. It will be necessary to assess any change in risk that this may pose. Climate change (warming temperatures) will affect UK energy demand for heating, and thus have implications for gas or hydrogen demand, see Risk H6.

4.5.1.6 Inequalities (I4)

There are no national assessments on bridge or pipeline risk which can be used to discuss observed inequality of current risk in relation to individual, place and region. However, past episodes have evidenced equality issues in crossing. For example, Workington had different services on two sides of the river (e.g. one supermarket on one side only) and in 2009 a bridge failure required extensive round

trips to the nearest crossing. Bridge failures elsewhere are unlikely to be as impactful (e.g. in Newcastle city centre there are 8 bridges to cross the River Tyne, and large services on both river sides). To better assess this, the DfT Resilience Review (2014) established the need to identify critical single points of failure in the transport network which have potentially high impacts for society and economy (and the potential to isolate remote communities) as a key priority.

4.5.1.7 Magnitude scores (I4)

Table 4.18 Magnitude scores for risks to bridges and pipelines from flooding and erosion					
Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Northern Ireland	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(low confidence)
Scotland	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Wales	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

The evidence supports a medium magnitude current risk for flooding and erosion on bridges and pipelines for all nations of the UK (Table 4.18). It is clear that bridges, long-life infrastructure built with past climates as their basis, are vulnerable to current hazards. This has been evidenced through previous catastrophic failures such as the 2009 Cumbria floods and the loss of the Tadcaster Bridge in 2015 (which also ruptured gas lines). Remediation costs in Cumbria cost £123.6 million over a four-year period (Ettema *et al.*, 2018). Annual expected costs associated with passenger delays from bridge scour across Network Rail's network have been estimated at between £6 million and £60 million (Lamb *et al.*, 2019). The literature on equivalent risks to pipelines is less well-established than for bridges, although it is noted that these infrastructures are often co-located. The authors give medium confidence in this assessment, whilst acknowledging that less evidence is available for pipelines.

The evidence also supports medium magnitude for future risk with low confidence across all future

climate scenarios in this assessment for the four countries of the UK. Increased winter precipitation and river flows will increase the scour hazard for bridges, and hence sustain or increase expected impacts above current levels. Vulnerability of bridges is an issue, with many built over a century ago. Currently there are no quantitative projections for climate change impacts for pipelines. The lack of quantitative studies on future impacts on bridges and pipelines means this assessment is given with low confidence.

4.5.2 The extent to which current adaptation will manage the risk (I4)

4.5.2.1 Effects of current adaptation policy and commitments on current and future risks (Risk I4)

4.5.2.1.1 England

Highways England addressed risks posed by climate change for the first time with the Climate Change Adaptation Progress Update (Highways England, 2016). They also updated the Design Manual for Roads and Bridges (DMRB), a series of standards, advice notes and other documents for the design, assessment and operation of roads in the UK, by including the document “LA114 Climate Change”, which sets out the effects of climate on highways (climate change resilience and adaptation), and the effect on climate of greenhouse gas emissions from construction, operation and maintenance projects (Highways England, 2019). Highways England’s climate risk assessment identified vulnerabilities in its network using a scenario at the upper end of the range defined as the CCRA3 pathway to 4°C global warming at the end of the 21st Century⁷. It used this assessment to update operational procedures and adaptation plans. The actions reported in NAP2 focussed particularly around flood risk, slope stability and bridges, with HE reporting that 95% of the network is in good condition, although this is not necessarily a true indication of the ability for roads to operate in hazardous conditions. The CCC Progress Report noted (2019b) that work is ongoing to improve understanding of the risk to gas networks crossing bridges.

4.5.2.1.2 Northern Ireland

Northern Ireland's Climate Change Adaptation Programme 2019–2024 (DAERA, 2019) refers to the DMRB and states the Department for Infrastructure is contributing to the review and update of the Manual which will take into account the latest climate change projections from UKCP18.

4.5.2.1.3 Scotland

The Scottish Ministers’ High Level Output Specification, Control Period 6, sets out how investment strategies must ensure enhanced network resilience from adaptation interventions. Scottish Ministers require Network Rail to develop and apply suitable Key Performance Indicators to monitor the impact and mitigation of climate change on network disruption. This is intended to provide the means to measure the benefits of adaptation interventions.

⁷ The 50th percentile of the UKCP18 probabilistic UK projections with RCP8.5 emissions. The 50th percentile of the UKCP18 global projections reaches 4.2°C warming at 2070-2099 with RCP8.5 emissions. See Chapter 2 (Watkiss and Betts, 2021) for further details.

For roads, the Second Scottish Climate Change Adaptation Programme (Scottish Government, 2019b) states that Transport Scotland will be undertaking the Second Strategic Transport Projects Review (STPR2). STPR2 will identify strategic transport infrastructure interventions. Transport Scotland implemented the Scour Management Strategy and Flood Risk Emergency Plan in 2018 across operating companies and Design-Build-Finance-Operate providers aimed at providing enhanced monitoring of trunk road bridges and other structures that are at risk.

4.5.2.1.4 Wales

The Welsh Government's climate adaptation plan, A Climate Conscious Wales (2019b) stated that more research is needed to identify the number of bridges at risk of bridge scour now and in the future, as well as the amount of adaptation underway nationally. The report mentions this would assist in enabling better decisions over the next 5 years (many actions may have long lead times such as relocating or rerouting bridges). They mention work is already underway with the British Geological Survey to discuss future research into fluvial scour; 1,000 listed and scheduled bridges have been mapped, with all bridges on the strategic road network having been risk-assessed and prioritised for scour repairs. More generally, Wales and West Utilities (working with Landmark Information Group) have developed an infrastructure vulnerability mapping tool (using sea level rise inundation, new tidelines, tidal flooding and fluvial flooding for different emission scenarios and probabilities). This includes potential bridge impacts and transport infrastructure impact.

4.5.1.2 Effects of non-governmental adaptation (I4)

The GB railway network is managed by Network Rail. Bridge scour is considered at the design stage and is based on a 1 in 200-year return period rainfall event for new construction, with a 20% allowance for climate change (RSSB 2016a). The CCC Progress Report (2019a) stated that Network Rail have deemed 181 bridge sites to be at an intolerable risk of bridge scour according to information from Network Rail (provided via personal correspondence). Standards require the risk of these assets to be reduced within two years of the bridge being assessed. Similarly, new drainage systems are designed based on a return period storm event of 10 to 50 years, with a 20% allowance for climate change. Moreover, the Network Rail Weather and Route Climate Change Adaptation plans contain actions based around preparing for a 4°C global temperature scenario (although these are based centred on preparation, rather than specific measurable goals to reduce risk).

4.5.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I4)

As summarised above, there have been positive developments in all UK nations to improve understanding of the risks to bridges and pipelines from scour, flooding and erosion, however more work is still needed to understand the extent of assets at risk, the amount of adaptation underway and how the risk is being reduced through those actions. As there is no evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

4.5.2.4 Adaptation Scores (I4)

Table 4.19 Adaptation scores to risks to bridges and pipelines from flooding and erosion			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

4.5.3. Benefits of further adaptation action in the next five years (I4)

4.5.3.1 Additional planned adaptation that would address the adaptation shortfall (I4)

For pipelines, the Energy Network Association (2015) stated improving drainage in areas that regularly flood during extreme weather events is one strategy of adaptation; monitoring of river and coastal erosion, as well as the development of flood, coastal and updated contingency defence measures as further strategies. Pipeline operators may be forced to follow new land zoning codes or adaptation measures such as re-routing lines from high-risk areas, and structural upgrades to existing infrastructure.

For bridges, Nasr *et al* (2019) found that scour depth can be reduced by streamlining abutments by means of wing walls, and piers by means of cutwaters. Alternatively, the use of stone pitching to armour the riverbed around abutments and piers is a very effective way to prevent scour. Reforming maintenance and inspection manuals should accommodate the effects of climate change, e.g. through a revision of the design codes to account for the effects of climate change, specifically in relation to bridge foundation scour and the effects of increased wetting and drying of soils in which pipelines are buried. Mitigation methods suggested include new protocols of maintenance and early-warning systems, however more data are needed to support this direction of development. Sayers *et al.* (2015) state that the most significant adaptation is likely to come through changes in maintenance operations, improving collaboration with emergency managers, recognising emergency management as an integral function of managing infrastructure.

4.5.3.2 Indicative costs and benefits of additional adaptation (I4)

The costs of adapting pipelines and bridges to climate change are very site-specific, and costs vary significantly between adapting the current stock versus new infrastructure. There is some older literature on the costs of adaptation for bridges (road and rail bridges) to address scour risk (Nemry and Demirel, 2012), which includes estimates for the UK and Ireland where annual costs are estimated at €47 million/year in the 2050s. Of these costs, 80% are for road and 20% for rail bridges. This is reported at approximately 2% of current road maintenance costs. The benefits of adaptation – in terms of avoided scour, possible failure, and subsequent repair or reconstruction (and indirect effects include travel time losses) – were not assessed, though the costs of any failures are normally large.

Bridges and tunnels have a long service life which makes them priority assets for adaptation. Lamb *et al.* (2019) considered the economic costs of bridge failures due to scour over the Great British rail network, including travel time costs, estimating the annual risk (expected annual utility cost to passengers, but excluding freight and speed restrictions when scour damage is suspected) of between £6 million and £60 million. This provides some baseline costs, onto which future climate risks will act, and adaptation could reduce. The Tomorrow's Railway and Climate Change Adaptation (TRaCCA) programme did look at options for the rail network overall to adapt in the most cost-effective way, with some quick wins suggested, although for scour this focused on better vulnerability information (RSSBa, 2016).

For the road network, Atkins (2013a) looked at the potential risks of climate change on road bridges for the Highways Agency (but considered all risks, not just scour). This looked at reduced service life, additional maintenance and associated lane closures, and found the benefits of adaptation were similar to costs for central scenarios (with benefit to cost ratios close to one) but BCRs rose significantly under worst case scenarios.

4.5.3.3 Overall urgency scores (I4)

Table 4.20 Urgency scores risks to bridges and pipelines from flooding and erosion				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	Low	Low	Low	Low

There have been positive developments in all UK nations to improve understanding of the risks to bridges and pipelines from scour, flooding and erosion and actions are being taken to reduce vulnerability. However, as future risk has been assessed as medium with limited evidence on the extent to which current and announced adaptation will manage the risk, Further Investigation scores have been assigned to each of the four UK countries (low confidence). There is a need to concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the CCRA range of future climate scenarios (2°C and 4°C global warming by the end of the century, and across the 10th - 90th percentile uncertainty range within each scenario) or whether more action is needed to achieve this.

4.5.4. Looking ahead (I4)

Identification and prioritisation of actions would benefit from a national assessment of bridge and pipeline risk. In terms of the railway sector, the CCC Progress Report argues that although delay data is of interest, as an impact indicator it does not give a sense of how vulnerability or exposure to climate risk is changing. They argue for better information on asset, slope and embankment condition and exposure, as well as the standards of new adaptation interventions. It is necessary to assess any potential change in risk brought about by the replacement of existing iron gas distribution pipes with plastic ones that will potentially make networks 'hydrogen ready' in a Net Zero context.

4.6. Risks to transport networks from slope and embankment failure (I5)

Increased incidence of high rainfall combined with preceding periods of desiccation and cracking are expected to lead to an increase in incidents of slope failure within the transport network. This conclusion is consistent with the evidence reviewed for CCRA2. Rainfall is seen as the main trigger of deterioration of the mechanical and hydraulic properties of engineered fill forming infrastructure slopes, especially considering wetting-drying and freeze-thaw cycles. Extreme weather is expected to increase the rate of these deterioration processes, however the publications reviewed suggest that these deterioration processes are not yet fully understood.

Underpinned by the 2020 Stonehaven derailment, the current risk magnitude score is medium (low confidence); for future scenarios, the risk magnitude is also medium (low) confidence. The urgency score for the whole of the UK indicates that more action is needed, although the confidence is low (e.g. deterioration methods are not fully understood) and it is difficult to ascertain whether current adaptation approaches are sufficient. Adaptation methods presently focus on providing improved numerical tools for infrastructure asset owners to predict failure occurrence. Improved instrumentation and monitoring systems is seen as promising for the understanding of slope failure processes in relation to meteorological conditions. However, additional work on the characterisation of engineered soil assets can also assist with understanding of the spatial distribution of risk.

4.6.1 Current and future level of risk (I5)

Note: it has not been possible to split the evidence by UK country for this risk.

4.6.1.1. Current risk (I5)

Slope deterioration and resultant failures have a significant negative impact on transport networks both in the UK and internationally. An important driver for this loss of performance is weather-driven annual cycles of pore pressure, and extreme weather is indicated as a potential factor contributing to the occurrence of failure. In the context of the potential impact of climate change, various works are studying a number of challenges, e.g. differences in initial asset condition related to historic construction techniques and hence baseline performance, or differences in age and hence the number of seasonal cycles that have contributed to asset deterioration.

CCRA2 (Dawson *et al.*, 2016) reported that there are 20,000 km of engineered cuttings and embankments supporting the UK's transport infrastructure. Older, less well compacted earthworks such as those supporting the rail network are deteriorating at a faster rate than newer earthworks built to more modern construction standards. In England and Wales, 5% of earthworks (embankments, cuttings and rock cuttings) were classed as being in a poor condition in 2012/13, with a further 48% classed as being in a marginal condition. There were, on average, 67 earthwork failures a year across the rail network between 2003/04 and 2013/14, of which 55 were in England and Wales and 12 in Scotland. There were some significant fluctuations during this period, with 107 failures in 2007/08 and 144 failures in 2013/14. The Western region has the highest average number

of failures (14 per year between 2004/05 and 2012/13). The busy West Coast and East Coast lines averaged 9 and 7 failures a year respectively. CCRA2 also reported that increased incidences of natural and engineering slope failure affecting the road and rail network in the winters of 2012/2013 and 2013/2014 demonstrate their vulnerability to the type of intense rainfall events that are expected.

Recent studies are consistent with the evidence reviewed for CCRA2. Increased incidence of high rainfall combined with preceding periods of desiccation and cracking are expected to lead to an increase in incidents of slope failure within the transport network. A number of studies have highlighted the potential for wetting-drying and freeze-thaw cycles to induce deterioration of the mechanical and hydraulic properties of engineered fill forming infrastructure slopes with more extreme weather expected to increase the rate of these deterioration processes. The publications reviewed suggest that these deterioration processes are not yet fully understood. Bergamo *et al.* (2016) assessed the potential of surface wave data to portray the climate-related variations in mechanical properties of a clay-filled railway embankment.

Railway cuttings have been identified as a major source of risk, with several high-impact examples of failure. In 2020 in Stonehaven (Scotland), following a severe rainfall event, a passenger train hit a landslip and derailed, causing three fatalities. The Harbury landslide (2015) is cited as one of the most recent examples of cutting and embankment slips triggered by localized extreme weather events. During this landslide, 350,000 tonnes of material slipped along a 160 m long stretch leading to the closure of the stretch of line between Banbury and Leamington Spa for several weeks.

Winter *et al.* (2016) assessed the economic impact of a number of debris flow events on the road network of Scotland. The study considered direct economic impacts (including emergency response and remedial works), direct consequential economic impacts (costs associated with loss of utility of infrastructure) and indirect consequential economic impacts (loss in business confidence associated with unreliable transport links). Direct costs were found to range between £400k and £1,700k, with direct consequential costs between £180k and £1,400k for the five case studies assessed.

More extreme weather conditions have triggered slope failures across the UK, especially during the extreme events of 2012. Field observations, centrifuge model testing and numerical models are methods to measure or simulate embankment behaviour; all can be supported by laboratory testing and an understanding of soil behaviour. For example, in County Down (Northern Ireland) hydrogeological processes caused unexpected instability and quick conditions during the excavation of a 25 m-deep cutting through a drumlin (Hughes *et al.*, 2016). Rouaina *et al.* (2020) demonstrated that a higher total magnitude of annual variation in pore pressures (as caused by future climate scenarios, for example) can have a significant effect on deformations in cuttings, leading to increased rates of deterioration and reduced time to failure.

Highway embankment failures induced by pore water pressure is increasing, while some railway embankments are susceptible to pore water pressure increase, seasonal shrink-swell deformation and progressive failure due to the age and nature of the dumped clay fill used in their construction (Briggs *et al.*, 2017). There is a lower risk of serviceability failure due to the shrink-swell movement of highway embankments, low plasticity fill embankments or grass covered embankments.

The effect of trees on risk due to slope and embankment failure is the subject of ongoing research. Simulations and field measurements show that while trees cause significant seasonal variations in pore water pressure and water content near the soil surface, they can maintain persistent soil suctions at depth within the tree rooting zone (Smethurst *et al.*, 2015). Leaving the trees in place over the bottom third of the slope can maintain persistent suctions at the slope toe.

Upland areas are more prone to natural slope failures due to their topography, in fact most of the studies are focused on Scotland. Similarly, mountainous areas are more prone to landslides. Regarding exposure and vulnerability, a high concentration of road/rail links or particular characteristics (e.g. high-speed rail) usually results in being more vulnerable to damage. Removal of trees in order to prevent falling branches and disruption to signals is likely to increase the landslides risk. No study has looked at slope and embankment failures comparing urban and rural context, however urban environments are more prone to flash flooding due to the high percentage of impermeable surfaces, which could cause subsidence due to run off (as in the high profile railway derailment in Stonehaven, 2020).

Landslides on coal tips are a known hazard in Wales. A major slope failure occurred at Llanwonno tip near Tylorstown in South Wales after heavy rain during Storm Dennis in February 2020. A number of minor landslips also occurred at other tips in South Wales. There are over 2,000 coal tips in Wales, predominately in the South Wales Valleys; 294 have been identified as high risk (Fairclough, 2021). With annual mean rainfall having increased in Wales, especially in South Wales (Chapter 1: Slingo, 2021), we suggest that it is possible that climate change may have already increased the risk of future slope failures.

4.6.1.2. Future risk (15)

Modelling suggests that soil moisture fluctuations will lead to increased risk of shrink-swell related failures. This will be most acute in the high plasticity soils of SE England and likely to be the most significant geohazard to UK infrastructure. Wilks *et al.* (2015) considered rising temperatures (drier summers) and increasing precipitation (wetter winters) leading to slope failures along transport infrastructure within the UK. A series of slope failure case studies were investigated under 18 Weather Event Sequences (WESQs) using possible weather patterns for 2050 using UKCP09 climate projections with the high emission scenario. Although this scenario warms faster than the pathway to 4°C global warming by 2100 (see Chapter 2: Watkiss and Betts, 2020), the projected increases in heavy precipitation were smaller for a given level of global warming than in the updated projections in UKCP18 (Johns *et al.*, 2021), and hence we consider this to still be an appropriate guide to this risk in the 2050s. Each of the 18 WESQs shows a year of possible weather for the year 2050 and covers the extremes of warmest, coldest, driest and wettest. A suite of thresholds was developed based upon case studies; the 20 case studies were not of sufficient number to draw a statistically significant conclusion, but rather they illustrate trends and give a first indication as to future slope behaviour. Vegetation management for warmer trends was mentioned as potential adaptation. Wetter climates are said to produce more landslides; autumn is the most likely month for landslides for the warm and wet scenario weather, while winter for the cold and dry scenario weather. For the cold and wet scenario both autumn and winter are likely times of failure, but landslides can also occur in the summer under storm conditions.

As well as meteorological extremes, slope condition is also mentioned as a key determinant of risk. Smethurst *et al.* (2017) stated that climate change presents an increased risk to slopes. It is argued that extreme periods of climate, coupled with ageing assets, may cause a higher rate of failure. Examples of this are extreme rainfall events (both heavy showers and long periods of rain), drought and increased freeze–thaw cycles. The main driver for slope failure is rainfall, and it is possible that a hotter future European climate will see rainfall arrive in more intense storm events. Drier summers may also pose difficulties for earthworks, causing cracking and shrinkage problems in clay soils. In Europe, new road and rail systems often operate at higher speed, and the hazard posed by running into slipped debris (causing derailment or crash) is greater. Moreover, new rail and road infrastructure often rely on large amounts of earthworks, which can be impacted from increased precipitation or drought, causing increased costs and delays; this potential impact constitutes an important risk during the construction phase. A greater use of instrumentation to monitor slope behaviour may help to manage the risk that climate change poses; proactive management of slopes can be much more cost effective than reactive repairs following failure.

The sequencing of weather conditions (see Chapter 1: Slingo, 2021) is also a key factor. Dixon *et al.* (2019) underlined that cyclic seasonal effects could be potentially influenced by a changing climate. Dry summer periods remove water, leading to shrinkage and cracking; prolonged and intense rainfall events cause swelling and increased porewater pressures. Repeated shrink–swell cycles can lead to accumulation of shear strains resulting in strain softening and progressive failure.

Although Briggs *et al.* (2017) found that highway embankment failures induced by pore water pressure is increasing, the simulations undertaken in this study may not be fully representative of future embankment deterioration or the dominant physical processes influencing pore water pressures in a changing climate (e.g. surface desiccation). Tang *et al.* (2018) noted that increased precipitation, temperature and evapotranspiration (non-specified emission scenarios, based on European Environment Agency data) are likely to characterise the northwest part of Europe, and thus the UK. They highlighted risk from increased surface erosion, desiccation cracking, saturation-induced failure and shrink-swell to the stability of infrastructure slopes.

Martinovic *et al.* (2016) showed post-processed findings from an airborne LiDAR survey of the entire Irish Rail network. Slope vulnerability to shallow planar type failures is expected to increase with predicted changes in climate such as increased environmental loading (rainfall events are predicted to be more intense and of longer duration, with longer dry periods in between). This study may also have some relevance to the rail network of Northern Ireland.

Regarding canal embankments and inland waterways, projected increase in winter precipitation may increase the frequency of high flow, flooding and ‘strong stream’ conditions whereas the additional evapotranspiration associated with higher air temperatures could lead to drying out and fissuring of clay embankments and other earth structures (Brooke, 2015). Reduced waterway channel freeboard and associated lack of operating headroom could similarly compromise safety of navigation. High water levels and flood flows can threaten the integrity of navigation infrastructure through seepage, overflow or erosion and the capacity of culverts, weirs and sluices might be reduced. Extreme events are also likely to exacerbate flash floods or debris flow events involving

erosion due to atypical magnitude of surface water, as opposed to conventional deeper-seated slips within the soil.

4.6.1.3 Lock-in and thresholds (I5)

Whilst minimal lock-in risks exist for known landslide sites (with engineering design codes for embankments), future climate change will increase landslide risks. There is therefore a risk of lock-in if future risks are not considered given the long lifetime and changes in land-use (with road or rails). Heavy rainfall is usually associated with a very high number of recorded landslides, thus hydrogeological triggering is seen as a main driver for slope instability. A large proportion of failures occurred on man-made slopes (embankment or cuttings), usually triggered by heavy rainfall that happens within a short time of prolonged rainfall. Pennington and Harrison (2013) developed a 'winter' threshold envelope to consider the antecedent period, water content, soil moisture and average rainfall for slope failure for SW England and S Wales. TRL (Winter *et al.*, 2019) has advanced preliminary rainfall duration-intensity thresholds based on 16 debris flow events in Scotland; these values are awaiting further validation. Briggs *et al.* (2019) developed performance curves showing the factors influencing the ultimate limit failure of embankments due to seasonal weather cycles. A key issue is the degree to which these thresholds might be exceeded under future climate change; the new UCKP18 projections indicate higher heavy rainfall projections (see Chapter 1: Slingo, 2021) than previously estimated, and these are likely to be much more evident with 4°C global warming.

4.6.1.4 Cross-cutting risks and inter-dependencies (I5)

The CCRA3 interacting risks project (WSP, 2020) identified the impacts which have the greatest number of downstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). Transport infrastructure damage is in the top 20 impacts with 3 connections. The project assessed the indirect impact of cascades from slope and embankment failures due to increased winter rainfall to be significant and lead to transport damage and subsequent travel delays. The level of risk of this interaction was assessed as being medium (based on impact and likelihood) in 2020 but increasing to high in 2080 (Table 4.2 in section 4.2.1).

4.6.1.4.5 Implications of Net Zero

Other than increased vegetation which has the potential to improve slope stability, no specific impact of Net Zero targets on risks to transport networks from slope and embankment failure could be found, although it is reasonable to assume that rail will play a greater role in a Net Zero world, hence increasing the exposure to this element of the risk.

4.6.1.4.6 Inequalities

There are implications here for the more rural areas of the UK where there is inherently less resilience in transport systems due to less dense infrastructure (i.e. single train lines). This is especially relevant where linear transport infrastructure frequently follows natural features such as steep sided river valleys prone to landslide risk. On the contrary, urban areas of deprivation are

often located close to rail lines and major roads, so their increased use could disproportionately affect these residents.

4.6.1.4.7 Magnitude Scores (I5)

Table 4.21 Magnitude scores for risks to transport networks from slope and embankment failure					
Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Northern Ireland	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Scotland	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Wales	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)

The UK has tens of thousands of km of engineered cuttings and embankments supporting its transport infrastructure. The Stonehaven incident in 2020, which led to three fatalities, and Harbury in 2015 highlight the disruption and human cost caused by rainfall induced landslides on transport infrastructure. Single landslip events in Scotland have been estimated to cause direct costs between £400k and £1,700k, with direct consequential costs between £180k and £1,400k. The length of network exposed to this risk, its vulnerability to the hazard and the observed impact of single events indicates this risk is of medium magnitude (Table 4.21). This is given with low confidence, as there is no nation-wide assessment of the economic and social consequences of slope and embankment failure on transport networks. The observation in CCRA2 that modelling shows soil moisture fluctuations will lead to increased risk of shrink-swell related failures is supported by current evidence.

4.6.2 The extent to which current adaptation will manage the risk (I5)

4.6.2.1 Effects of current adaptation policy and commitments on current and future risks (I5)

4.6.2.1.1 UK wide

There is considerable investment being delivered to renew and repair rail embankments and cuttings, as part of the £2.3 billion being spent on renewing civil engineering structures between 2013/14 and 2018/19. An average of £100 million a year was to be spent on earthwork renewals during the current price control period (2014/15 to 2018/19), an increase from the average of around £75 million a year in the previous period (2009/10 to 2013/14). Expenditure on track and earthwork drainage renewals has also increased, from around £50 million a year in the previous price control period to nearer £70 million a year in the current period. Both the industry and regulator recognise that historic investment in ageing structures has been insufficient to deliver acceptable levels of risk in the long-term. There is therefore a significant backlog that will require sustained investment over the next 40-50 years to clear.

CCC (2019b) state that actions relating to rail infrastructure are associated with risk reduction, and it is likely they are reducing vulnerability in some areas, but there is not the evidence at present to quantify this. The main indicators available for rail reliability is delay data and although of interest, as an impact indicator it does not give a sense of how vulnerability or exposure to climate risk is changing. It would be useful to have a better understanding of asset, slope and embankment condition and exposure, and the standards of new adaptation interventions.

4.6.2.1.2 Scotland

Specifically for Scotland, the Second Scottish Climate Change Adaptation Programme (Scottish Government, 2019b) states that Transport Scotland will be undertaking the Second Strategic Transport Projects Review (STPR2). STPR2 will identify strategic transport infrastructure interventions. The adaptation programme document also mentions the Scottish Road Network Landslides Study and Implementation Report (Transport Scotland, 2008), which takes into consideration the potential seasonal increase or decrease in rainfall and the potential impact on increased frequencies of landslides. The Integrated Roads Information System and Disruption Risk Assessment Tool has been used to record incidents including inundation and subsidence, allowing identification of vulnerable locations in the trunk road network that require engineering interventions or monitoring. More generally, the Scottish Road Network: Climate Change Study and Implementation Plan (Transport Scotland, 2008) set out recommendations to adapt the Scottish road network to cope with climate change. This used the older UKCP09 climate projections. Consideration is now being given to updating it utilising the UKCP18 projections. In terms of rail, the Scottish Ministers' High Level Output Specification, Control Period 6, sets out how investment strategies must ensure enhanced network resilience from adaptation interventions. Scottish Ministers require Network Rail to develop and apply suitable Key Performance Indicators to monitor the impact and mitigation of climate change on network disruption. This is intended to provide the means to measure the benefits of adaptation interventions.

4.6.2.1.3 Wales

The Welsh Government's climate adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b) states that Wales and West Utilities (working with Landmark Information Group) have developed an infrastructure vulnerability mapping tool (using sea level rise inundation, new tide-lines, tidal flooding, fluvial flooding for different emission scenarios and probabilities). This includes potential bridge impacts and transport infrastructure impact. There is no reference to landslips in the Future Wales: National Plan 2040 (Welsh Government, 2021a). This is Wales' new national plan, setting the direction for development in Wales to 2040, addressing key national priorities through the planning system, encompassing climate resilience.

In March 2020, the Coal Authority and the Office of the Secretary of State for Wales announced an emergency review of all coal tips in Wales (Coal Authority, 2020), categorising tips according to both their level of inherent risk and also whether the location poses a risk to people or critical infrastructure, or a risk to the environment such as rivers or other infrastructure, or are situated in a remote area (Coal Authority, 2020). This follows calls for more monitoring of coal tips following the major slope failure at Tylorstown in South Wales after heavy rain during Storm Dennis in February 2020, along with a number of minor landslips at other tips in South Wales triggered by the storm. 294 coal tips have been identified as high risk (Fairclough, 2021). The Welsh Government statement on coal tip safety (Welsh Government, 2021b) highlights the difficulties in reducing the risk of slope failures. Substantial shortcomings in current legislation and the fiscal framework regarding tip inspections and remediation have been identified. Regular inspections of disused tips is not currently mandated.

Welsh Local Authorities are responsible for 32,000km of roads in Wales. This amounts to 95% of the total road network as the Welsh Government is responsible for the Trunk and Motorway Network. Local authorities work with transport operators – bus and rail, the construction sector, planning, utilities and transport groups. The Welsh Local Government Association (WLGA) works on behalf of the 22 authorities on policy and investment in Wales' roads. A State of Wales Roads Report (Welsh Local Government Association, 2018) was published by WLGA, this did not reference the potential impact of climate change on slope and embankment failure.

4.6.2.1.4 Northern Ireland

In Northern Ireland, Translink have committed to a continued geotechnical inspection regime for road and rail embankments and to prioritise actions (DAERA, 2019). Translink have been upgrading the management and infrastructure of their sites in order to adapt to climate change, including culverts on the Coleraine to Londonderry line and on the Larne line which have been sized to the latest design requirements for expected flow. A project was completed in County Antrim to replace three bridges and strengthen embankments on both the Dublin line and the Antrim Branch line. This was a scheme that was completed to ensure the area was future proofed for climate change predictions and was done as part of the improvements in that area for flood management by DfI Rivers and Coca Cola, who operate a nearby bottling plant. There is also an ongoing programme of repairs to structures and repairs following storm damage which includes activities such as rock armouring, masonry repairs, etc.

Other asset management initiatives include ongoing maintenance of 28 ‘hotspot’ areas on the rail network. These are areas of potential flooding that are managed prior to, during and after heavy rainfall. Risk analysis has also been carried out on cuttings and embankments using available DfI Rivers flooding information and we follow the weather forecasts and manage these assets during heavy rainfall periods with additional inspections, reducing train speeds, etc.

4.6.2.2 Effects of non-government adaptation (I5)

Programmes have been developed to determine the amount of investment and volume of renewals required. For example, Network Rail has developed the Weather Resilience and Climate Change (WRCCA) programme which includes (i) an enhanced vegetation management strategy to mitigate the impact of extreme winds; (ii) forensic investigation of earthworks failures; (ii) earthworks remote condition monitoring pilot; (iii) improvement of drainage management; (iv) agreed thresholds (e.g. water/wind levels for alert) and definitions; and (v) an enhanced Future Weather Service for user defined geographic areas across (Network Rail, 2015). Highways England have embedded a culture of climate change adaptation planning across its assets by giving ownership of the adaptation plans to the areas of their operations at risk from climate change (Highways England, 2017), especially the increase in precipitation and temperature. These plans cover (i) drainage and pavement improvement, e.g. for overflow or thermal damage; (ii) structure and geotechnics work, e.g. earth pressure design; and (iii) sign, signal and road marking improvement for better communication.

In response to the tragic derailment at Stonehaven in 2020, which was thought to have been caused by a landslide, Network Rail launched two taskforces to look at how to prevent future impacts, as part of its long-term response to climate change and the challenge of maintaining its massive portfolio of earthworks (embankments and cuttings), many of which date from the Victorian era. The findings from the taskforces are pending at the time of writing.

4.6.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I5)

As with risk I4, there have been positive developments in all UK nations to improve understanding of the risks to transport networks from slope and embankment failure, however more work is still needed to understand the extent of assets at risk, and positive action of reducing the risk. This indicates that the risk is being partially managed and that actions are reducing vulnerability in some areas. However, as there is no quantified evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

4.6.2.4 Adaptation scores (I5)

Table 4.22 Adaptation scores for risks to transport networks from slope and embankment failure			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

4.6.3 Benefits of further adaptation action in the next five years (I5)

CCRA2 stated that further action was required to ensure that projected increases in heavy rainfall events are factored into long-term renewal programmes for earthworks, especially for the rail network. This will reduce vulnerability now and is likely to be cost-effective to implement, given that the risk is increasing with further asset deterioration combining with heavier and more frequent rainfall events.

Adaptation methods suggested within the current literature focus on providing improved numerical tools for infrastructure asset owners to predict failure occurrence, improved instrumentation and monitoring systems to detect pre-failure slope behaviour linked to decision support systems, more detailed characterisation of engineered soil assets, continued use of slope inspection programs, and greater use of soft engineering techniques such as vegetation management to reinforce vulnerable slopes. Some deterioration methods are not fully understood, which will impact adaptation strategies. Hughes *et al.* (2016) discuss the need for continuous monitoring of pore pressures during and after construction; this is mentioned as an adaptation measure.

4.6.3.1 Indicative costs and benefits of additional adaptation (I5)

There are some clear low-regret options for addressing these risks. For railways, inspection and maintenance are key activities to monitor slope and embankment failure risks in advance, at a relatively low cost (RSSB, 2016b). Currently, routes use a drainage decision support tool and data collected from drainage inspections, surveys and assessments, with drainage assets currently required to be inspected at least every five years (Haines, 2020). A low-regret option would be to increase inspection frequency (especially for higher risk areas).

Drainage is also key for the stability and resilience of earthworks. There are obvious low-regret and easily implementable options for enhanced maintenance of drainage systems for addressing surface and groundwater water away from roads and railways. The costs of increasing drainage capacity in new road infrastructure also appears to be low regret, adding only a small percentage to the overall construction costs. For new builds, there are also options for improving monitoring around complex systems such as embankments; Tang *et al.* (2018) recommend remote sensing tools and report that new engineered slopes are an opportunity to design intelligent monitoring systems in a cost-efficient way, e.g. by installing systems during construction rather than retrofitting them later.

There is mixed evidence about the effectiveness of specific interventions such as vegetation management. This can help manage soil moisture fluctuations in the near-surface zone (Tang *et al.* 2018), and there is evidence that mature trees have positive effects on embankment slopes (Smethurst *et al.*, 2015). However, Network Rail reported that the removal of trees is not necessarily the cause of landslips; during summer they may cause the earthworks to dry out, and they can pose additional risks during windstorms. On the contrary, there is an increased incidence of trains running into fallen trees; vegetation management has a role to play in mitigating climate risk of earthworks, but it needs trade-off between benefits and risks (e.g. at the toe of an embankment).

Network Rail spent approximately £100 million on earthworks and drainage investment per annum

(on average) from 2009 to 2014 and was planning to double this in the subsequent five years. The benefits of these investments are in terms of avoided damage, which are very large for rail slope and embankment failure. Similar considerations are made for highways, where the costs of planned maintenance work are weighed against the risks of highway closure and repair and travel time delays. However, there is high heterogeneity with site and location (Glendinning *et al*, 2014) which means adaptation is context specific (and thus so are benefits and costs).

4.6.3.2 Overall urgency scores (I5)

As discussed above, there have been positive developments in all UK nations with considerable investment being delivered to renew and repair rail embankments and cuttings. The formation of taskforces to specifically report on improved ways to manage the rail earthworks portfolio could be instrumental in the future management of this risk. There is also evidence that the latest UKCP18 projections will be utilised in adaptation work. However, as with the previous risk I4, there is presently limited evidence on the extent to which current and announced adaptation will manage the risk (although this could change pending the findings of the Network Rail taskforces), ‘more action needed’ scores have been assigned to each of the four UK countries (with low confidence). This action should concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the CCRA range of future climate scenarios (2°C and 4°C global warming by the end of the century, and across the 10th to 90th percentile uncertainty range within each scenario) or whether more action is needed to achieve this.

Table 4.23 Urgency scores for risks to transport networks from slope and embankment failure				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More Action Needed	More Action Needed	More Action Needed	More Action Needed
Confidence	Low confidence	Low confidence	Low confidence	Low confidence

4.6.4 Looking ahead (I5)

Improved instrumentation and monitoring systems will help in the understanding of slope failure processes in relation to meteorological conditions. Work on the characterisation of engineered soil assets will assist with understanding of the spatial distribution of risk. There would be clear benefits of infrastructure owners to identify or value particular assets, such as slopes at optimal angles and direction, as natural capital, and possibly in some cases optimal for renewables generation (e.g. PVs or other renewables).

4.7. Risks to hydroelectric generation from low or high river flows (I6)

Hydroelectric power is vulnerable to both low river flows and extremely high river flows, however it may also benefit from increased output under more moderate increases in river flow. CCRA2 did not report a magnitude for current risk for hydropower (unknown magnitude/unknown impact). In this assessment, current risk levels are deemed to be medium (low confidence) based on the magnitude of the loss of revenue (tens of millions) caused by a reduction in generation in part due to reduced rainfall in 2018.

The future level of risk magnitude has been evaluated as medium. There is limited evidence assessing these risks, however the evidence that is available points to mixed impacts of climate change on hydroelectric generation, with generation potentially increasing in the winter and decreasing in the summer under scenarios of 2°C global warming by 2100. No studies were found which quantified the UK effects for the late 21st Century in a 4°C global warming scenario. While increased rainfall may again increase the potential for generation, there is also the possibility that more extreme rainfall events generate flow rates which are too fast to be exploited and lead to a risk of equipment damage, as well as damage downstream of hydro schemes. No research has been found on the likelihood of future physical damage to infrastructure in high flows, although it is known to be vulnerable to extreme high flows. Given future climate projections indicate more frequent, drier summers, the magnitude of risks to summer generation of hydro schemes is likely to remain medium, given it is medium under the current climate. The magnitude of risk associated with extreme rainfall events which could lead to equipment damage and consequences downstream is unknown, as these have not been included in the studies reviewed here. Further investigation would be needed to assess this risk.

Adaptation measures would include considering future river flows and incorporating climate impacts into the design of new schemes together with risk assessments for existing infrastructure and appropriate action.

4.7.1 Current and future level of risk (I6)

4.7.1.1. Current risks (I6)

4.7.1.1.1. UK-wide

Hydropower provided 2% (5,935GWh) of net electricity supplied in the UK in 2019 (BEIS, 2020b). There is currently 1875 MW (2% UK) installed capacity of natural flow (either run-of-river or impoundment) hydro power in the UK (BEIS, 2020b). The majority of existing installations, including all large (>20MW) plant, are in rural, often upland areas, however there are some smaller schemes within urban areas such as Longbridge Weir Hydro on the River Derwent in Derby. The majority of large installations are in the Scottish Highlands and North and Mid-Wales, with some in the North of England and none in Northern Ireland (UK Government, 2019; BEIS, 2019 page 99).

Hydroelectric power is vulnerable to climate impacts which lead to lower or extremely high rainfall

in the catchment area of the river or reservoir / impoundment and the resulting flow, but may also benefit from higher flows. A reduction in river flow will reduce the output of hydro power, whereas an increase in flow can increase output, up to the maximum rate for which the turbine has been designed. The impact of lower or higher rainfall on flows is mediated by the surrounding catchment area, and the consequent rate at which water reaches the river or reservoir/impoundment. Energy generation from hydro schemes is closely linked to changes in runoff (Sample *et al.*, 2015). Extreme high flows can damage or wash away generation equipment and associated infrastructure and flood the turbine house (Solaun and Cerda, 2019). Duncan *et al.* (2010) also highlight the need to assess the potential impacts of severe flood events on existing designs of spillways and weirs.

CCRA2 did not report a magnitude for current risk for hydropower (unknown magnitude/unknown impact). Since then, a reduction in all hydro generation of 7% (500GWh) in 2018 compared to 2017 was in part attributed to lower rainfall (BEIS, 2019) this includes an 11% reduction for large natural flow schemes in 2018 compared to the average output between 2014-2019 and approximately 0.2% of total power generation in 2018 (BEIS, 2020b, Tables 6.4 and 5.1.2). The magnitude of revenue from electricity associated with this reduction in output is in the order of £10s of millions. A reduction in generation of 500GWh would equate to approx. £29m of lost revenue using average 2018 prices for baseload contracts (Ofgem, 2020b). While the reduction in rainfall in 2018 has not been attributed to climate change and fluctuations in output are to be expected, the figures give an indication of the magnitude of financial losses that can be incurred from just a 7% drop in output. However, it is the pattern of output over a period of years, and its correlation with climate change, that are necessary to identify an impact. There is insufficient evidence to demonstrate that climate change is currently having an impact on hydropower. Therefore, the current magnitude is deemed low for England, Wales and Scotland and low for Northern Ireland.

4.7.1.2. Future risks (I6)

4.7.1.2.1. UK-wide

Future risks to UK hydropower depend on both the climate and the future of hydro capacity. Estimates suggest the potential for the development of further hydropower of 120-185MW in England and 27-63 MW in Wales (BHA and IT Power 2010); a further 400-500MW in Scotland (Sample *et al.* 2015) and 12MW in Northern Ireland (Redpath and Ward, 2014). However, the studies use different methods and technical and economic assumptions to assess feasibility, and some of the sites identified for development may have since been developed. Furthermore, their capacity estimates may be underestimated given Coire Glas, a pumped hydro scheme in Lochabar was granted planning permission in 2020 for up to 1,500MW. Although the potential for further large impoundment schemes is limited due to both environmental concerns and limited suitable sites, there is potential for further development of run-of-river hydroelectric schemes which have a design life of at least 25 years, though are likely to operate for far longer (Sample *et al.*, 2015; UK Government, 2019; BHA, 2020).

Turner *et al.* (2017) assessed the impacts of climate change on global hydropower for dam or impoundment-based schemes' output using projections reaching approximately 2°C and 4°C of

global warming by 2100⁸, but only presented UK results for 2050. The results for the UK as a whole for 2050 are an increase in electricity production of between -2.1–9.8% in the +2°C by 2100 scenario and 6.8–20.4% for the scenario on a pathway to +4°C by 2100, with the ranges arising from the use of 3 climate models with each scenario.

Tobin *et al.* (2018) assessed the total annual hydroelectric energy potentially available when all natural runoff in the UK is harnessed using stream flow projections consistent with future precipitation, temperature and humidity. Using several combinations of regional and global climate models and emissions scenarios, the range of projected changes in UK hydropower included both increases and decreases. At 2°C global warming reached in approximately the 2020s to 2050s, projected changes in hydropower ranged from approximately -1% to 5%, with a mean of 2%. For 3°C global warming reached in approximately the 2040s to 2070s, uncertainties were larger, with projected changes ranging from -4% to 5% and a mean of 0.5%. No clear conclusions on the projected sign of the change can therefore be drawn from this study.

Després and Adamovic (2020) used a different set of climate models and, for the UK and Ireland combined, projected similar ranges of changes in hydroelectric production as seen in the UK results of Tobin *et al.* (2018); the projections included both decreases and increases of a few percent, but with slightly more model consensus towards increasing production with 3°C of global warming compared to 2°C. Both Tobin *et al.* (2018) and Després and Adamovic (2020) assume all potential power from river flows are utilised and are resolved to the country scale rather than assessing individual sites and neither study assessed extreme events.

The relatively small changes of both these studies suggest the potential for opportunities for increased hydro production from higher river flows is marginal. van Vliet *et al.* (2016) estimated a 5 to 10% *reduction* in usable hydropower capacity by 2050 compared to a 1971-2000 baseline, using 5 climate models and scenarios reaching approximately 2°C and 4°C global warming at the end of the century⁹ with both RCP2.6 and RCP8.5 concentration pathways. Overall evidence on future impacts is therefore mixed.

The impact of climate change on hydro output is very much dependent on future patterns of rainfall, temperature and humidity together with changes in the water catchment area. The studies reviewed demonstrate the differences in results from the use of both different climate scenarios and different hydrological models. Run-of-river schemes have at least a 25-year lifetime, with impoundment schemes having far longer lifetimes, so construction needs to consider future flow regimes, otherwise the installation can be locked in to sub optimal operation (BHA, 2020). Both winter increases in rainfall and summer droughts combine to have an overall effect on hydro output with the seasonal fluctuations in output affecting both operator and local network management.

One element missing from the studies reviewed is the impact of more extreme high and low flow

⁸ CNRM-CM3, ECHAM5/MPIOM and LMDZ4 climate models with the SRES B1 and A2 scenarios.

⁹ Based on five CMIP5 climate models in the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP), with projections with the RCP2.6 concentration pathway approximately consistent with 2°C global warming by 2100, and the central estimate of the CMIP5 projections with the RCP8.5 concentration pathway being in the upper part of the range of the CCRA3 scenario of approximately 4°C global warming at the end of the century.

events (or a series of such events) on the infrastructure itself. Extreme events can damage both run-of-river and impoundment schemes, damage which can go on to affect communities and the wider environment downstream. Abstracting water for hydro-generation during periods of low flow are usually restricted to prevent or mitigate damage to the aquatic environment caused by low flows through abstraction licencing. Droughts/hotter weather can pose risks to the embankments of reservoirs which are part of impoundment schemes (Atkins 2013b). Both high peak flows and the combination of climate related hazards such as high peak flows coupled with increased debris in the water causing blockages are likely to exacerbate the risk of infrastructure damage. This interacts with increases in vegetation associated with climate change and afforestation schemes planned to mitigate climate change. Climate hazards can also exacerbate existing vulnerabilities of infrastructure schemes, even though the failure mechanisms do not relate to climate change (Atkins, 2013b).

CCRA2 did not score the future level of risk or opportunity (unknown magnitude/unknown confidence). The evidence presented here through climate impact projections points to a mixed impact of climate change with several studies suggesting the possibility of either increases or decreases in total output by various times in the 21st Century. The potential outcomes include an overall reduction in hydro power output of 10% by 2050 (van Vliet *et al.*, 2016). Impoundment schemes have the greatest ability to benefit from increased winter flow and to absorb the impact of decreased summer flow (although this depends on reservoir capacity). Run-of-river schemes cannot absorb the impact of reduced summer flows but can benefit from increased winter flow with turbines designed to operate efficiently under that regime. No research has been found on the likelihood of future physical damage to infrastructure in high flows or floods. By extrapolation, it is also assumed that an increase in any extreme flows associated with intense periods of rainfall would increase the risks of equipment damage, particularly if combined with debris within the water flows. The magnitude of risk associated with extreme rainfall events which could lead to equipment damage and consequences downstream is unknown.

4.7.1.2.2. England (I6)

No specific studies on hydro output for England were identified.

4.7.1.2.3. Northern Ireland (I6)

No specific studies for Northern Ireland were identified.

4.7.1.2.4. Scotland (I6)

Duncan *et al.*, (2010) modelled the impact of climate change on flow duration curves of 6 catchment areas in Scotland using projected changes in rainfall in winter and summer in 2040-2050 on a pathway to 4°C global warming at the end of the century¹⁰. The results show an increase in rainfall and flow during January to April across all catchments modelled and a decrease in summer. While the study's chosen methodology limited the representation of peak flow, the results show a

¹⁰ UKCP09 Medium emission scenario

potentially far greater degree of change in the level of peak and higher flows compared to low flows. Duncan *et al.*, (2010) conclude that changes in peak winter flow and the return period of flood events raise questions about the suitability of existing spillways and weir designs. The authors suggest impoundment schemes could benefit from climate change, under the medium emission projection used, if they are able to increase their reservoir size or increase turbine capacity. Furthermore, benefits in increased mean flow could be realised if the turbine in place has been designed to operate efficiently under that flow regime.

Sample *et al.*, (2015) review current and future projections of hydropower resource in Scotland and summarise the current literature on climate impacts on hydropower more generally together with adaptation options. They conclude that run-of-river schemes are more vulnerable to climate change compared to impoundment schemes as they do not have the storage capacity to buffer seasonal changes, and that decreases in run-off during summer could be offset by increases during winter – but only if schemes are designed to operate at higher flow levels (Sample *et al.*, 2015). They suggest that decreases in summer run-off and consequent reductions in generation potential may partially be offset by increases in potential for winter generation, but most schemes would be unable to benefit due to design limitations.

4.7.1.2.5. Wales (16)

Carless and Whitehead (2013) assessed the impacts of climate change on a hypothetical scheme in Plynlimon, Wales using average temperature and precipitation data from the UKCP09 High Emissions scenario for the 2080s for comparison with the projected power outputs associated with historic river flow and climate data for the Plynlimon Flume catchment area from 1985-2008. They conclude reduced output during summer could be compensated for by increased output in winter as long as there is sufficient installed capacity to take advantage of this – leaving annual generation unchanged. However, the pattern of increased output in winter months and decreases in summer months has ramifications for local power network management. While the UKCP09 High Emissions scenario warms faster than a pathway to 4°C global warming by 2100 (see Chapter 2: Watkiss and Betts, 2021), some aspects of extreme weather including heavy precipitation are projected to be more severe at a given level of global warming in more recent projections (Johns, 2021) and hence we expect the broad conclusion to still be applicable to that pathway.

4.7.1.3 Lock-in and thresholds (16)

If schemes do not take into account future flow regimes, they could be locked-in to sub-optimal operation or severe damage during extreme flow events. Run-of-river schemes are designed to operate within a specified range of river flows, specific to the site's characteristics. Power will not be produced outside of these ranges and damage can occur during high flow events.

4.7.1.4. Cross-cutting risks and inter-dependencies (16)

The CCRA3 Interacting Risks project (WSP, 2020) did not include risks to hydroelectric generation in the systems maps and dependency model due to hydroelectric generation being a highly localised process.

Land use changes within the catchment area of hydro schemes as well as changes in water requirements for other uses such as agriculture affect river flow (Sample *et al.*, 2015). Changes in land use could include afforestation which would both reduce the rate of run-off as well as reduce the volume through increased evapotranspiration. Afforestation forms part of current strategies to mitigate climate change, with increases in the use of land for forests in place of grassland proposed (CCC, 2018b). Conversely, future land use changes which remove vegetation within a catchment area (e.g. increased urbanisation) could increase the rate of run-off further and exacerbate peak flow.

4.7.1.5 Implications of Net Zero (I6)

As electricity is decarbonised and other sectors increasingly become electrified, the provision of a reliable supply becomes ever more important to society and the economy. Large fluctuations in year to year or month to month generation from hydro schemes are likely to increase the challenges faced by local network operators in managing fluctuating renewable energy demand.

Neither the CCC's Net Zero scenarios (CCC, 2019a) nor the 6th Carbon Budget (CCC, 2020a) include growth in the installed capacity or output of hydro-electricity, however the 6th Carbon Budget does consider the use of further impoundment schemes with pumped storage to support electricity system flexibility (CCC, 2020b). Furthermore, changes in future costs and legislative incentives to decarbonise electricity – together with technology development – may change the economic viability of schemes currently thought to be feasible. Any climate impacts on pumped storage schemes that limit their ability to operate when required will restrict their ability to support grid flexibility and as a result the integration of renewable supplies with fluctuating outputs without wider system measures. Afforestation schemes could provide protective co-benefits to hydro schemes from high river flows if sited in relevant catchment areas, however they may also lead to an increase in the amount of woody debris entering the water following heavy rain or flooding.

4.7.1.6 Inequalities (I6)

Although hydroelectric power is primarily located in rural upland locations of the UK, the centralised nature of the electricity grid ensures that this does not lead to inequalities.

4.7.1.7 Magnitude scores (I6)

The present-day risk magnitude score for England, Scotland and Wales is judged as low due to a lack of evidence indicating an impact of climate change to date (Table 4.24). It is assessed as medium in the future for England, Scotland and Wales based on the reduction in output by 2050 projected by van Vliet *et al.* (2016) and the consequence of potential magnitude of foregone opportunities to the hydro power generators (based on the costs associated with a reduction in output in 2018). While the evidence presented is not in agreement on the overall impacts of 2°C global warming it does include a potential reduction in output of 5% by 2050 (van Vliet *et al.*, 2016) which could lead to £10's of millions of revenue losses (plus potential costs to the consumer, cf. I9). Secondly there are as yet no studies that evaluate the potential impacts of extreme high flows associated with either 2°C or 4°C global warming scenarios. The costs of replacing and repairing damaged equipment could

in principle be in the £10s of millions, which would be considered a medium magnitude. In combination, these reasons underpin the magnitude for England, Scotland and Wales for 2°C global warming by 2100 as medium with low confidence. The risk magnitude in Northern Ireland is deemed low because there are few major hydro power producers there (Table 4.24). Confidence is scored as low because existing studies provide diverging results and are largely based on older climate models and projections. In particular, there is a lack of studies that quantify the effects at 4°C global warming or capture the conditions leading to more extreme river flows.

Table 4.24 Magnitude scores for risks to hydroelectric generation from low or high river flows

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Northern Ireland	Low (Low confidence)	Low (Low confidence)	Low (Low confidence)	Low (Low confidence)	Low (Low confidence)
Scotland	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Wales	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)

4.7.2 The extent to which current adaptation will manage the risk (I6)

4.7.2.1. Effects of current adaptation policy and commitments on current and future risks (I6)

4.7.2.1.1 UK-wide

Current adaptation policies differ between existing and new schemes. New schemes that are subject to current Environmental Impact Assessment Regulations require an Environmental Statement that should include an assessment of their vulnerability to climate change. Schemes that fall under these regulations include:

- New hydro-electric schemes above 0.5MW, as well as smaller schemes in a sensitive area

- deemed likely by planning authorities to lead to potentially significant impacts,
- Dams and other installations designed for the holding back or permanent storage of water, where a new or additional amount of water held back or stored exceeds 10 million cubic metres; and smaller schemes if they are deemed likely to cause significant impacts.

It is not clear, however, how often a climate vulnerability assessment is carried out, or how. Smaller schemes in general would fall out of this mechanism. In terms of licensing arrangements, schemes' influence on flood risk are considered and if the scheme is in a flood risk area advice on future flood risk allowances are provided. Future developments in licensing arrangements may incorporate climate adaptation requirements.

For existing schemes, owners may consider upgrading equipment for commercial purposes if financially feasible or in response to safety concerns. Those schemes which are part of reservoirs above defined limits (25,000m³ in England and currently Scotland, 10,000m³ in Wales, Northern Ireland and in future Scotland) would fall under the inspection regimes set out under the Reservoirs Act 1975 as amended for England and Wales, the Reservoirs Act 1975 Scotland and Reservoirs Act (Northern Ireland) 2015. The inspection regimes do not currently take climate change into account. The regulatory authorities for reservoirs are the Environment Agency (England), Natural Resources for Wales, Scottish Environmental Protection Agency and Department of Agriculture and Rural Development (Northern Ireland). Mechanisms to evaluate the climate risk or adapt existing hydro schemes to more extreme flows and potential associated damage have not been identified to date.

4.7.2.2. Effects of non-government adaptation (I6)

Internationally, the need to make new hydro projects climate resilient is widely acknowledged and there is now a Hydropower Sector Climate Resilience Guide issued by the International Hydropower Association (IHA, 2019). This recognises the challenges of climate uncertainty, and recommends decision making under uncertainty approaches.

4.7.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I6)

It is not clear the extent to which appraisals of vulnerability of new hydro-electric schemes to climate change are being requested and/or how they are being carried out. While schemes in flood risk areas receive advice on this, other impacts of climate change may be missed. Mechanisms to evaluate the risks to or adapt existing hydro schemes to different flow regimes or more extreme flows and potential associated damage have not been identified to date. Therefore, future levels of risk are currently only partially managed.

4.7.2.4 Adaptation Scores (I6)

Table 4.25 Adaptation scores for risks to hydroelectric generation from low or high river flows			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

4.7.3 Benefits of further adaptation action in the next five years (I6)

4.7.3.1. Additional planned adaptation that would address the adaptation shortfall (I6)

For new schemes, ensuring climate impacts are considered in both site selection and design will enable owners to maximise the system outputs under future climate and minimise risks of damage as far as it is possible to protect from high end events. As highlighted above, guidance is available to help such assessments (IHA, 2019). For existing schemes, retrospective climate risk assessments can better inform operational planning and take action, if necessary, to protect assets and the downstream environment from harm during high water flows or flooding. For both run-of-river and impoundment schemes, UKCP18 consistent projections of river flow and catchment processes would be required to assess the implications of future flow patterns on their operation and revenues, and in particular to assess the risks of damage to hydro-electric power infrastructure from extreme high flow events, together with the implications of changing temperatures and the patterns of drought and rainfall on embankment safety.

For existing reservoir or impoundment-based hydroelectric schemes, the suitability of spillways to future peak flow should be ensured, updating probable maximum flow rates to include climate change (Duncan *et al.* 2010). For existing and future run-of-river schemes assessing their suitability under future low and peak flows is necessary, adaptations could involve incorporating a weir – however there are wider ecological implications of weirs, making this option unsuitable (Duncan *et al.* 2010). To increase hydro power output from existing run-of-river schemes during periods of increased winter flow, larger turbines can be installed (Sample *et al.* 2015), although Sample notes that increasing turbine size to take advantage of increased flows during winter would likely be at the expense of reducing further output during periods of low flow. For impoundment schemes to take advantage of higher winter rainfall, increases in reservoir sizes and or turbine capacity will be necessary (Duncan *et al.* 2010; Sample *et al.* 2015).

4.7.3.2. Indicative costs and benefits of additional adaptation (I6)

There is now considerable information on the technical adaptation options available for the hydro-electric generation sector, including sector specific guidance (IHA, 2019), albeit primarily focused on new builds. There are also many international studies that look at the costs and benefits of adaptation, for current plants and especially new build (e.g. Nassopoulos *et al.* 2012; Cervigni *et al.*, 2015; NRD, 2016).

There are also several studies that look at the potential economic costs of changes in rainfall and river flows, and thus hydroelectric generation at the European level, which include analysis of the UK (van Vliet *et al.* 2016; Tobin *et al.*, 2017; Després and Adamovic, 2020). These studies project increases in hydro generation output with climate change, but there are large differences between studies (and projections and scenarios) including some projections of reductions in output, and differences between storage and run-of-river. Consideration of different studies reveals the considerable uncertainty involved, and thus the need for both low and no-regret options and iterative adaptive management. For new plants (although these are not a major focus for the UK, even under net zero scenarios), decision making under uncertainty is key, and has been applied (see international studies above).

For existing plants there are a set of no-regret options for high flows, notably with weather and climate services, for both extreme events and early warning but also more general reservoir operation optimisation. There are also various engineering options for additional spillways, and measures such as fusegates which can be added, which are generally considered low-regret options for addressing high flow risks. There are more structural options to address changes in flood return period and peak intensity, but these tend to be much more expensive.

The large downside risks for hydropower revenues are from low flows during periods of drought, especially for run-of-the-river plants. Most adaptation studies focus on turbine upgrades (e.g. EBRD, 2015) which are more cost-effective than larger structural changes (dam heightening, conveyance structures), although there is usually some degree of trade-off (i.e. lower optimisation but greater flexibility for flow variation). Turbine upgrades also offer some potential to take account of upside risks.

There is greater potential for including all these adaptation measures in the design and construction of new projects, and decision scaling has been quite widely applied to take account of climate risks and plan adaptation at the international level for such assessments (e.g. Ray *et al.*, 2015; Karki *et al.* 2015), and is incorporated in the IHA guidance (2019). However, there is often a careful balance of costs and benefits of adaptation, because of the upfront costs, versus the benefits in terms of future (and thus discounted) benefit streams.

4.7.3.3 Overall urgency scores (16)

Table 4.26 Urgency scores for Risks to hydroelectric generation from low or high river flows				
	England	Northern Ireland	Scotland	Wales
Urgency score	Further Investigation	Watching brief	Further investigation	Further investigation
Confidence	Low	Low	Low	Low

Due to the Medium rating of future risk and the gaps in assessing and managing the vulnerability of

new and existing hydroelectric schemes to climate change, Further investigation is required for this risk in England, Scotland and Wales. The score for Northern Ireland is 'watching brief' due to the small number of hydro schemes in Northern Ireland, if future developments were to take place their vulnerability to climate impacts would need to be considered.

4.7.4 Looking ahead (I6)

Further information on the circumstances and related thresholds at which damage to hydroelectric schemes may occur is warranted, particularly for impoundment schemes. For new schemes assessments of future flow duration profiles which include climate impacts are needed to optimise their design. An understanding of how climate change may exacerbate other failure mechanisms is also necessary to inform both the design of new schemes and inspection and maintenance regimes of existing and future installations. Quantitative information would be particularly useful for decision makers.

4.8. Risks to subterranean and surface infrastructure from subsidence (I7)

Ground subsidence can occur due to shrinking and swelling of clay soils due to changes in soil water content and can also occur due to the collapse of pre-existing cavities in the ground (e.g. voids in soluble rocks and mine workings). Most subsidence is a result of shrinkage and swelling of high plasticity clays which are typically found in the south and east of England and notably around London. Damage to infrastructure often occurs as a direct result of interaction with vegetation and associated water content changes. This form of subsidence is regarded as the most damaging geohazard in Britain today by the British Geological Survey (BGS, 2018).

The majority of damage from subsidence occurs to residential and commercial property. However, transport and buried infrastructure is vulnerable to damage and disruption due to climate change-driven subsidence effects. Shrinkage and swelling of high plasticity earthworks disrupt rail track alignment leading to speed restrictions and disruption to service while repairs are carried out (Network Rail, 2018). Highway pavement can also be damaged, though this is considered a low risk due to more modern compaction methods being used in the construction of the highway network (Highways England, 2016). Buried electrical cables are sufficiently flexible to accommodate small movements due to shrink-swell subsidence and are usually located at depths where little movement occurs, hence these are considered to be at low to medium risk of damage (UK Power Networks, 2014). The potential for increased levels of leakages and burst frequency in water pipes due to shrink-swell damage has been identified by water supply companies (South East Water, 2015).

Where evidence is available, this indicates low current magnitude (e.g. £40m in costs due to subsidence in the period 2006–2016 (Network Rail, 2017a)), although it should be noted that quantitative evidence on costs is generally limited so this assessment is given with low confidence. Climate drivers suggest a potential increase in magnitude to medium, although no quantitative impact projections exist, therefore confidence in the risk scores is low. Insufficient evidence is

available to adequately differentiate between risks in the four countries of the UK. Although the risk of subsidence is well-understood, there is no systematic and comprehensive account of the amount of adaptation underway and how the risk is being reduced through these actions. Further investigation is needed to ascertain the extent to which current adaptation is managing risk.

4.8.1 Current and future level of risk (I7)

4.8.1.1. Current risk (I7)

Note: It has not been possible to split the evidence by UK country for this risk.

4.8.1.1.1. UK wide

CCRA2 (Dawson *et al.*, 2016) reported that deformation of the ground has the potential to damage the foundations of buildings and other infrastructure, with shrinking and swelling of clay soils due to excessive rainfall, drought or land use changes being one of the most widespread forms. This is a particular problem in London and the East of England. It was reported that over one-third (35%) of 132-400kV subterranean electricity cables and 12% of high-pressure natural gas pipelines in England are located in areas of high susceptibility to shrink-swell subsidence. Additionally, some surface infrastructure assets are also located in areas of high susceptibility, including 10% of clean water treatment works, 15% of small (<50m) telecommunication masts and 8% of high voltage (<400kV) electricity pylons. Over one-fifth (22%) of Category 1 rail lines, 29% of major train stations and 9% of the major road network are located in high susceptibility areas. Modern compaction methods ensure that the clay fill in highway embankments have a low permeability, which together with the road surfacing and effective drainage measures, mean that rainfall infiltration into road foundation soils is relatively low and hence shrink-swell is a comparatively lower risk. However, it should be noted that roads have been observed to be subject to apparent drought-related subsidence (Pritchard *et al.*, 2014).

Soil shrinkage during dry periods followed by swelling causes disruption to track alignment and road surfaces (Tang *et al.*, 2018; Markolf *et al.*, 2019). On railway lines this leads to periods where speed restrictions must be applied and increases maintenance costs. Network Rail reported £40m in costs due to subsidence in the period 2006–2016 (Network Rail, 2017a), and whilst subsidence was not one of the most frequent climate-related events, these events were amongst the highest in terms of costs per incident.

Roadways are less vulnerable but may experience some additional damage to pavement surfaces. The magnitude of surface movement is strongly influenced by the presence of deep-rooted, high-water-demand trees (Briggs *et al.*, 2016, Kamchoom and Leung, 2018). Magnitudes of shrink-swell can also be increased by changes in near surface permeability caused by the formation of desiccation cracking in warm weather (Dixon *et al.*, 2019). Nasr *et al.* (2019) also identified a risk to bridge foundations from shrink-swell action, though did not present cases where such damage had occurred.

The formation of sinkholes under road and rail infrastructure can be caused by prolonged or

extreme rainfall. Areas underlain by soluble rocks are most vulnerable where rapid dissolution can lead to the formation of new voids which can then collapse, leading to settlement at the surface. The collapse of poorly capped and filled mineshafts can exhibit the same effects. Indeed, many areas of the UK have a rich heritage of mining which can lead to collapse or subsidence of the overlying surface. For example, there are over 2,400 known abandoned mine workings in Northern Ireland, containing vertical shafts and horizontal adits extending underground to great distances.

Buried services are located close to the surface within the zone where wetting and drying effects are at their greatest, meaning they are also exposed to the shrink-swell effects impacting transport infrastructure listed above. Shrink-swell ground movement can cause damage to pipes and cables and disruption of services particularly where these are made from rigid materials or are poorly maintained. In 2011 a prolonged period of high temperatures and dry conditions in Houston, USA, saw the number of water main breaks increase by 250%, though high water demand was also believed to have played a part (Markolf *et al.*, 2019). Studies in the Netherlands have also identified patterns of increased frequency of water pipe failure during periods of drought (Wols *et al.*, 2018).

4.8.1.2. Future Risk (I7)

4.8.1.2.1. UK-wide

CCRA2 reported that no data were available on future risks from subsidence. The British Geological Survey have since projected an increased risk of shrink-swell subsidence in high plasticity soils in the South East of England due to moisture content changes which has the potential to impact road and rail corridors (BGS, 2018). This study used a scenario at the upper end of the range defined as the CCRA3 pathway to 4°C global warming at the end of the century¹¹. Asset owners have reported subsidence as a risk in climate adaptation plans. It can be assumed that railway track and road surfaces, buried pipelines of water, electricity mains and gas supplies are likely to be impacted by climate change. Ground movement/subsidence, shrinkage and heave of high plasticity soils are expected to be exacerbated by projected increases in drought conditions and periods of prolonged heavy rainfall (Tang *et al.*, 2017; Markolf *et al.*, 2019). Dixon *et al.*, (2019) demonstrated changes in seasonal permeability of a number of UK infrastructure cuttings and embankments and concluded that increased summer drying would lead to additional desiccation cracking and higher permeabilities. This in turn would lead to shrink-swell effects permeating deeper into the soil. Development of sinkholes after periods of prolonged rainfall, local flooding and erosion are also anticipated to be causes of damage.

Insufficient evidence is available to adequately differentiate between risks in the four countries of the UK. However, it has been noted that a knowledge and research gap exists around the potential impact of climate change on soils, landslips and subsidence in areas which have been mined, particularly in Wales.

¹¹ The 50th percentile of the UKCP18 probabilistic UK projections with RCP8.5 emissions. The 50th percentile of the UKCP18 global projections reaches 4.2°C warming at 2070-2099 with RCP8.5 emissions. See Chapter 2 (Watkiss and Betts, 2021) for further details.

4.8.1.3 Lock-in and thresholds (I7)

The buried and surface infrastructure exposed to subsidence risk have long operational lifetimes, so consideration of this risk for correct construction and maintenance is essential. The quality of evidence available indicates that there are presently no easily defined thresholds.

4.8.1.4 Cross-cutting risks and inter-dependencies (I7)

Buried services are frequently co-located beneath or alongside transport corridors. In the context of climate change this geographic interconnectedness could result in a variety of failure modes (Markolf *et al.*, 2019). For example, extreme drought could lead to shrink-swell around a water pipe leading to fracture, in turn leading to local flooding and erosion of subsoil, potentially forming a sinkhole affecting nearby roads. Soil shrinkage during dry periods followed by swelling causes disruption to track alignment and road surfaces. On railway lines this may lead to increased periods where speed restrictions must be applied and increase maintenance costs.

The CCRA3 interacting risks project (WSP, 2020) identified the impacts which have the greatest number of downstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). Impacts to earthworks and pipe movements had four downstream connections identified and are starting points for cascading risks related to transport. For example, a reduction in summer rainfall could lead to soil desiccation in the natural environment, then earthworks and pipe movement and subsequently impact transport through failures and delays. However, the project did not define these interactions as being significant in 2020 or 2080 (i.e. contributing to the overall level of risk).

4.8.1.5 Implications of Net Zero (I7)

Increased tree planting (e.g. on embankments) may increase shrink-swell risk (Briggs *et al.*, 2016). It can also be expected that rail travel will be of greater importance in a Net Zero future and hence the level of disruption caused by shrinking and swelling soils under rail lines, particularly in the densely populated south-east of England, would increase with higher volumes of rail traffic.

4.8.1.6 Inequalities (I7)

Damage due to shrinking and swelling related subsidence is more likely in the south and east of England and around London. Other parts of the UK are less likely to be impacted due to lower incidence of high plasticity clay soils. Void collapse related subsidence is related to the presence of soluble rocks and abandoned mine workings. Collapse of cavities created by the dissolution of soluble rocks is rare. The majority of soluble rocks in the UK occur within England. Abandoned mine workings are concentrated in the midlands, North East England, South Wales and southern Scotland.

4.8.1.7 Magnitude scores (I7)

Where evidence is available, this indicates low current magnitude (e.g. £40m in costs due to subsidence in the period 2006–2016 (Network Rail, 2017a)), although it should be noted that

quantitative evidence on costs is generally limited so this assessment is given with low confidence (Table 4.27). Climate drivers suggest a potential increase in magnitude to medium, although no quantitative impact projections exist therefore confidence in the risk scores is low. Insufficient evidence is available to adequately differentiate between risks in the four countries of the UK.

Table 4.27 Magnitude scores for risks to subterranean and surface infrastructure from subsidence

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Northern Ireland	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Scotland	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Wales	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)

4.8.2 The extent to which current adaptation will manage the risk (I7)

4.8.2.1. Effects of current adaptation policy and commitments on current and future risks (I7)

4.8.2.1.1 UK-wide

Limited information is available to assess the extent to which current adaptation will manage this risk in the four current National Adaptation Programmes covering the UK. This might be a result of the ‘watching brief’ urgency score given to the risk across the UK in CCRA2. Some general actions are included that are relevant to managing subsidence, such as raising awareness of the risks to infrastructure networks from climate impacts.

4.8.2.2 Effects of non-governmental adaptation (I7)

It was stated in CCRA2 that ‘Infrastructure operators understand this risk well and there are established processes in place to monitor the risk and manage assets accordingly’. Subsidence risks

are widely recognised in the infrastructure asset owner community. For example, this risk is handled within Network Rail’s Earthworks Technical Strategy covering Great Britain (Network Rail, 2018). Furthermore, transportation infrastructure asset owners are actively engaging with academic researchers regarding geotechnical risks. Utilities companies have collaborated with the UK Geospatial commission to establish a national underground asset register (NUAR) which may prove useful in identifying utilities located in shrink-swell susceptible soils. However there remain gaps in understanding the level of the risk at the national level.

4.8.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I7)

Although the risk of subsidence is well-understood, there is no systematic and comprehensive account of the amount of adaptation underway and how the risk is being reduced through these actions. As there is no evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

4.8.2.4 Adaptation Scores (I7)

Table 4.28 Adaptation scores risks to subterranean and surface infrastructure from subsidence			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

4.8.3 Benefits of further adaptation action in the next five years (I7)

4.8.3.1 Additional planned adaptation that would address the adaptation shortfall (I7)

More research is needed for the production of more accurate and consistent data, for investigating the interdependencies of infrastructure and understanding potential adaptation strategies (mainly limited to monitoring at present). The heterogeneity of railway earthworks is a challenge to understanding their future behaviour. More detailed information on sub-surface composition would assist in predicting future behaviour but would be costly to achieve. Quantifying the uncertainty in soil properties would be beneficial.

Removal of trees from railway embankments has been shown to reduce shrink-swell movement, though this comes at a cost of reducing the reinforcement effect of tree roots and increases in pore water pressure leading to loss of stability (Briggs *et al.*, 2016). Increased ground and weather monitoring and the use of real-time decision support tools has been proposed as a potential method to mitigate the risks of shrink-swell.

4.8.3.2 Indicative costs and benefits of additional adaptation (I7)

Land subsidence tends to be a slowly progressing threat, which can reduce the incentives for early

action (Erkens and Stouthamer, 2020). As a result, most information is on repair costs, i.e. after subsidence has occurred (especially for residential and commercial properties). As highlighted above, there are some potential risks for rail tracks (but lower risks for highway pavements) as well as potentially some risks to buried infrastructure. There are some low-regret options, e.g. increased monitoring in higher risk areas, as well as vegetation control, but there appears to be little information on the costs and benefits for future climate risks.

4.8.3.3 Overall urgency scores (17)

Further Investigation scores have been assigned to each of the four UK countries (low confidence). There is a need to concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the likely range of future climate scenarios (2–4°C, and across the 10-90th percentile uncertainty range within each scenario) or whether more action is needed to achieve this.

Table 4.29 Urgency scores for risks to subterranean and surface infrastructure from subsidence				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further Investigation	Further Investigation	Further Investigation	Further Investigation
Confidence	Low	Low	Low	Low

4.8.4 Looking ahead (17)

The railway network in the South East of England is particularly exposed to this risk and the costs associated with subsidence are disproportionately high. Therefore, this is a risk that may become increasingly important as the trend towards wetter winters and hotter, drier summers continues.

4.9. Risks to public water supplies from reduced water availability (18)

The UK faces an increased demand for water in a changing climate. Analysis commissioned for CCRA3, and consistent with other studies, indicates that the UK as a whole currently has a supply/demand surplus of 950 Ml/day. However, without adaptation and under a central population scenario, a deficit across the UK of between around 1220 and 2900 Ml/day (for the range between 2°C to 4°C global warming) is projected by the late 21st century, equating to the daily water usage of around 8.3 to 19.7 million people (based on the present day average per capita consumption of 140 l/h/d). Without adaptation, all water resource regions in England and parts of Wales are projected to be in deficit under a central population scenario with 4°C global warming by the late 21st century. Adaptation efforts in the sector are advancing, driven by 5-yearly Water Resource Management Plans which take an outlook of at least 25 years. These currently demonstrate a commitment to a number of ambitious targets to reduce leakage, reduce per-capita consumption and outline a range of options to improve resilience via new water supply infrastructure.

Evidence from the CCRA projections of future water availability (HR Wallingford, 2020) suggests that current and announced adaptation will manage risk in Northern Ireland, Scotland and Wales. In England, the current and announced adaptation scenario is less successful in reducing the magnitude of deficits to a low magnitude in the late 21st century. Current action should be sustained in Northern Ireland, Scotland and Wales. More action is needed in England. The Environment Agency's recent National Framework (2020c) provides direction on what this action may involve.

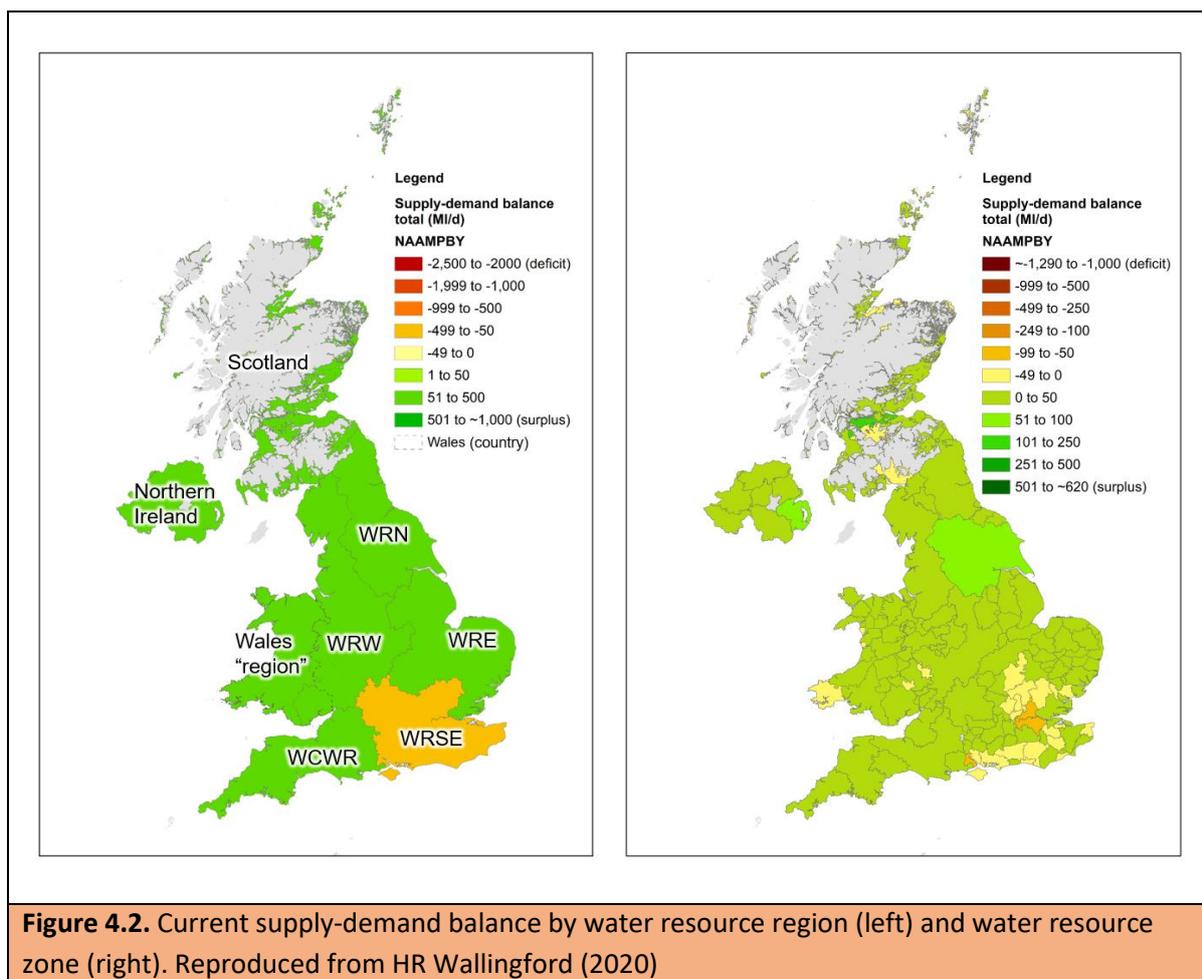
4.9.1 Current and future level of risk (I8)

4.9.1.1. Current risk (I8)

4.9.1.1.1. UK-wide (I8)

CCRA2 (Dawson *et al.*, 2016) reported a (then current) overall supply/demand surplus of around 2,000 Ml/day across the UK. Modest deficits in water resource zones (mainly in some parts of southern England) were identified, although these deficits were all lower than the target headroom (the minimum buffer that companies should plan to maintain between supply and demand in order to cater for current and future uncertainties). These results have since been superseded by the future water availability analysis conducted for CCRA3 (HR Wallingford, 2020) which gives an overall current supply/demand surplus of around 950 Ml/day for the UK as a whole. The reduced surplus compared with CCRA2 is attributed to changes in the way water companies in England and Wales account for climate change in the 2019 Water Resource Management Plans; companies were required to incorporate climate change in Deployable Output, including an allowance for historical impacts. It should be noted that the HR Wallingford assessment of present-day risk is based on water company draft baseline plans for WRMP19, as at the time of completing the CCRA3 analysis the final plans had not been approved.

Although the vast majority of water resource zones (the standard spatial unit of water supply evaluation in England and Wales) currently operate a surplus, around 16.7 million people live in water resource zones that are nominally in deficit (7.89 million people in London) (Thames Water, 2019; HR Wallingford, 2020). This indicates that there are a minority of water resource zones where the 1 in 200-year drought resilience level of service is yet to be reached based on draft baseline plans (although it should be noted that WRMPs ensure that this level of service will be reached within the next 5-10 years). Analysis also aggregates supply-demand deficit at a regional level (South East, East, West Country, West, North, Wales, Scotland, and Northern Ireland), with the South East the only region with a present-day (nominal) deficit (HR Wallingford, 2020). However, the regionalisation assumes that water can be readily shared between water resource zones within the regions, which in reality varies in feasibility across the country (for example, in Scotland and parts of Wales this can be prohibitively expensive). Present day supply-demand balances at the regional and water resource zone levels of aggregation are given in Figure 4.2. It must be noted that regionalisation can obscure hotspots in regions that are otherwise at surplus.



HR Wallingford (2020) state that the projected present-day deficits often reflect recent sustainability reductions or climate change impacts to which companies have yet to adapt, as all water companies have to produce a positive supply-demand balance as part of their WRMPs. In reality, this means that a water company may not currently meet its specified target levels of service and drought resilience (noting that specified levels of service vary between companies). It is stated that water companies may already be attempting to obtain other sources of water through new supply schemes or transfers and/or are taking advantage of reductions in demand in other areas such as power plant closures. This suggests that some of the projected present-day deficit in the HR Wallingford (2020) projections may be the result of the discrepancy between the data used in the analysis and the data used in final water company plans. However, Thames Water (2019) identified an immediate and increasing supply-demand deficit in the London Zone, in their final WRMP (2019).

A review of recent scientific evidence for past changes in UK water availability shows that there has been no robust, formal attribution of observed changes (to date) in any component of the UK water environment to anthropogenic climate change (Garner *et al.*, 2017 – see also Chapter 1: Slingo, 2021). The review also found, however, comprehensive evidence for observed changes in precipitation and river flows.

Further complexity derives from risks to key assets in the sector. Water is often stored in reservoirs, which are vulnerable to high water flows and increased temperatures due to their implications for

bank integrity. This was previously highlighted in CCRA2 and further reinforced by the incident at Whaley Bridge earlier in 2019, (see case study, section 4.15: although not related to public water supply) which demonstrated that high levels of rainfall can be a contributing factor to spillway failure. The vulnerability of reservoirs largely depends on their construction method, which in the UK normally includes earthfill embankments and non-erodible structures such as concrete or masonry. Earth banked construction methods are vulnerable to erosion from rainfall, whereas concrete surfaces are vulnerable to conditions causing cracking or joint movement (Atkins, 2013). Overflow structures and spillways may also be vulnerable due to increasing frequency and size of flows and catchment impacts that might increase debris and vegetation. Auxiliary structures such as valves or draw off towers may be vulnerable to similar effects and can be prone to other factors such as siltation or heat induced expansion.

4.9.1.2. Future risk (18)

The updated projections of future water availability for the UK produced for CCRA3 (HR Wallingford, 2020) provide analysis for the potential impact of climate change at a number of different scales of spatial aggregation and for a variety of population and adaptation scenarios. These water availability projections for the UK are the first of their kind to use the UKCP18 Climate Projections. Population scenarios, developed by Cambridge Econometrics (2019), are used at the water resources zone, regional and country scales, flow scenarios from Future Flows and UKCP18 global projections are used, along with demand modelling developed for Water UK (Artesia). A summary of the projections is given below.

4.9.1.2.1 Mid-century supply-demand balance

4.9.1.2.1.1 UK-wide

HR Wallingford (2020) assessed mid-century supply-demand balance under a central population projection scenario with no additional adaptation for pathways to approximately 2°C and 4°C global warming in the late 21st Century¹². These were termed “2°C world” and “4°C world” in that study. Under these assumptions the UK faces a supply-demand balance deficit of between 650 and 920 Ml/d (equating to the daily water usage of around 4.4–6.2 million people for 2°C and 4°C global warming respectively). It is projected that three of the eight regions in the UK will be in deficit by mid-century. The increase in demand from a rising population places additional pressure on water resources even when the impact of climate change is relatively low. When simulating future balances using a high population scenario, a UK-wide supply-demand balance deficit is evident. In the mid-century, population scenario is the key determinant of supply-demand balance, with the difference in impact between the low and high population projections around 3,220 Ml/d day at a

¹² The HR Wallingford (2020) method defined the 2°C and 4°C pathways as the global warming levels (GWLs) reached late century (2070-2099) at the 50th percentiles of the UKCP18 probabilistic projections with the RCP2.6 and RCP8.5: 1.8°C and 4.2°C respectively. The former is near the centre of the lower CCRA3 scenario, and the latter is on the upper bound of the CCRA3 higher scenario (see Chapter 2: Watkiss and Betts, 2021). Late-century regional climate states were taken from the UKCP18 perturbed-parameter ensemble (PPE) of global 60km projections at those GWLs. Mid-century climate states were taken from the 60km PPE at the GWLs reached with RCP2.6 and RCP85 50th percentiles in 2040-2069. See HR Wallingford (2020) for details.

national scale. The projected impact of climate change on the supply-demand balance at the UK scale is around 10% of the range of the potential projected impact of population growth. However, while the difference between supply-demand balances for 2°C and 4°C worlds under the central population scenario is relatively small at 270 MI/d, this is nearly 30% of the current supply-demand balance surplus. It should be noted that the regionalisation of results assumes that water can be readily shared between water resource zones within each region.

4.9.1.2.1.2 England and Wales

Figure 4.3 indicates deficits in regions of England and the south east region of Wales by mid-century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action. Water Resources South East, Water Resources West and Water Resources East are all projected to have deficits under both scenarios. Figure 4.4 shows the supply-demand balance for the more granular water resource zone scale, which shows deficits in zones within the Wales Region, in addition to the regions of England identified above.

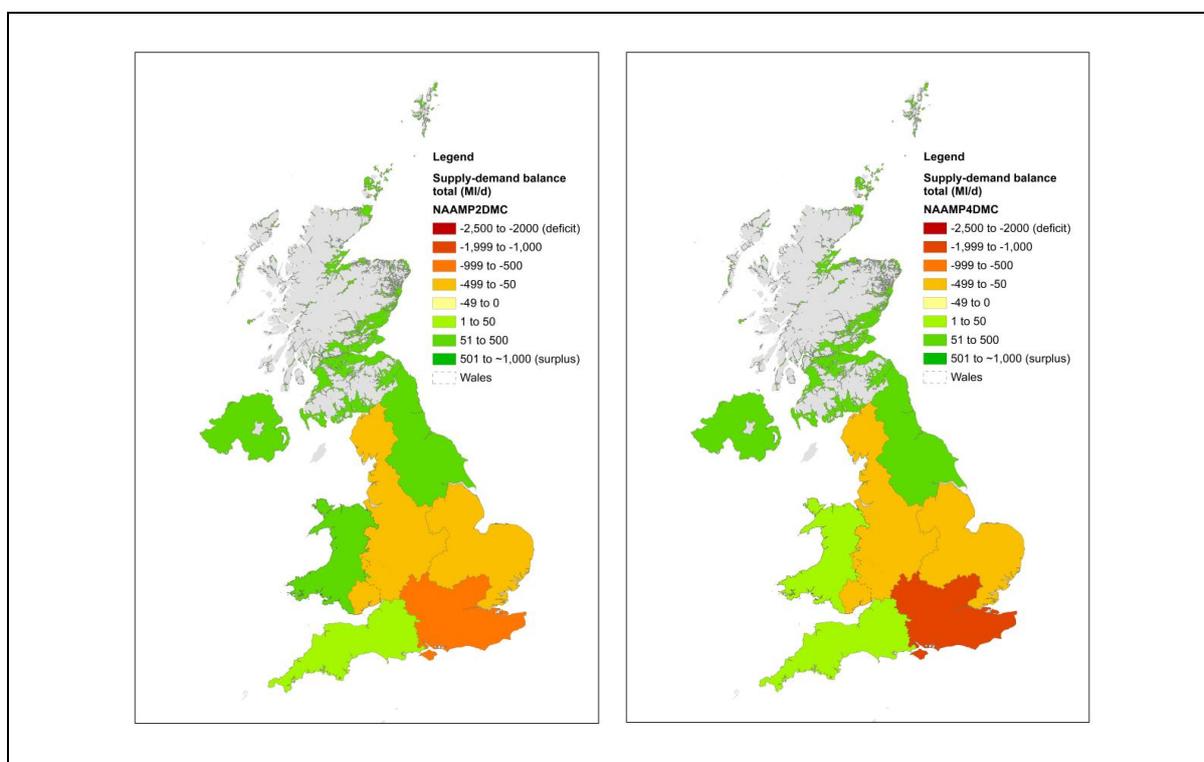
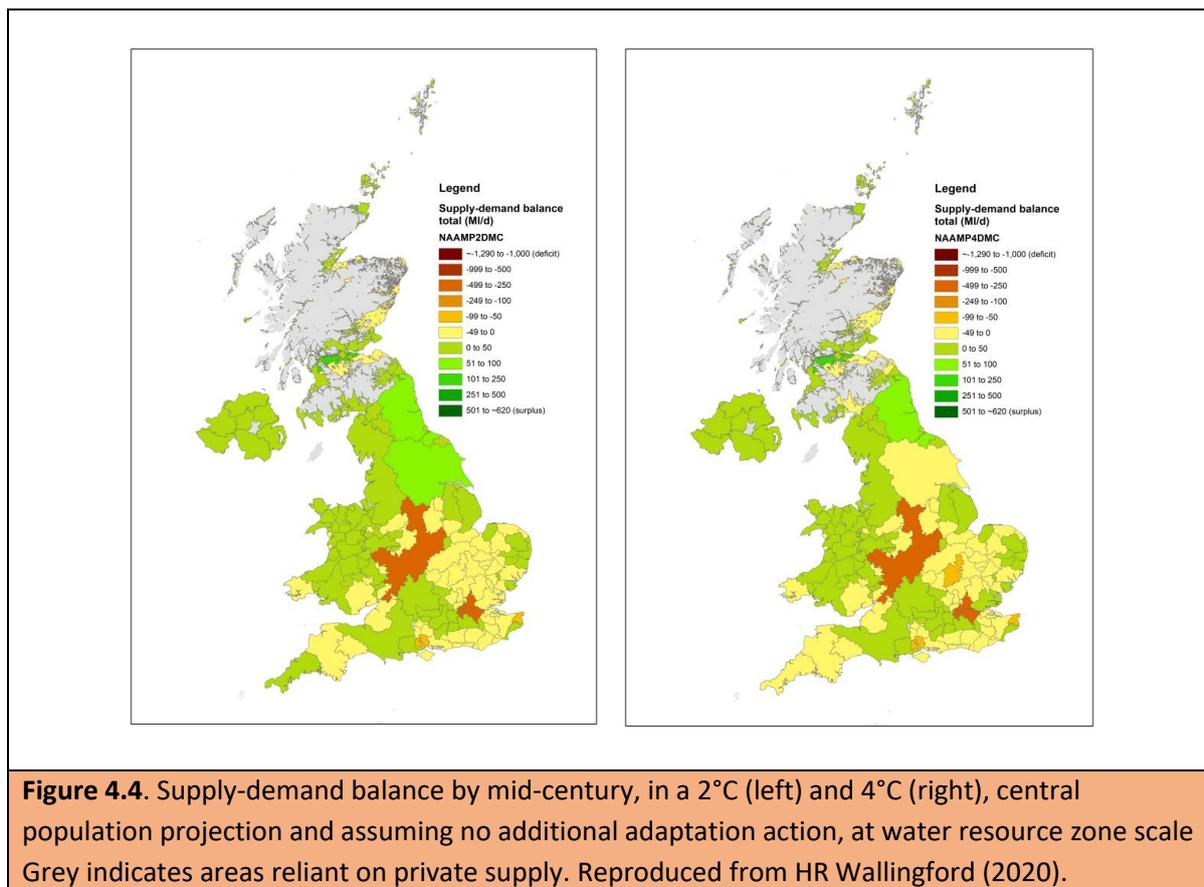


Figure 4.3. Supply-demand balance by mid-century, in a 2°C (left) and 4°C (right) world, central population projection and assuming no additional adaptation action, at water resource region scale. Grey indicates areas reliant on private supply. Reproduced from HR Wallingford (2020).

4.9.1.2.1.3 Northern Ireland

All water resource zones in Northern Ireland remain in supply-demand surplus in the mid-21st century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action. Surpluses are also projected in all water resource zones (Figure 4.4).



4.9.1.2.1.4 Scotland

Scotland has an overall supply-demand balance surplus by mid-century under the central population scenario and for both 2°C and 4°C worlds (Figure 4.3). However, some water resource zones in Scotland are in supply-demand deficit by the mid-century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action (Figure 4.4). Scotland has 191 water resource zones and large areas of the country have no public water supplies, only private ones.

4.9.1.2.2. Late-century supply-demand balance

4.9.1.2.2.1 UK-wide

Under a central population scenario with no additional adaptation, a deficit across the UK of between around 1220 and 2900 MI/d (2°C and 4°C worlds) is projected by the late century, equating to daily water usage of around 8.3 to 19.7 million people (based on the present day average per capita consumption of 140 l/h/d). The central population scenario is taken from the CCRA3 socio-economic scenarios developed by Cambridge Economics (2019), based on ONS 'principal projection scenario', which assumes demographic patterns in future such as fertility, mortality and migration trends remain the same as current trends. Indeed, the Environment Agency (2020c) highlights the relative importance of population change when compared to climate change with the former contributing to the deficit significantly more (notwithstanding measures to increase drought

resilience).

4.9.1.2.2.2 England and Wales

Figure 4.5 indicates deficits in regions of England and the south east of Wales by the late 21st century in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action. Notably, in a 4°C world, all water resource regions in England are in deficit (as well as part of South East Wales). Figure 4.6 shows the supply-demand balance for the more granular water resource zone scale.

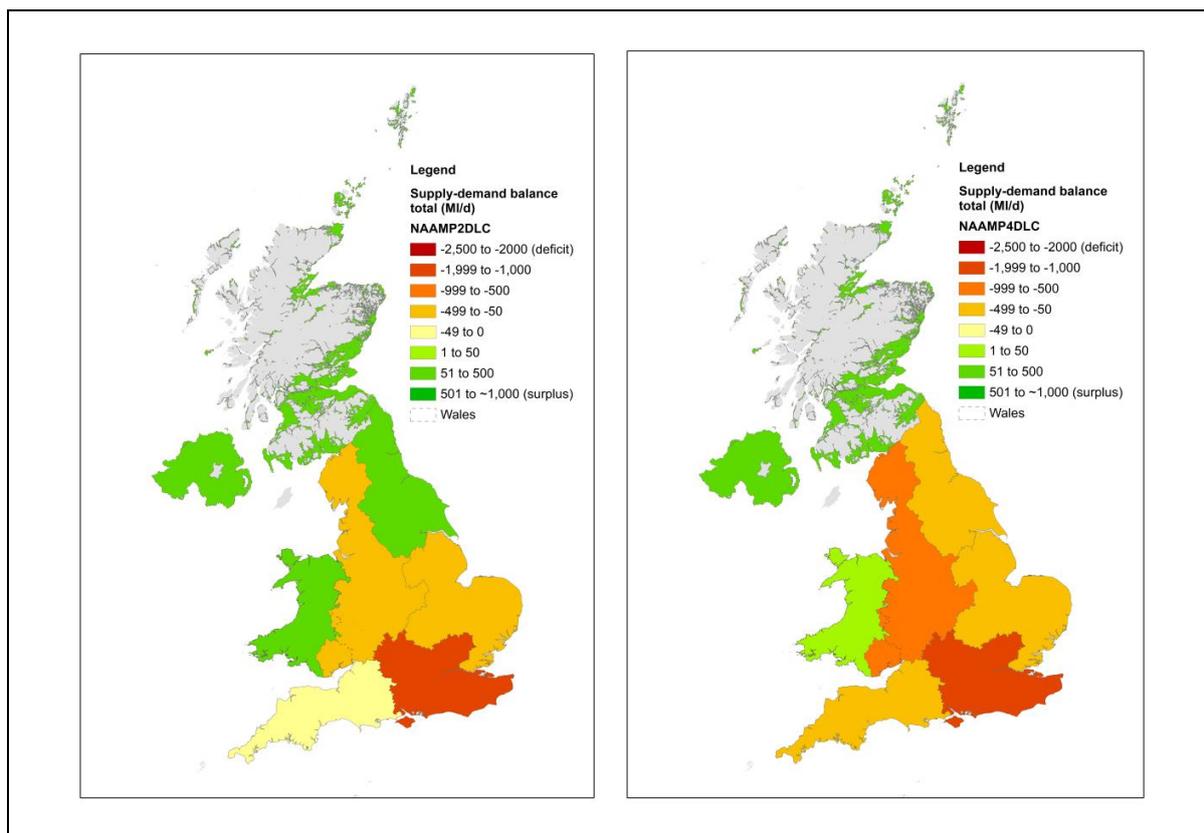


Figure 4.5. Supply-demand balance in the late 21st century, in a 2°C (left) and 4°C (right) world, central population projection and assuming no additional adaptation action, at the water resource region scale. Grey indicates areas reliant on private supply. Reproduced from HR Wallingford (2020).

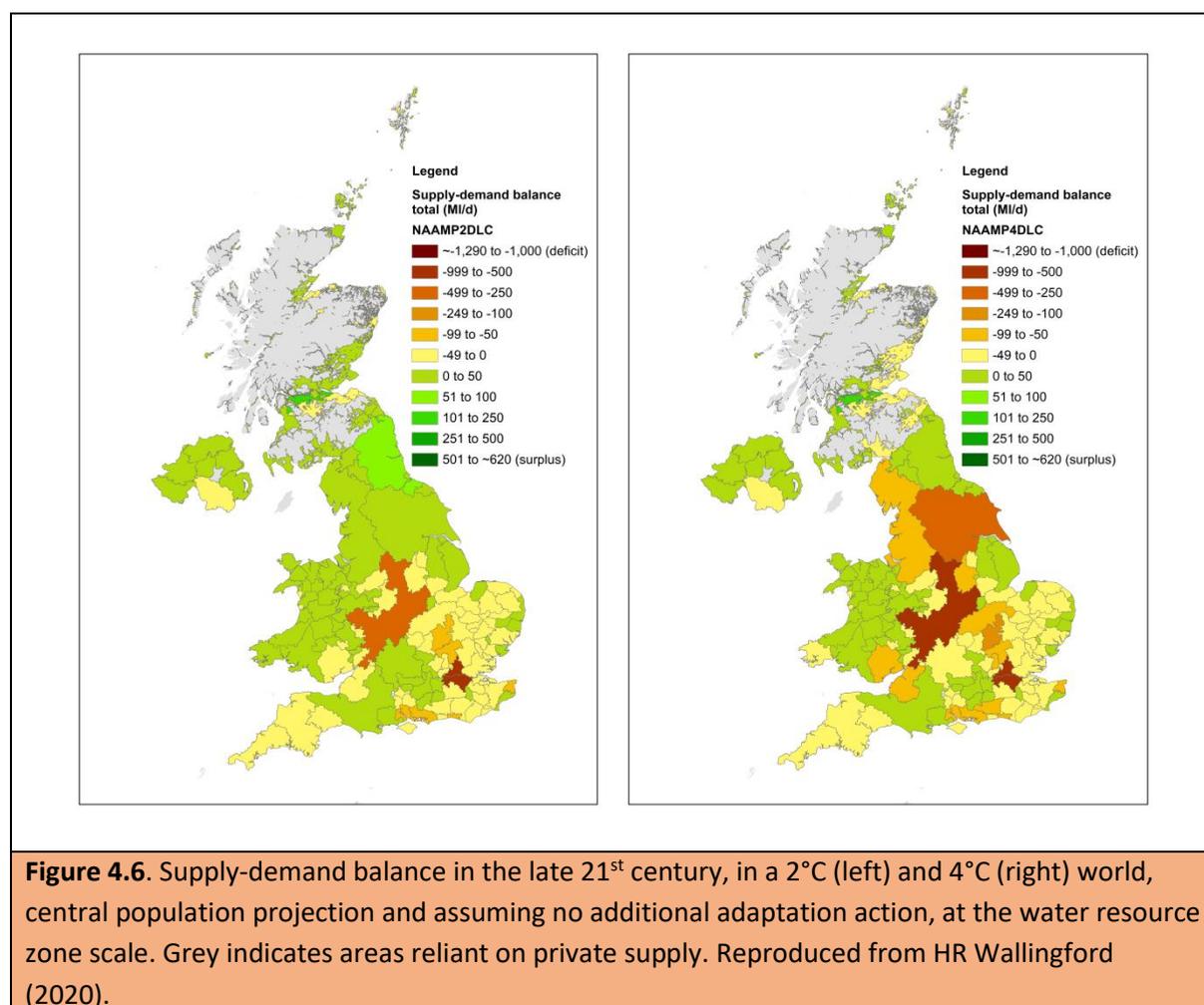
The NIC proposal to increase water supply resilience in England to withstand a 1 in 500-year drought has recently been accepted by the Government, meaning the next round of water company plans due in 2024 will have to plan to deliver resilience to these events. This also applies to the area of Water Resources West in Wales. This was informed by the NIC’s (2018b) report on preparing for a drier future. In this, the NIC demonstrated that, at the time of analysis, a severe drought (0.5% annual probability) would result in an additional shortage of between 600 and 800 MI/day, rising to between 800 and 1000 MI/day for an extreme drought (0.2% annual probability). The report compared the costs of proactive, long-term resilience versus relying on emergency responses beyond current resilience levels. It was found that providing proactive, long-term resilience was cost

effective (costing between £18 billion and £21 billion) compared with relying on emergency responses (between £25 billion and £40 billion).

Building on previous work by Water UK (2016), the Environment Agency produced their National Framework for Water Resources (Environment Agency, 2020c). The work focuses on the regional requirements for the five regional water resources groups to meet future demand. Analysis using the WRMP19 plans demonstrate that if no action is taken between 2025 and 2050 around 3,435 MI/d) extra capacity would be needed in England by 2050, and 5,500 to 6,000 MI/d by 2100 (again, assuming no further action). It must be noted that this analysis is based on older UKCP09 projections, with water companies using a variety of approaches in their WRMPs.

4.9.1.2.2.3 Northern Ireland

Northern Ireland has an overall supply-demand balance surplus by the late-century under the central population scenario and for both 2°C and 4°C worlds. One water resource zone in Northern Ireland is projected to have a supply-demand deficit in the late 21st century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action (Figure 4.6).



4.9.1.2.2.4 Scotland

Scotland has an overall supply-demand balance surplus by late-century under the central population scenario and for both 2°C and 4°C worlds (Figure 4.5). However, Figure 4.6 shows that a number of water resource zones in Scotland will be in deficit by the late 21st century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action.

In a low likelihood, high impact, scenario (4°C global warming reached more rapidly than the CCRA3 higher scenario¹³) with high population and no additional adaptation actions, all regions of the UK are projected to be in supply-demand balance deficit by late-century.

The relative contribution of climate change to changes in public water supply is mediated by changes in water demand, land use change and water resource management (Water UK, 2016; Hutchins *et al.*, 2018). Changes in demand for water include changes in both population size and per capita consumption, economic growth and the demand profile of the future economy together with associated abstraction licences, and the success of measures to reduce leakage (Water UK, 2016). Changes in land use can alter the rate and pace of run off as well as groundwater recharge and the environmental quality of water bodies from which water can sustainably be extracted (Hall *et al.*, 2019b). Furthermore, different water resource planning methods (such as those based around bulk water balance calculations or on system simulation modelling) can inform how resources are managed in the context of these changes (Hall *et al.*, 2019b). In addition to the multiple factors influencing future public water supplies, the relative impacts are likely to vary across the UK due to variations in population density, topography, geology, the profile of economic activity, patterns of rainfall, and the water system (with some being more resilient to perturbations than others).

4.9.1.3. Lock-in and thresholds (18)

The challenge remains the reliable supply to regions where a deficit is projected. Addressing this may require larger investment in areas of low rainfall, or strategic water infrastructure, such as for cross-regional transfers, all of which would have a long lead time to plan, finance and build, thus there are some early lock-in risks if early studies and plans are not implemented. Similarly, implementing transfers without sufficient long-term modelling and planning could lead the region from which water is being transferred to experience a deficit. It will likely require innovation that may become redundant over time with population shifts or have significantly increased energy requirements/risk of cascade failures (e.g. desalination plants – currently only one large plant in the UK).

Strategic water infrastructure, such as cross-regional transfers or new reservoirs, takes a long time to plan and organise; leaving such approaches too late could lead to implications for household water interruptions that could be avoided.

¹³ The UKCP18 60km global projections with a climate model with high climate sensitivity driven with a range of greenhouse gas concentration pathway arising from RCP8.5 emissions and accounting for uncertainties in carbon cycle feedbacks (Murphy *et al.* 2018)

4.9.1.4 Cross-cutting risks and inter-dependencies (I8)

The risk of reduced water availability for public water supply interacts with risks to energy generation which is covered in Risk I9 (Risks to energy generation from reduced water availability). The implications of supply interruptions from reduced water availability as they pertain to public health and wellbeing are covered in Chapter 5: Kovats and Brisley, 2021 (Risk H10: Risks to water quality and household water supplies).

Yawson *et al.* (2019) assessed variations in potential groundwater recharge from spring barley crop fields in the fourteen UK administrative regions for 30-year periods centred on the 2030s, 2040s and 2050s using UKCP09 low, medium and high scenarios, with the medium scenario corresponding to a pathway to 4°C global warming by 2100. Agriculture covers the largest share of UK land use, with cereals accounting for the largest share of cultivated crops. Crop fields contribute to potential recharge. Groundwater is an important water resource in the UK – groundwater crucially supports public water supply, agricultural and industrial water uses, especially in central, eastern and southern England where water stresses during summer are a major concern. For all emissions scenarios, time slices and regions, the largest reduction and increase in potential groundwater recharge over baseline values were 38% and 41%, respectively. Northern Ireland, Northwest Scotland, Southwest Scotland, and Wales will have large increases in potential recharge from spring barley crop fields, while Eastern England, East Midlands, Northeast England, Southeast England, West Midlands and Yorkshire and the Humber would have the largest reductions in potential recharge. The study did not consider changes in soil management practices which can influence the spatial and temporal magnitude of potential recharge. Groundwater depletion could interact with declines in river flows to negatively affect overall public water supply in the UK. As groundwater is an important water resource in summer, a reduction in groundwater recharge could combine with hotter and drier summers to significantly impact public water supply under climate change.

This risk also interacts with risks to aquatic ecology, and risks to agriculture and other licenced abstractions (e.g. summer abstraction for agricultural irrigation and cooling water required for power stations) from reduced water availability which may compete with public water supplies for a finite resource. In 2019, the industry committed itself to achieving Net Zero carbon emissions by 2030 (Water UK, 2019) and Scottish Water (2019) are working towards becoming a Net Zero emissions business by 2040, five years ahead of the Scottish Government's 2045 target. Details of the potential changes to the industry (and any resulting changes to exposure and vulnerability to climate risk) are not clear as yet. Current work is focussing on baselining existing activities and sharing best practice. Supply options such as desalination and potable reuse are likely to increase the energy intensity of water supply compared to current baseline, due to the energy requirements of treatment. Inter-basin transfers that involve additional pumping compared to current supply may also increase energy consumption in the water sector.

WSP (2020) suggested that many climate impacts are affected by a high number of risks further up a chain of interactions. This is the case for water supply which was found to be the recipient of risk flows from interacting pathways. Most of these pathways are due to impacts on infrastructure (such as power supply failure, IT and communications disruption, and sewage flooding) leading to water supply issues. However, some causes are from the natural and built environment – for example

competing demands for water with the natural environment, drought, impacts on water quality and increased water demand due to heatwaves and very hot days. Water supply interruptions can have a subsequent impact on health and welfare (Risk H10, Chapter 5: Kovats and Brisley, 2021). The project assessed the most significant interactions relating to water supply disruptions and found that the overall risk of these interactions (based on magnitude and likelihood) are rated as low in 2020 but increase to medium by 2080. These interactions are as follows:

- Power infrastructure flooding leading to a disruption in power supply and subsequent disruptions to water supply. For example, in the 2015/16 winter floods, 350,000 people had their water supply interrupted for 17 days (costing £18/household/day).
- River, surface and groundwater flooding leading to an increase in run-off and debris causing a reduction in water quality, subsequently disrupting water supply.
- In addition, in 2050 and 2080 under a scenario of 5°C warming by 2100, the impact from increased severity of drought results in water supply disruption directly. Indirectly, an increase in the probability of drought combined with an increase in mean summer temperatures leads to soil condition and quality impacts, resulting in reduced water quality, and in turn leads to water supply disruption.
- Slope or embankment failures leading to reservoir failures and impacts on water supply. In 2018, ~1,500 people in northwest England were asked to evacuate Whalley Bridge over concerns that the dam wall of a reservoir could burst following days of heavy rain (see Case Study).

Significant interdependencies exist across the non-public water supply sectors reviewed as part of Defra (2020c). There may be unexpected water demand consequences of meeting the most ambitious decarbonisation strategies noting that locational decisions of energy companies may have a major influence on how each catchment is affected.

4.9.1.5 Implications of Net Zero (I8)

Water is an energy intensive industry, accounting for approximately 6% of industrial sector energy consumption in 2019 (BEIS, 2020c), and therefore there are potential impacts on the industry from the Net Zero commitment, especially as climate change and population growth will increase water demand. Current work is focussing on baselining existing activities and sharing best practice. Supply options such as desalination and potable reuse are likely to increase the energy intensity of water supply compared to current baseline, due to the energy requirements of treatment. Inter-basin transfers that involve additional pumping compared to current supply may also increase energy consumption in the water sector. It is possible that more efficient achievement of net zero will occur through the water sector procuring net zero or net negative energy via the power sector rather than seeking to achieve local or scheme level net zero for Water Resource Zones or individual major projects.

4.9.1.6 Inequalities (I8)

Regionalisation can lead to inequalities with plentiful rainfall in wetter upland areas and the increasingly drier South East. The challenge remains to ensure reliable and sufficient supply across all

regions. Any knock-on impacts to drinking water availability may disproportionately affect protected characteristics groups who require more water and those unable to afford any associated increases in cost.

4.9.1.17 Magnitude scores (I8)

The magnitude scores given in Table 4.30 are based on the current and projected supply-demand balances given in the CCRA3 projections of future water availability (HR Wallingford, 2020) for the central population and 'no additional adaptation' scenario. The scores take into consideration deficits at both the water resources region and water resource zone level. HR Wallingford state (2020) that the assumption that deficits at the water resource zone can be resolved via intra-region transfers may be prohibitively expensive to achieve in practice and restricted by topography (particularly in Scotland and Wales). The water resource regions of Northern Ireland and Scotland have a current supply-demand surplus and have projected surpluses under all population and climate scenarios. Several water resource zones in Scotland are projected to be in deficit by the mid-century under both climate scenarios, with the score moving from low to medium. Surpluses are projected in all water resource zones in Northern Ireland in the mid-century, but the southern water resource zone of Northern Ireland is projected to be in deficit in both scenarios by the late century, hence the score moves from low to medium in the 2080s.

Table 4.30 Magnitude scores for risks to Public Water Supplies from reduced water availability					
Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium (medium confidence)	High (medium confidence)	High (medium confidence)	High (medium confidence)	High (medium confidence)
Northern Ireland	Low (medium confidence)	Low (medium confidence)	Low (medium confidence)	Medium (low confidence)	Medium (low confidence)
Scotland	Low (medium confidence)	Medium (low confidence)	Medium (low confidence)	Medium (low confidence)	Medium (low confidence)
Wales	Low (medium confidence)	Medium (medium confidence)	Medium (medium confidence)	Medium (medium confidence)	Medium (medium confidence)

England has a nominal present-day supply-demand deficit in the South East water resource region

and has been scored as medium magnitude due to the population exposed in this region. Deficits at the water resource region scale increase under all climate scenarios, with the 2080s and 4°C world seeing all regions in England at deficit. All water resource regions in Wales have a present-day supply-demand surplus, hence the low magnitude score. Supply-demand deficits are apparent in the southeast of Wales under all future scenarios, although the majority remains in surplus (medium magnitude). Confidence is given as medium where the magnitude score is based on projections for the water resource region (concordant with the CCRA3 future water availability assessment), and low where based on water resource zones, given the uncertainty around the feasibility of intra-region transfers.

4.9.2 The extent to which current adaptation will manage the risk (I8)

4.9.2.1. Effects of current adaptation policy and commitments on current and future risks (I8)

4.9.2.1.1 Legislation (UK)

Water supply is regulated under the Water Industry Act 1991 (as amended) and the Water Resources Act 1991 (as amended – England and Wales), the Water Resources (Scotland) Act 2013, and the Water and Sewerage Services (Northern Ireland) Order 2006. The Water Act 2014 introduced a ‘resilience duty’ that requires Ofwat and the Secretary of State/Welsh Ministers to secure the long-term resilience of water company supply systems and ensure that water companies take steps for the purpose of enabling them to meet, in the long term, the need for the supply of water. Water companies already plan for droughts as part of their Business Plans, and the Water Act also includes an additional power for the Secretary of State/Welsh Ministers to direct water companies to plan for droughts of a specified magnitude.

4.9.2.1.2 UK-wide adaptation for mid-century projected deficits (demand-side adaptation)

Figure 4.7 shows a selection of the adaptation scenarios that were simulated for the mid-century time period at the UK scale presented in the CCRA3 projections of future water availability (HR Wallingford, 2020). The deployable output and water available for use under the baseline, 2°C and 4°C worlds is given on the left-hand side in dark and light blue. The demand under a variety of demand-side adaptation and population scenarios is given on the right-hand side (the components of this demand such as household and non-household demand are also given). The water available for use in a 2°C and 4°C world is represented by horizontal blue dotted lines. If demand on the right-hand-side of the graph is below these lines this represents a surplus at the national scale.

The current and announced demand-side adaptation scenario, which has been designed to reflect current levels of policy ambition in the water sector, sees a projected surplus at the national scale in the mid-century period under both 2°C and 4°C worlds with a central population estimate. Under a high population scenario, the planned adaptation scenario does not go quite far enough to balance projected deficits due to climate change. The influence of additional demand-side adaptation actions over and above what is planned, through reducing leakage and per capita consumption, are evident when comparing the scenarios that use the central and high population projections.

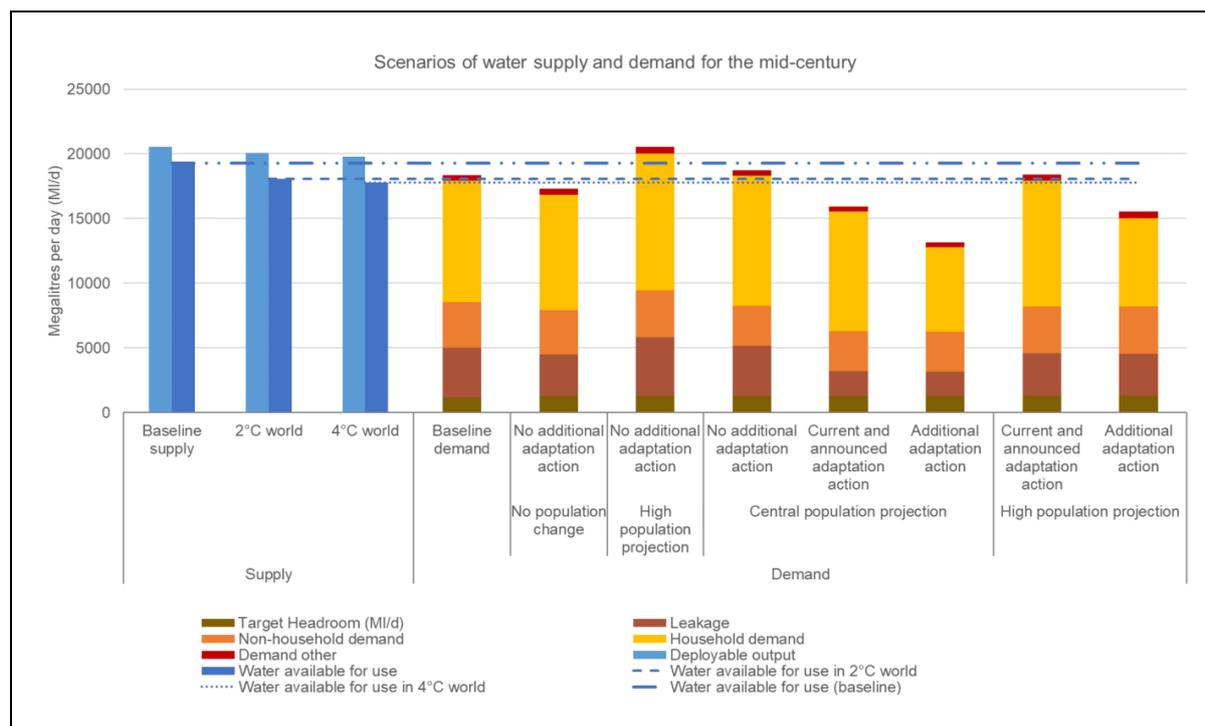


Figure 4.7. Scenarios of UK water supply and demand in the mid-century for different climate, adaptation and population scenarios. Only demand-side adaptation actions are included in the scenarios above. Reproduced from HR Wallingford (2020).

Figure 4.8 shows the projected supply-demand balances at the water resource region scale by mid-century under a central population scenario. The left-hand map presents balances for a 2°C world with current and announced demand-side adaptation actions, the middle map shows a 4°C world with current and announced demand-side adaptation, and the right hand map shows a 4°C world under the ‘additional adaptation’ (demand-side) scenario. The current and announced demand-side adaptation actions are projected to result in surpluses for all regions in a 2°C, central population world, but would result in a deficit for Water Resources South East in a 4°C, central population world. The ‘additional adaptation’ scenario would result in surpluses for all regions at the mid-century.

4.9.2.1.3 UK-wide adaptation for late-century projected deficits (demand-side adaptation)

Figure 4.9 shows scenarios for the late-century time period at the UK scale presented in the CCRA3 projections of future water availability (HR Wallingford, 2020). Here, the current and announced adaptation scenarios use the per capita consumption values in the latest water company resource plans up to 2044/45 and then remain the same for the rest of the century. Average per capita consumption is projected to be around 122 l/h/d (England ~120 l/h/d; Wales ~105 l/h/d; Scotland ~156 l/h/d and Northern Ireland ~152 l/h/d) by mid-century. These figures are based on the water companies’ final plans in England and Wales (which include companies' ambitions for reducing per capita consumption). As final plans were unavailable for Scottish Water and Northern Ireland Water and no intention to significantly increase meter penetration across households to reduce household consumption has been reported, baseline plan values were used (leading to higher per capita consumption compared to England and Wales. In the analysis, leakage was reduced to 50% of

baseline values by the mid-century were then fixed to the end of the century across all regions.

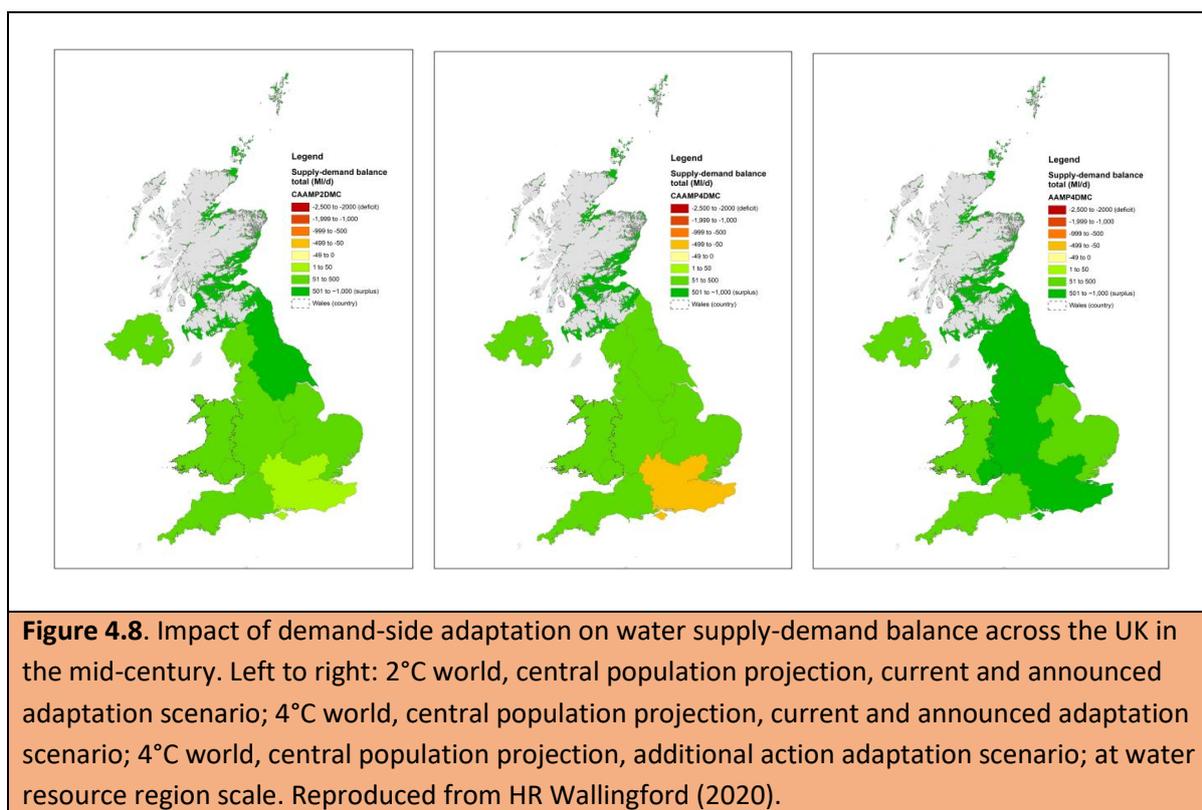


Figure 4.9 shows that for 2°C and 4°C worlds under a central population scenario, current and announced demand-side adaptation actions are projected to result in a supply-demand surplus in the late 21st century. Under a high population scenario, the current and planned scenario is not enough to manage the projected deficits and only the additional action scenario (i.e. a more ambitious level of demand-side adaptation than is currently planned), results in a UK-wide supply-demand balance surplus by late-century (both 2°C and 4°C worlds).

Figure 4.10 shows supply-demand balance for different water resource regions around the UK in the late-century, in a 2°C (left hand map) and 4°C (right hand map) world, under a central population projection and with the current and announced demand-side adaptation action scenario. For the 2°C world, current and announced demand-side adaptation results in a deficit for the Water Resources South East region. The deficit for this region is of the order of 310 MI/d (the supply for a little more than 2.1 million people every day based on present day levels of UK water consumption). For a 4°C world, the South East is in deficit by nearly 750 MI/day. In addition, Water Resources West has a projected deficit of 180 MI/d, with Water Resources East at 15 MI/d. It is estimated that by the late century, the projected impact of climate change on the supply-demand balance for the UK is around 40% of the potential impact of population growth. Deficits are also projected in the southeast of Wales. It should be noted that at a country scale, only England has projected deficits due to climate change under this scenario.

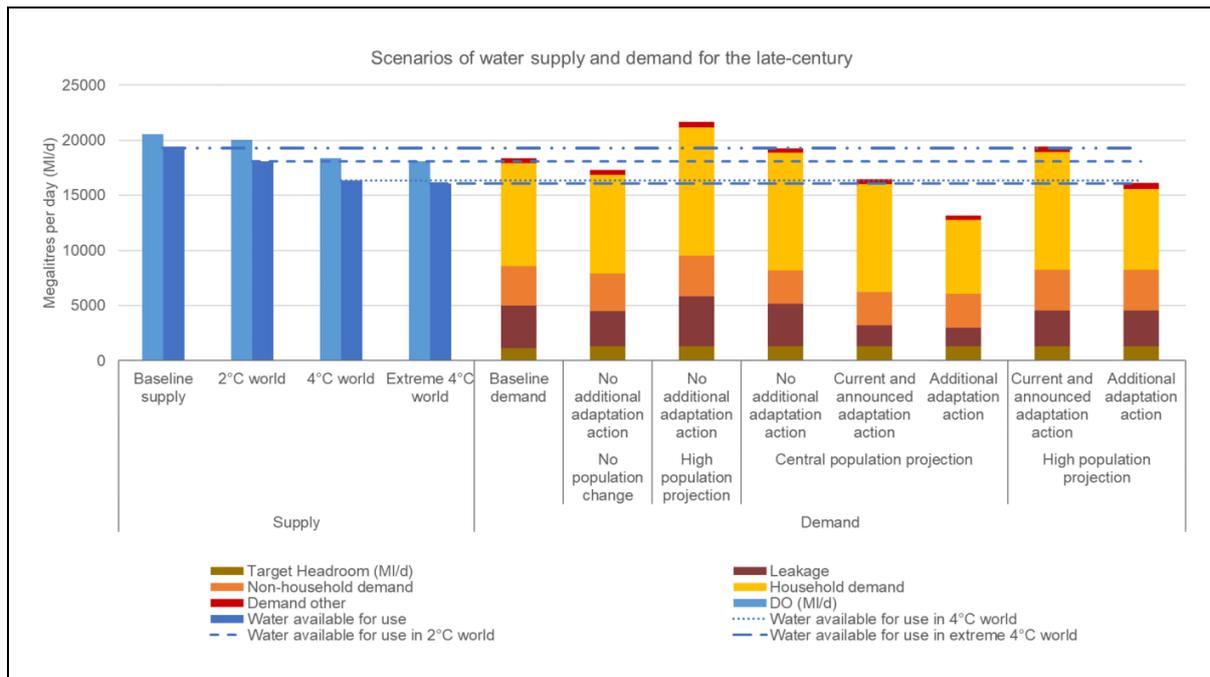


Figure 4.9. Scenarios of UK water supply and demand by late-century for combinations of climate, adaptation and population scenarios. Only demand-side adaptation actions are included in the scenarios above. Reproduced from HR Wallingford (2020).

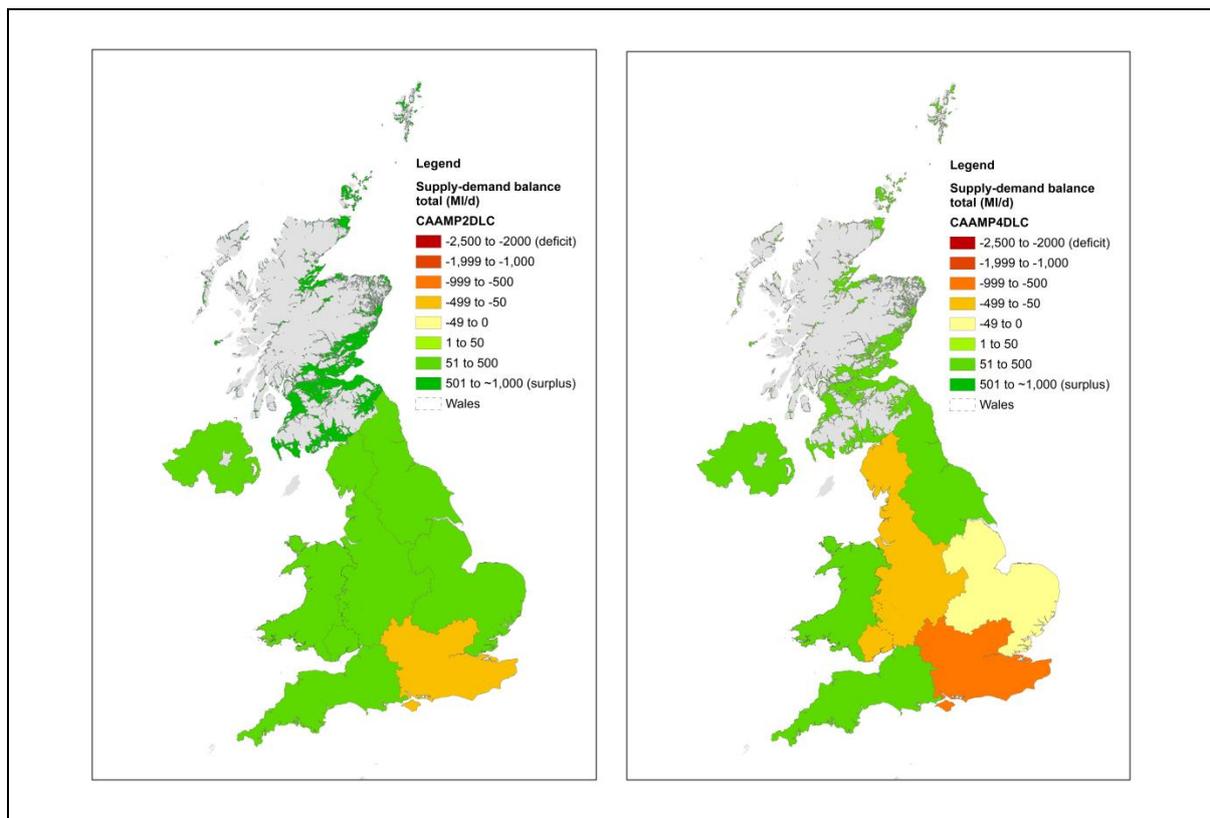


Figure 4.10. Supply-demand balance in the late 21st century, in a 2°C (left) and 4°C (right) world, central population projection and current and announced adaptation action scenario, at water resource region scale. Grey indicates Wales areas reliant on private supply. Reproduced from HR Wallingford (2020).

England shows the largest range in supply-demand balance. HR Wallingford (2020), state that this is most likely due to the fact that more sources are yield-constrained in England and therefore cannot provide any more water than they currently do without exceeding environmental protection measures. In addition, the greater application of sustainability reductions in England compared to the other countries increases dependency on the remaining abstractions, meaning any change in river flows as a result of climate change will impact upon the deployable output of these sources.

It must be noted that Wales and Northern Ireland water resource plans model climate change impacts to the 2030s and 2020s respectively. It is highlighted in the HR Wallingford (2020) report on water resources that this may not be far enough into the future to identify thresholds at which yield may become the dominant factor on resource availability, and that this relative lack of climate sensitivity permeates through the CCRA3 water resources assessment. It is argued that this lack of climate sensitivity may be genuine, although could be due to the water companies not projecting far enough into the future to identify tipping points in the systems' resilience.

4.9.2.1.4 Supply-side adaptation

The CCRA3 water resources project (HR Wallingford, 2020) also modelled the potential impact of water supply-side adaptation options and inter-regional transfers on future supply-demand balances. The analysis utilised the preferred supply options identified by water companies in the draft WRMP19 plans available at the time of the analysis. These total around 940 MI/d planned for by water companies in England and Wales. 430 MI/d of water in transfers between regions were also identified. These were applied to the mid- and late-century periods in the analysis.

By applying the identified additional water to use to the supply-demand balance scenarios for England and Wales and assuming no additional demand-side adaptation, the preferred supply-side measures or transfers, when utilised in isolation, were projected to not be sufficient in reducing the supply-demand balance deficit in Water Resources South East, Water Resources East or Water Resources West, across the majority of the scenarios in the mid- or late-century.

When taking demand side and supply-side adaptation measures together, HR Wallingford report surpluses in England apart from a minor deficit in Water Resources West by late century in a 4°C world. When inter-regional transfers are included, the deficit in Water Resources West increases. It is assumed in this analysis that Water Resources West and Water Resources South East are linked by a large potential transfer option, from the River Severn to the River Thames. It is however, pointed out that the identified supply-side adaptation options may not be cost-effective solutions, particularly in regions such as the South East.

4.9.2.1.5 Combined impact of increased drought resilience and supply and demand options

HR Wallingford (2020) modelled the effect of moving to a 1 in 500-year level of resilience to drought and the associated deployable output cost for water resource regions in England (including Water Resources West which supplies parts of South East Wales – Figure 4.11). All preferred supply-side adaptation options (but not inter-regional transfers) are utilised, along with current and announced demand-side options. It is clear that moving to a 1 in 500-year level of resilience creates significant

reductions in deployable output at the regional level, particularly for Water Resources South East. As the analysis is at the water resource region scale, it is unclear whether the nominal deficits would affect the Welsh part of Water Resources West.

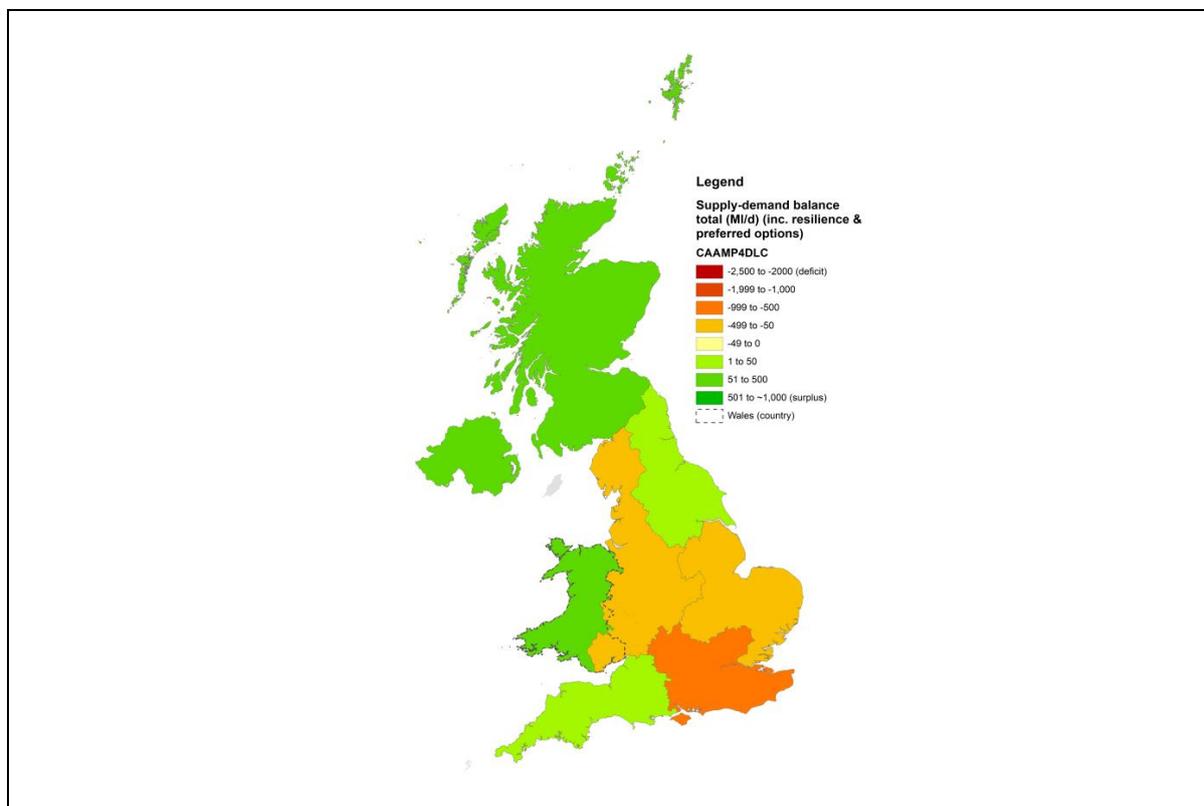


Figure 4.11. Supply-demand balance in the late 21st century, in a 4°C world, central population projection under a current and announced adaptation scenario for water demand and assuming all preferred supply-side options (excluding interregional transfers) are implemented. Drought resilience in England is moved to a 1 in 500-year level. Water resource region scale

4.9.2.1.6 Policy in England and Wales

Regulators use the WRMPs to assess the measures companies need to undertake to manage the risk of supply-demand deficits. Water companies are required to prepare WRMPs every five years. These set out how water companies plan to balance water supply and demand over the next 25 years, taking into account the effects of climate change as well as other factors such as population growth and reductions in abstraction required to improve the ecological condition of rivers and lakes. Water companies also submit their business plans to the economic regulator as part of a five-yearly process known as a Periodic or Price Review. Price reviews set the price, service and incentive package for a five-year period. They set out the allowed revenues, expected levels of service and the set of financial and reputational incentives for each company.

CCC (2019b) scores the English water industry’s adaptation plans as ‘high’ stating that the WRMPs set out how water companies have committed to more ambitious targets to reduce leakage and many have considered possible options for new water supply infrastructure and improving resilience to extreme weather. Progress in managing the risk is scored as ‘medium’, stating that after large

reductions in leakage during the 1990s, there has been slower progress. Nonetheless water companies are expected to deliver a 15% minimum reduction in leakage by 2025 (Ofwat, 2019) and have committed to halving leakage by 2050.

The Environment Agency's recent National Framework (2020c) sets out England's water needs to 2050. The aim of the framework is to ensure that the best strategic solutions are taken for the country as a whole, as it is acknowledged that this may not be achieved through individual water company plans. Regional plans by groups such as Water Resources East and Water Resources South East will be prepared based on this framework by September 2023. The document sets out that a total of 3.4 billion additional litres (3,400 MI) will be needed between 2025 and 2050. The framework lays out measures for meeting this figure including reducing demand to an average of 110 litres per person per day by 2050, improving water efficiency across all sectors, working with water companies to halve leakage rates by 2050, developing new supplies such as reservoirs, water re-use schemes and desalination plants, making it easier to move water through regional water transfers, and reducing the use of drought measures that can impact the environment. The government has committed to set an ambitious personal water consumption target for England in the 25 Year Environment Plan (Defra, 2020).

4.9.2.1.7 Wales

In Wales, the 2019 climate change adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b) and the Welsh Government's Water Strategy for Wales set out high level strategies and plans for the water sector. RBMPs and WRMPs provide an overall indication of water supply and demand based on UKCP09. However, the next round of WRMPs will be based on UKCP18. Four areas of concern related to climate change in terms of demand and supply are North Eryri/Ynys Mon in North Wales, the SEWCUS area in South Wales covering Cardiff, Newport and the Valleys, Tywyn Aberdyfi in West Wales, and Pembrokeshire. Two water deficit zones have also been identified using climate projections. Current intervention in the Welsh Government's adaptation plan is not specific to water supplies but supports management of this risk through the development of ecological resilience at a water catchment level.

In its 2019 Annual Report, the National Infrastructure Commission for Wales (2019) recognises the risk to water supply for the UK as a whole but notes the particular issue for Wales of the potential future need to transfer water supply to England. It also recognised the demand challenges found in growing urban centres. This is further mirrored in policy 1 of *Future Wales: National Plan 2040* (Welsh Government, 2021a).

4.9.2.1.8 Northern Ireland

The Water and Sewerage Services Act (NI) 2016 requires the preparation and review of a Water Resource and Supply Resilience Plan (WR&SR Plan), which takes into account adaptation measures in response to climate change predictions to calculate supply/demand balance for the water supply. At a regional level in Northern Ireland, in 2014 the Northern Ireland Executive approved the development of a Strategic Drainage Infrastructure Plan (SDIP) for Belfast, an outcome of a consultation on 'Living with water in Belfast'.

Northern Ireland Water (NI Water) has a legislative requirement to produce a Water Resource Management Plan (WRMP) and a Drought Plan as part of its forward planning process. These two plans have been combined into the WR&SR Plan. The WR&SR Plan shows how the company will manage and develop water resources to make sure there is enough water to meet future supply needs. The WR&SR Plan takes into account changes in population, housing and water usage, and incorporates predicted changes to the climate. This includes how water supplies would be maintained during critical periods such as severe winters and droughts, and also includes a drought plan. Northern Ireland has a long-term sustainable water strategy. NI Water recommends revisiting the plan using UKCP18 climate change projections to provide an improved understanding of future hydrological conditions in Northern Ireland.

4.9.2.1.8 Scotland

In Scotland, SEPA's Water Supply and Wastewater Sector plan (2019) has the high-level aims to:

- inspire and enable communities and businesses to take action to prevent water being wasted and to use it more efficiently,
- make low water use designs, including designs involving the use of recycled waters and rainwater, the norm for new developments,
- ensure opportunities to reduce leakage are taken when buildings are being refurbished or other infrastructure is being maintained or renewed,
- enable Scottish Water to find new ways of efficiently detecting and fixing leaks, targeting areas where the ability to meet demand for drinking water is threatened by climate change and population growth or where opportunities to reduce energy and chemical use are greatest.

4.9.2.2 Non-government adaptation (18)

Water companies are investing to improve resilience, but it is not clear if this investment will be adequate to address future risks, particularly in the context of a 4°C global temperature scenario. This is because although the planned level of adaptation can be modelled as shown above, adaptation measures are not funded more than five years ahead. Indeed, there is uncertainty whether the current scenarios are sufficient to cover future risks, although as WRMPs are revised on a five-yearly basis, there is a framework within which future risks will be mitigated. There is uncertainty regarding future funding, which is subject to the Price Review process.

Ofwat (2020) sets out spending for water companies over the subsequent five years. Several of the features of the latest round have implications for resilience and adaptation, with allowances for resilience schemes, metering and new supply options. English and Welsh companies and competitively appointed providers are allowed to invest £2.6 billion in protecting customers and the environment from the risks of extreme weather conditions (such as drought and floods) and critical asset failures. Companies also plan to invest £650 million in the installation of at least 2 million new water meters over the 2020-25 period (smart meter installations should also provide more insight into consumer demands and help identify leaks). Up to £469 million has been allocated to help

companies work together on solving long-term drought resilience challenges, through measures such as reservoirs and the national transfers of water from the northwest to the southeast of England. This will be overseen by Ofwat, in collaboration with the Environment Agency and the Drinking Water Inspectorate, via RAPID, the Regulatory Alliance for Progressing Infrastructure Development. RAPID has been formed to help accelerate the development of new water infrastructure and design future regulatory frameworks, working with water companies to promote the development of national water resources infrastructure that is in the best interests of customers and the environment. Thus, RAPID will help to meet the challenges articulated in documents such as the WRLTPF (Water UK, 2016).

Separate evidence from the National Infrastructure Commission (2018b) found that ‘maintaining the current levels of resilience (to the worst historic drought) in the face of rising population, environmental and climate pressures to 2050, would require additional capacity of about 2,700-3,000 MI/day in England. An additional shortage of between 600 and 800 MI/day would result from a severe drought (0.5% annual probability), and between 800 and 1,000 MI/day in an extreme drought (0.2% annual probability). The ranges reflect uncertainty about the impact of changes in population and climate, but the overall additional capacity required is between 3,500 and 4,000 MI/day.’ Additional capacity of 4,000 MI/day should provide resilience to an extreme drought until 2050 even with high climate change and population growth, with most of it likely to be needed by the 2030s. Much of this additional capacity would still be needed even assuming medium climate and low population growth. In any case, the full 4,000 MI/day is likely to be needed within a few decades of 2050 so can be considered ‘low regret’. This figure is around 20% of baseline (2019) deployable output in the CCRA3 water resources analysis (HR Wallingford, 2020), demonstrating the considerable scale of the challenge. For climate projections, the study uses: ‘Central: medium emissions Future Flows, average water balance scenario, Dry: medium emissions Future Flows, with less water in the South East’. For socio-economic scenarios, ‘Population growth: Low: ONS 2014-based low migration population projection, High: ONS 2014-based high fertility population projection’ scenarios are used. However, an initial analysis of the 2019 draft WRMPs by CCC (2019b) shows that around 1,200MI/d will be delivered through new infrastructure, roughly in line with the NIC’s recommendation.

Hutchins *et al.* (2018) assess how water resources in the Thames river basin will be affected by three future climate and planning scenarios for the 2030s and 2080s. The two most extreme scenarios (based on RCP8.5 and related socio-economic assumptions) could not be supported by current management strategies to meet water demand. To satisfy these scenarios, transfer of river water from outside the Thames river basin would be necessary. The authors conclude that the projected climatic changes under the most extreme RCP (8.5) might result in drying of the river (i.e. the River Thames) for part of the year which could only be mitigated with significant changes in water management through building a new reservoir or water transfer from outside the catchment. For socio-economic scenarios, the study uses three scenarios developed in the MARS project: one an extension of present-day rates of economic development, the others representing more extreme and less sustainable visions.

4.9.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I8)

The adaptation scores below are based primarily on the HR Wallingford (2020) analysis on the potential impact of current and announced demand- and supply-side options on supply-demand balances by the late-century under a central population estimate.

The current and announced adaptation scenario in the HR Wallingford analysis based on demand management only is on the whole successful at managing risks to public water supplies by the mid-century and late-century across Scotland and Northern Ireland, so there is not deemed to be a shortfall for public water supplies in these nations (though note that both may experience significant risks to private water supplies, this is covered in risk H10). HR Wallingford (2020) show that current planned and announced demand-side adaptation actions are sufficient to bring the vast majority of Wales into surplus. However it must be noted that part of the mainly English water resource zone, Water Resources West, supplies parts of South East Wales, which may be in deficit in certain scenarios (although it is not indicated whether this will cause deficits in those water resource zones in Wales). It is the authors' view that sufficient evidence is not available to determine a future medium magnitude impact on Wales from the projected deficits in Water Resources West, but it is noted that this should be explored further in future projections. Low confidence is given in this assessment as a result.

In England, the current and announced adaptation scenario is less successful in reducing the magnitude of deficits to a low magnitude by late-century (hundreds of thousands of people could still be affected by deficits across England). When considering supply-side and demand-side measures in combination, it is suggested by HR Wallingford (2020) that surpluses are theoretically possible for the vast majority of regions, however it is argued that the identified supply-side options are likely not to be a cost-effective way to create surpluses, particularly in regions such as the South East. It should also be noted that the analysis is aggregated at the regional level, which may hide deficits at the water resource zone level. It is the authors' view that transfers should not be relied upon as the means of adaptation in the late 21st century for England as they are not currently included in planned adaptation. While a lot of positive adaptation has been announced which is projected to manage the risk, the announced adaptation is ambitious relative to present day progress with leakage and per capita consumption (PCC) reduction, and there remain concerns regarding water availability in the late century and the ability of transfers to cover deficits, therefore it is concluded that the risk will be partially managed in England.

Regarding the climate impacts on reservoir integrity, climate change projections are presently not used to inform the risk assessment or inspection regime for reservoirs in England, Northern Ireland, Scotland or Wales and remains an area for future attention.

4.9.2.2 Adaptation Scores (I8)

Table 4.31 Adaptation scores for risks to Public Water Supplies from reduced water availability			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)	Yes (Low confidence)

4.9.3 Benefits of further adaptation action in the next five years (I8)

4.9.3.1 Additional planned adaptation that would address the adaptation shortfall (I8)

The CCRA3 water resources project (HR Wallingford, 2020) finds that the only scenarios that result in a significant UK-wide supply-demand balance surplus are ones in which additional adaptation action is taken to reduce demand or where the current and announced adaptation scenario is applied to the central population. This scenario includes the water companies' own ambitions for reducing per capita consumption for England and Wales, baseline values were used for Scottish Water and Northern Ireland water as those companies have reported no intention to significantly increase meter penetration in households or other measures to reduce household consumption. Considering reservoirs, the routine use of climate projections and their potential impacts on the bund and spillways during safety inspections and mid- to long-term planning would better protect them from failures exacerbated by climate change. Establishing appropriate leakage targets using a sufficiently wide assessment framework considering all potential users may improve multi-sector resilience and economic efficiency of water and water rights use. Defra announced it is looking to bring in a statutory long-term water demand target by October 2022. The target will likely combine demand on public water supplies from households, business and due to leakage.

4.9.3.2 Indicative costs and benefits of additional adaptation (I8)

There are estimates in the literature on the benefits of further action. In terms of the supply side there are several studies that have considered additional measures, but these focus more on drought. Water UK (2016) estimated that a 'twin track' approach of demand management coupled with development of new resources and potential transfers is the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the business as usual base demand management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. The National Infrastructure Commission (2018b) estimated that in England alone the total costs between 2020 and 2050 of implementing emergency measures to provide household water supply during a 0.5% drought, weighted by the occurrence probability, range between £13 and £16 billion. The total costs over the same period of implementing emergency measures against a 0.2% drought range between £21 billion and £27 billion (costs on a present value basis (2018 prices) weighted by the occurrence probability). Atkins

(2018) used cost benefit analysis to build marginal abatement cost curves of emergency measures, i.e. when drought severity is beyond the capacity planned for through long-term water resources planning. This included examples for the Thames Basin. The results indicate that many emergency measures would be challenging to implement, provide uncertain yields and incur significant costs (Atkins, 2018).

There is also a suite of demand side measures that can be introduced by homes, many of which are no-regret and low-regret. Water UK (2016) assessed a twin track approach of demand management coupled with appropriate development of new resources and potential transfers as being the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the business and usual base demand management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. There are several studies that have looked at demand side measures for households that identify a large number of low- and no-regret options. The study by ARUP (2008) looked at a range of water saving measures, and estimated costs and pay-back times. A similar study was commissioned by the CCC (Davis Langdon, 2011) looking at cost-effectiveness of alternative household options, and this was updated by Wood Plc (2019), updating a previous cost-curve study. These studies identify estimated measures with benefit to cost ratios above 1 for different house types, comparing new-built vs discretionary retrofit. The study provides unit-cost estimates for different measures, and calculated cost-curves to show their relative cost-efficiency. When considering wider benefits from a societal perspective (including avoided GHG emissions), additional no-regret measures are identified. Generally, end-of life upgrades and measures installed in new builds were more cost-effective compared to retrofits. These studies highlight the high economic benefits of further action.

Research by Artesia (2019) for Water UK assessed the savings, costs and benefits of 18 water demand reduction interventions. It was estimated that with concerted effort by government departments, regulators and water companies, £64 benefit for every £1 spent could be achieved. The report found that the best strategy to maximise demand reductions involved mandatory water labelling and increased smart metering (above that in current water company plans). It was estimated that a 2,300 MI/d reduction in demand beyond current ambitions could be achieved through these measures.

Additional information on research regarding the costs and benefits of additional measures is set out in Table 4.32 below.

Table 4.32 Costs and benefits of implementing additional adaptation in next 5 years			
Strategy	Benefits	Costs	Source
Mandatory government led scheme to label water-using products, linked to tightening building Regulations and water supply fitting regulations	Reduce consumption by an additional 31 l/h/d or 2,012 MI/d by 2065.	£64 benefits for each £1 spent	Energy Saving Trust, (2020)
The National Infrastructure Commission recommended building resilience to 1 in 500-year drought. Supply infrastructure that supplies a further 1300MI/day will need constructing.	Net increase of at least 4000 MI/d based on the medium emission scenario.	Between £18 billion and £22 billion over 30 years to provide proactive, long-term resilience.	(NIC, 2018b)
Metering aim (95% of households) by 2030-2035.	Save 400-800 MI/d of water in 2050 (depending on the meter used). The proportion of households with metres in 2017 was 54%.	Unknown	(CCC, 2019a)
Demand management and new water resource options.	Increase resilience. Additional costs of becoming resilient to 'severe drought events' are becoming less than £4 per household-customer per year.	Between £50 million and £500 million per annum for severe drought resilience. Between £80 million and £800 million per annum for extreme drought resilience.	(Water UK, 2016)

4.9.3.3 Overall urgency scores (18)

More action is needed to address future supply-demand deficits in England, identified by the updated future water availability results discussed above. Urgency scores for Scotland and Northern Ireland are 'sustain current action', owing to only a low magnitude of risk of water deficits being

projected by the end of the century in the highest likely scenario on the basis of current planned adaptation measures. The urgency score for Wales is also ‘sustain current action’, although it is noted that there is a need to determine any potential deficit in Wales from the mostly English Water Resources West region.

Table 4.33 Urgency Scores for risks to Public Water Supplies from reduced water availability				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	Sustain current action	Sustain current action	Sustain current action
Confidence	Medium	Medium	Medium	Medium

Actions to reduce future risk have been identified in the Environment Agency’s national framework for water resources (2020c). In terms of demand, the Environment Agency state that the regional groups should:

- contribute to a national ambition on average PCC of 110 l/p/d by 2050 (reviewed every 5 years),
- reduce the water lost from networks by 50% by 2050 from a baseline of 2017 to 2018,
- pursue ambitious reductions in non-household demand and contribute to the evidence available on the potential savings (including working with non-household water retailers and new appointments and variations (NAVs)),
- identify ways to reduce water use outside of public water supply,
- explore how they can coordinate the use of temporary use bans (TUB) among the water companies,
- review their planned frequencies of use for TUB and non-essential use bans (NEUB) in the light of the planned increase to drought resilience.

To support this, the Environment Agency request that the Government and regulators should introduce a new monitoring and reporting framework to monitor and report on progress on demand management. In terms of supply, the Environment Agency state that regions should:

- scope a wide range of supply options, such as reservoirs, water reuse and desalination (determining how long each would take to implement to allow options to be brought forward if required),
- explore the strategic options funded as part of Ofwat's gated process,
- identify new options not included in current plans and engage in the catchment-based approach (particularly priority catchments), to develop cross-sector options with broader societal benefits,
- investigate the potential for increasing connectivity within and between regions (including longer distance transfers (over 100 km), and shorter transfers that increase resilience to interruptions in supply),
- When exploring transfers, regional groups should consider the potential to make them reversible so that they can increase the resilience of both parties, be clear on how transfers would be used during droughts and work with the DWI and RAPID to ensure planned

transfers are feasible and that any issues are carefully managed.

4.9.4 Looking ahead (I8)

A useful additional piece of analysis for determining potential future risk and benefits of adaptation would be breakdowns across the UK of what could be achieved with different levels of adaptation, broken down further by benefits achieved from reducing leakage, adding new infrastructure (including desalination) and reducing demand respectively. It is clear that additional water demand management is an important component element of adaptation. This would include decentralised supply options (rainwater harvesting and greywater reuse), as well as water efficiency standards in new homes and retrofits. Widespread rainwater harvesting holds potential for adaptation to increased surface water flooding. Ricardo's 2020 report for Waterwise overviews the costs and benefits of rainwater harvesting and greywater reuse for flooding and water resources.

Transformational adaptation could include construction of strategic resources that would enable adaptation over the long-term (the last major phase of strategic resource development was in the 1960s and 70s to serve growth). Similarly, universal metering, and ultimately smart metering, could significantly assist with controlling demand.

Further work is needed on the assessment of the costs of adaptation options (cost/benefit analysis), including the feasibility of water transfer from regions of surplus to regions of deficit. CCRA4 would also benefit from testing the assumption that under projected climate change scenarios, water can be freely transferred between existing supply systems. It should also be noted that spatial changes in demand brought about by shifts in working patterns brought about by COVID-19 (as well as broader socio-economic trends) should be taken into consideration in future assessments. Frontier Economics (2020) observed that changes in consumption as a result of the pandemic may put extra stress on certain parts of the water network in the long term.

There are potential multi-sector benefits of solutions with flood resilience schemes such as wetlands and peat bogs. Looking ahead at the 25 Year Environment Plan range it may be worth exploring a more natural capital approach, placing more value on ecosystem services.

4.10. Risks to energy generation from reduced water availability (I9)

The electricity supply industry dominates surface and groundwater abstractions in England, accounting for 49% of estimated actual abstraction in 2016 and 2017 and 65% of estimated licenced abstraction; 82% of abstractions from tidal waters and 30% from non-tidal waters (Defra, 2019a). The statistics include both thermal and hydropower. While hydro-electric plants are considered separately in Risk I6, in terms of other electricity generation, thermal power generators (including energy from waste plants) sited inland are the main type of generation vulnerable to reduced water supply. Around 60%, by capacity, of all thermal power plants in the UK are cooled with sea and tidal water, including all nuclear generation with the remaining plants reliant upon freshwater for cooling (BEIS, 2020b). While thermal plants cooled by tidal waters may not necessarily face restrictions in

water availability, the operation of all plants may face restrictions on discharging cooling water in order to protect aquatic ecology. This is a different risk than water availability but is also related to warmer temperatures and similarly may restrict plant output.

The oil and gas industry also require water for operation at existing locations in the UK, their offshore and coastal locations enable the use of salt water for many operations, however international supply chains may be vulnerable to restrictions in freshwater availability (Holland *et al.*, 2015). Test sites for shale gas also use freshwater for the fracturing process; this industry is not yet established in the UK so does not at present require significant volumes of water, however, were it to grow, its water requirements should be reassessed.

This section has focussed on risks to thermal plants, as these are most relevant to the UK's current energy portfolio. Current risks to thermal plants arise from restrictions to either abstracting (freshwater reliant plant) or discharging water (both tidal and freshwater plant) due to periods of low rainfall and/or elevated temperatures. Significant interruptions to thermoelectric generation have not been reported to date, therefore the current risk across the UK is deemed low. Analysis of future risks to the sector suggest there are particular areas of England where existing inland thermal plants are likely to be exposed to reduced water supply. The effects of climate change on discharge constraints on thermal plants are out of the scope of this assessment, however, relevant impacts relate to regulatory standards as well as to the wider effects of climate change on water quality and aquatic ecosystems – such as temperature, oxygen levels, flow patterns and salinity profiles (Arnell *et al.*, 2015; Watts *et al.*, 2015). The Net Zero commitment will see a significant turnover in current thermal plants; thus, it is important to assess the suitability of locations and the water dependence of Net Zero compliant plants in light of future constraints on water availability.

4.10.1 Current and future level of risk (I9)

4.10.1.1. Current risk (I9)

Although vulnerable to reduced water availability, to date there have been no significant interruptions to inland thermoelectric generation reported.

4.10.1.2. Future risk (I9)

4.10.1.2.1. UK-wide

Under climate changes projected by five CMIP5 models, a reduction in usable thermal power capacity in the UK of between 5 and 15% is projected by the 2050s on a pathway to approximately 2°C global warming by 2100¹⁴ and between 10 and 15% or more (depending on location) on a pathway to approximately 4°C global warming by 2100¹⁵, due to changes in freshwater water

¹⁴ Based on five CMIP5 climate models in ISIMIP, with projections with the RCP2.6 concentration pathway approximately consistent with 2°C global warming by 2100

¹⁵ ISIMIP, with the central estimate of the CMIP5 projections with the RCP8.5 concentration pathway being in the upper part of the range of the CCRA3 scenario of approximately 4°C global warming at end of century.

availability and water temperatures based on existing plant locations (van Vliet *et al.*, 2016). The magnitudes are supported by Tobin *et al.* (2019) who estimate a reduction in the usable capacity of UK thermoelectric plants reliant on river water of 8% with 2°C global warming and 14% at 3°C global warming, assuming no other changes. While these studies assessed impacts of existing thermal plants, the future vulnerability of energy generation due to reduced water availability caused by both drought and restrictions due to water temperature increases is dependent on how the UK's energy supply changes, while conventional thermal generation will reduce in order to deliver carbon reduction commitments, biomass and gas coupled with carbon capture and storage (CCS) technology, nuclear and hydrogen may play an important role in delivering Net Zero. The UK's Net Zero report (CCC, 2019a) outlines a future with approximately 190 TWh of generation from gas and biomass coupled with CCS by 2050, together with an increase in the use of hydrogen and biofuels. In addition to the requirements for water in thermal generation, electrolysis, carbon capture and storage (including with hydrogen generation) and biofuel production all require water, with the potential to increase the UK's energy systems' vulnerability to reduced water availability (see risk I9).

4.10.1.2.2. England

Within England there is concern that a future deficit of water will compromise the UK's current energy policy to meet an increasing demand for electricity using biomass and gas with CCS (Murrant *et al.*, 2017a). Studies assessing future freshwater availability and a range of future generation scenarios conclude that there could be restrictions in certain areas, particularly around the Thames and Trent Basins and Yorkshire Ouse by 2030 (Byers *et al.*, 2014; Murrant *et al.*, 2017a; 2017b; Konadu and Fenner, 2017). Their analyses conclude that new thermal plants would be better placed on the coast and use sea water as a coolant. Konadu and Fenner (2017) used water availability from CCRA2 data, based on UKCP09, while Murrant *et al.* (2017a) used Environment Agency Data based on UKCP09. The impacts of more recent projections of water availability using UKCP18 have not been used to update this analysis, however it would be anticipated that these projections would confirm the results, or potentially bring forward the date when they may occur. For existing combined cycle gas turbine (CCGT) and conventional plants that remain operating within the Trent Basin and Yorkshire Ouse, there is a risk that by 2030 their output is restricted and their locations become unsuited for uses requiring significant amounts of freshwater (Byers *et al.*, 2014; Murrant *et al.*, 2017a; 2017b; Konadu and Fenner, 2017). An assessment of the system electricity prices attributable to disruption to the supply from thermal plants due to restricted water availability caused by climate change estimates that in the period 2020-2049, costs would be in the region of £93 million and in 2070–2099, £129 million a year, using a large ensemble of the HadAM3P global climate model with RCP8.5 (Byers *et al.*, 2020). Impacts in a pathway to 4°C global warming at the end of the century would be expected to be slightly smaller than for this RCP8.5 projection.

4.10.1.2.3. Northern Ireland, Scotland and Wales

No studies specific to Northern Ireland, Scotland or Wales were found, likely owing to their large thermal power generation being located in coastal areas. Projections by HR Wallingford (2020) of future catchment water availability suggest there could be reductions in catchment water availability by mid-century in some catchments of Northern Ireland, Scotland and South East Wales under a pathway to 2°C global warming by 2100. This would have implications for the siting of any future

thermal generation plants.

4.10.1.3 Lock-in and thresholds (I9)

There is potential for lock-in depending on the future mix of electricity supply technology and siting of thermal power stations and other water intensive activities. The use of carbon capture and storage is highlighted by Byers *et al.* (2014) and Konadu *et al.* (2015) as particularly water intensive. The level of deployment and its siting is therefore important to plan. The CCC (2019b) include both gas and bioenergy-CCS in their pathways to Net Zero as well as nuclear. If these were sited in existing locations where there are likely to be restrictions on freshwater availability due to climate change, the affected plant would be locked-in to these potential future constraints (i.e. the risk of stranded assets). However, for CCS, the CCC (2019a) note that access to CO₂ storage will constrain siting, which excludes Northern Ireland and Wales but highlights Scotland as having the most potential. The locations proposed would likely lie on the coasts of Scotland and England rather than relying upon freshwater. Including an assessment of the future demand for and availability of freshwater in planning considerations would avoid this potential for lock-in.

Thermal electric plants are designed to operate within specific thresholds of water availability and temperature, beyond these limits output is reduced or stopped. There are also limits on the temperature at which water can be discharged back into the aquatic environment, which can restrict future cooling water use.

In addition to the impacts of climate change on freshwater water availability, the effects on the temperature of river, estuarine and marine waters are also relevant to thermal power stations. An increase in water temperature reduces the efficiency of cooling, and water used for cooling is returned to the environment at a higher temperature, potentially >10°C above ambient (Garcia *et al.*, 2016). An increase in average water temperature due to climate change further exacerbates the effects of returned cooling water on the aquatic environment. This could in turn result in some power stations being unable to abstract during periods when water temperature is high because of potential environmental damage if it were to be returned to the aquatic environment, in addition to periods when there is insufficient water available in a catchment.

4.10.1.4 Cross-cutting risks and inter-dependencies (I9)

There are a range of associated interacting risks. Failure to provide a robust means of power has the potential to cascade across the infrastructure sector impacting people, the built environment, business and industry. This was highlighted by the Interacting Risks project, which found the power supply had the highest number of knock-on interacting impacts (WSP, 2020).

Future freshwater requirements from the energy sector are also likely to compete with other users such as agriculture and public water supplies (Risk H10 and I9) as well as safe water levels required for the flora and fauna living within the catchment. Low summer rainfall, increased water temperatures during extreme summer temperatures and droughts can all lead to cooling water capacity being reduced (WSP., 2020).

The risks associated from the use of freshwater for thermal generation also interact with aquatic ecology. When water (freshwater, estuarine or marine) temperatures are raised the temperature at which water is discharged back into the environment is raised further, such elevated output temperatures have an effect on aquatic life and potentially a detrimental effect on reliant bird populations who are unable to adapt their diets (Garcia *et al.*, 2016). Furthermore, elevated water temperatures can enhance biological growth which could block the water intake (ETI, 2018d).

4.10.1.5 Implications of Net Zero (I9)

To deliver Net Zero, a new generation of electricity power options is likely. This will increase the turnover of current thermal plants, but create a stock of new energy technology associated with carbon capture and storage, hydrogen, nuclear (including small modular reactors (SMRs)) biomass and biofuel production, and thus change the nature of these risks as compared to the present. This evolution in supply could potentially increase risk from low water supply if the technologies that are favoured have high water demand. Current CCGTs with closed loop wet tower cooling require abstraction of 0.97 l/kWh and consume 0.78 l/kWh, rising to 1.92 and 1.49 l/kWh with CCS (Byers *et al.*, 2014). Assessments of the full water demand of alternative scenarios consistent with net zero have not been identified (although this work is being undertaken by Energy UK), however, water requirements for hydrogen are given here as an example. A potential future demand of 270 TWh hydrogen could be produced by electrolysis, gas or biomass reformation/gasification coupled with CCS (CCC, 2018c). For hydrogen produced by electrolysis, 0.5 litres of potable water is required per kWh of hydrogen and for gas reforming or gasification require 0.1-0.3 litres non-potable water per kWh and for cooling an additional 0.1 litres (cooling tower) – 30 litres (sea water) (CCC, 2018c). If all hydrogen were provided by electrolysis, 135,000ML of potable water would be required annually. The CCC (2019a) scenarios suggest the majority of the hydrogen requirements in the UK would be provided through gas reforming with CCS, with the use of electrolyzers particularly suited for vehicle refuelling stations due to their size and modular construction. However, other analyses have highlighted the potential for electrolyzers to be deployed faster than CCS technologies (Offshore Renewable Energy Catapult 2020). Related to this, the issues of water could make the Net Zero target more difficult to achieve, in that it could constrain the location of plants or require siting in certain areas (e.g. coasts).

4.10.1.6 Inequalities (I9)

The proposed relocation of infrastructure to the coast in future scenarios (Murrant *et al.*, 2017a; 2017b) does result in some inequalities where local communities in the locations affected share both the benefits and negative impacts of new developments and their eventual closure.

4.10.1.7 Magnitude scores (I9)

Current risk is Low for England, Scotland, Wales and Northern Ireland (Table 4.34). Only England currently has thermal plant greater than 65MW capacity reliant upon freshwater. Assuming current patterns of development and technology remain, England is therefore more exposed to this risk than Scotland, Wales and Northern Ireland. On this basis the future risk is Medium for England in the 2050s under pathways to 2°C and 4°C global warming at the end of the century (Table 4.34), due to

the magnitude of the losses to operators from van Vliet *et al.* (2016) and impact on electricity prices from Byers *et al.* (2020). It is assessed as low for Scotland, Wales and Northern Ireland based on their current exposure. As noted above, changes to the energy mix introduced by Net Zero policy could potentially increase this risk if the technologies that are favoured have high water demand; future water availability should be considered in selecting sites for these technologies.

Table 4.34 Magnitude scores for risks to energy generation from reduced water availability

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low (Medium confidence)	Medium (Medium confidence)	Medium (Low confidence)	Medium (Medium confidence)	High (Low confidence)
Northern Ireland	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)
Scotland	Low (medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)
Wales	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)

4.10.2 The extent to which current adaptation will manage the risk (I9)

4.10.2.1 Effects of current adaptation policy and commitments on current and future risks (I9)

4.10.2.1.1 England and Wales

The National Planning Policy Statements in England require the latest climate projections to be taken into account when major new thermal energy infrastructure projects are developed. Plans must give specific reference to the consideration of the increased risk of drought restricting cooling water and the effects of higher water temperatures for fossil fuel plants (DECC, 2011a; 2011b), and the resilience of biomass and Energy from Waste plants to the increased risk of droughts affecting river flow (noting biomass plants are more likely to be proposed for coastal and estuarine sites) (DECC, 2011b). However, it's unclear whether risks are being managed for new smaller infrastructure projects (CCC, 2019). In Wales, Technical Advice Notes include considerations on climate change for developers and are incorporated into Local Development Plans. Currently National Planning Policy

Statements do not provide specific guidance on hydrogen and large-scale biofuel production (whereas their combustion is covered by DECC (2011c)). This gap may be partially addressed through the new abstraction licensing regimes planned by Defra and the Welsh Government; however, these are not yet implemented (Defra, 2019b). The water used by existing thermal power generators is licensed by the relevant environmental regulator and will be subject to proposed water abstraction reforms in England and Wales. Currently abstraction licensing is managed by the Environment Agency and Natural Resources Wales. In England the recently established National Framework for Water Resources brings together regional groups including water companies and other major water users including power station operators to produce long term water resource plans to enhance the resilience of the region's water use to future uncertainties including climate impacts of drought and flood. Their first collective plans are due to be published in September 2023.

4.10.2.1.2 Northern Ireland

In Northern Ireland, the Strategic Planning Policy Statement states the planning system should help adapt to climate change through avoiding development in sites vulnerable to climate impacts. Currently abstraction licensing is managed by NIEA. While water should remain abundant for the existing sites located on the coast and near major estuaries, if new plants reliant on freshwater were to be built, their operations could become constrained if freshwater availability falls.

4.10.2.1.3 Scotland

In Scotland, the National Planning Framework sets out an ambition for new national developments to adapt to climate change, and major new developments of thermal power stations >300MW, nuclear and CCS sites to assess their vulnerability to climate change as part of the EIA under the Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017. Currently abstraction licensing is managed by SEPA. While water should remain abundant for those sites located on the coast and near major estuaries, any built inland and reliant on freshwater may find their operations become constrained if freshwater availability reduces, depending on where in Scotland they are sited.

4.10.2.2 Effects of non-government adaptation (I9)

Energy UK report adaptation plans on behalf of the sector under the Government's Adaptation Reporting Power (ARP). In their submission to ARP Round 2 in 2015, Energy UK highlighted the lack of probabilistic data on future river flows required to quantify risks of freshwater restrictions. As such it is not clear whether the progress reported in adapting to this risk is consistent with future freshwater availability projections, e.g. from HR Wallingford (2020). Third round risk assessments are not yet available to assess progress. Any risks to the energy system may be compensated by other forms of generation with price implications for electricity outlined by Byers *et al.* (2020). Individual sites would need to manage their risks to the financial losses incurred by any future abstraction restrictions. The water requirements of future energy infrastructure, particularly hydrogen and biofuels, require further consideration.

4.10.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I9)

Based on the evidence available, current and announced adaptation is expected to partially manage this risk as plans exist in the UK that consider the risks of water scarcity in the future for new developments. However, while the National Framework for Water Resources in England has been established, the group are yet to produce a risk management strategy for existing thermal plant in England. Furthermore, more analysis is needed for hydrogen and biofuel production to understand their risks. An assessment of progress of adaptation measures by energy providers has not been possible as the third round of Adaptation Reporting Power reports have not yet been submitted.

4.10.2.4 Adaptation scores (I9)

Table 4.35 Adaptation scores for risks to energy generation from reduced water availability			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)

4.10.3 Benefits of further adaptation action in the next five years (I9)

4.10.3.1 Additional planned adaptation that would address the adaptation shortfall (I9)

With respect to guiding new small plants which fall under the major infrastructure project thresholds and those already built on inland sites, further actions are warranted given abstraction reforms remain to be implemented in England and Wales, which, together with climate projections for the future water resources available in different catchment areas (Sayers *et al.*, 2020), could guide new infrastructure siting and cooling technology choices. The evidence for risks to energy generation due to higher water temperatures and/or reduced river flows should be kept under review, with long-term monitoring of risk levels and adaptation activity as advised in CCRA2, with additional consideration of how an expansion in hydrogen and biofuel production in the UK would affect vulnerability to reduced water availability.

4.10.3.2 Indicative costs and benefits of additional adaptation (I9)

The costs of further monitoring, and some strategic analysis to look at water related risks (water demand and flooding) for Net Zero generation, are low-regret options and would have clear benefits through the information provided.

For existing thermal plants, there are low regret adaptation options centred on monitoring of risk levels, including early warning and subsequent emergency management during extremes. In other European countries, where these risks have already materialised, adaptation options have focused on demand management and there is some analysis (Perrels *et al.*, 2015) of the economic benefits of demand management options (for industry) and the potential use of smart grids to help manage

non-essential energy use during these events; these might provide options should risks increase in the UK. There are also studies that look at the economic benefits of alternative cooling systems (Després and Adamovic, 2020), which find high benefits, but these tend to be focused on nuclear with river water abstraction (which is not relevant in the UK) or thermal plant (which are being phased out under Net Zero), however these technologies are suitable for biomass and CCS sites.

For the new mix of energy generation for Net Zero, and especially for biofuel, biomass, CCS and hydrogen, the most obvious no regret option is for further analysis of the possible risks with respect to water demand of new generation plant, the number required, and the linkages with Risk I8 on water supply. These factors could lead to important adaptation options around siting and technology options, and at the very least, the cost implications for any water use under a changing climate.

4.10.3.3 Overall urgency scores (I9)

Further Investigation is required in England to understand the extent of future risk to energy generation from reduced water availability in the context of wider demands for freshwater. Updated projections indicate that England is most vulnerable to water supply shortages in future and the impact of this on energy generation is unknown, particularly in the context of an uncertain future energy mix due to Net Zero policy. Scotland, Northern Ireland and Wales have been scored as a Watching Brief, as they have no (Wales and Northern Ireland) or few (Scotland) major thermal plants sited inland and are therefore deemed to have a Low magnitude current and future risk. However, it will be important for climate impacts on freshwater availability to be considered when siting new water dependent energy generators.

Table 4.36 Urgency scores for risks to energy generation from reduced water availability

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further Investigation	Watching Brief	Watching Brief	Watching Brief
Confidence	Medium	Medium	Medium	Medium

4.10.4 Looking ahead (I9)

Catchment level assessments of the long-term sustainability of existing thermal plants, together with the provision of updated advice on the suitability of catchments for future projects, could now be delivered with the use of Sayers *et al.* (2020). In England, this work should fall within the remit of the newly established Regional Water Resources Groups. A framework for regular re-assessment as climate and socioeconomic conditions change would enable users to gain confidence when making long term investments in this area. Assessments of the water needs for Net Zero energy portfolios are also required.

4.11. Risks to energy from high and low temperatures, high winds and lightning (I10)

The risks within this descriptor are broken down by climate hazard. In summary, there has been little evidence published since CCRA2 that provides additional information on the magnitude of existing or future risks to the energy sector from high and low temperatures, wind or lightning. However, further evidence on the effects of climate change on wind and lightning conclude the effects are uncertain (Clark *et al.*, 2017; Finney *et al.*, 2018; Fung *et al.*, 2018). The future risks related to the energy sector are also influenced by the future profile of energy demand and supply together with the resilience of society and the economy to constraints on or interruptions to supply. Differing generation and supply technologies have their own profile of vulnerability to weather and climate and therefore the balance of these technologies in future will influence the profile of the energy supply's vulnerability to climate change (Bloomfield *et al.*, 2018). Furthermore, Fu *et al.* (2018) conclude that infrastructure policies strongly shape the long-term spatial configuration of electricity networks and that this has profound impacts on their resilience. Current and future magnitude are assessed as high for the four countries. Urgency is scored as 'further investigation' required.

4.11.1 Current and future level of risk (I10)

4.11.1.1. Current risk (I10)

Note: It has not been possible to split the evidence by UK country for current risk.

4.11.1.1.1. UK-wide

4.11.1.1.1.1 High and low temperatures (current risk)

Temperatures affect the energy sector through a variety of different mechanisms. Above thresholds (specific to individual components of the energy system) high temperatures can (i) reduce the amount of electricity generation from thermal generators and the efficiency of photovoltaic cells; (ii) reduce the amount of power which can be transmitted and distributed; (iii) cause line sag; and (iv) affect the running of gas compressor stations, while accompanying solar heat (arising typically under conditions of high temperature and low wind) can also cause faults on the electricity network (McColl *et al.*, 2012; National Grid Gas, 2016; CCRA2, 2017). Studies on the impacts of lower temperatures on the energy sector are generally related to the coincident effects of snow, sleet and ice, which are associated with line faults (McColl *et al.*, 2012). While the interactions of high and low temperatures on energy are well understood, evidence that climate change is having an impact currently is less clear.

The ETI (2018a) highlight potential hazards associated with current temperatures in the UK including exports being cut to serve domestic energy demand, price surges, decreased efficiency of thermal conversion, decreased capacity of transmission lines to convey energy, and excessive sag of transmission lines. These risks affect both the supply of electricity and its transmission and distribution. These risks are currently managed by the network operators across the UK.

Temperature is one of the major drivers of energy demand in the UK, notably for winter heating and increasingly for summer cooling (in homes, business and industry). Changes in temperatures affect the temporal and seasonal profile of energy demand, with milder winters on average contributing to lower winter average demand, and hotter summers increasing demand from air conditioning (Thornton *et al.*, 2016; 2017). These effects are discussed in Risk H6 in Chapter 5 (Kovats and Brisley, 2021) and are not included in this risk. Current magnitude is given as low with low confidence (Table 4.37).

4.11.1.1.1.2 High winds (current risk)

ETI (2018b) state the major impacts of wind for energy infrastructure arise from damage caused by wind-blown debris and fallen trees, disruption to transport (relevant for staff accessing critical energy infrastructure locations), reduction in wind power due to low wind speeds and personal safety risks for staff (e.g. due to wind chill during periods of cold weather affecting outdoor workers), and injuries/fatalities from wind-blown debris and fallen trees. In addition, high wind speeds can reduce output from wind farms if speeds are above their safety cut-offs (25 ms^{-1}) and wildfires in the US have been attributed to winds causing nearby tree branches to touch power lines or as a result of power lines being blown down onto dry vegetation (W. Atkinson, 2018, Electrical Conductor Magazine cited in Gerlak *et al.* (2018)).

The resilience of the power system, or components thereof, to wind has also been explored using a fragility-modelling approach (e.g. Panteli *et al.*, 2017, Dunn *et al.*, 2018, Trakas *et al.*, 2019). When used in a meteorological context, fragility curves describe the impact on a system that results from a meteorological hazard. They are typically presented as failure probability (or simply the number of failures) as a function of a specified hazard, such as wind speed. The resulting curves have a characteristic form, with low fault numbers / failure probabilities at low wind speed, and a rapid rise in fault numbers / failure probabilities when particular wind speed thresholds (which vary depending on the assets being analysed) are exceeded. Here, the impacts of wind speed on energy are understood but there is less evidence that climate change is currently having an impact, hence low confidence in this aspect. Current magnitude is given as high with low confidence (Table 4.37).

4.11.1.1.1.3 Lightning (current risk)

The ETI (2018c) characterise the major impacts of lightning for energy infrastructure as physical damage, fire, power surge, and shock wave. In addition, wind turbines can enhance their own vulnerability to lightning, as their rotating blades can themselves trigger lightning (Montanya *et al.*, 2014, cited in Yair (2018)).

A report by National Grid to Ofgem (2019) detailed the significant and widespread power cut that affected the UK on 9th August 2019 following a lightning strike. Over a million electricity customers were affected, but there were wide-ranging additional impacts. Certain classes of electric trains shut down in SE England as their internal protection systems were triggered, causing unpleasant and potentially hazardous conditions for those on board and delaying other services. A subsequent report (Energy Emergencies Executive Committee: E3C, 2020) presented additional detail, including reporting of the societal impacts in the transport, health, water and wider energy sector. A total of

371 trains were cancelled, 220 part-cancelled and 873 delayed on the 9th and the morning of the 10th of August. There were interruptions to rail signalling and traction. Four hospitals and two airports were affected by the outage. An oil refinery and a chemical manufacturing plant were disconnected by their internal safety systems in response to the power disruption; both plants shut down operations but it took weeks for operations at the refinery to resume fully.

Lightning was found to be a factor in the power cut: *“Two almost simultaneous unexpected power losses at Hornsea and Little Barford occurred independently of one another – but each associated with the lightning strike. As generation would not be expected to trip off or de-load in response to a lightning strike, this appears to represent an extremely rare and unexpected event.”* (Ofgem, 2019).

Despite this being an unusual event, affecting infrastructure that is normally relatively resilient to lightning, it demonstrates the relevance of interdependencies for infrastructure, and has resulted in investigations as to why the interdependent assets/systems reacted to the power disruption as they did (E3C, 2020).

Population and urbanisation trends were identified by Yair (2018) as drivers of change in global lightning risk (note that such changes in risk would be linked to changes in exposure and vulnerability, rather than hazard). In particular, the potential for cities themselves to affect thunderstorm characteristics and thus potential lightning hazard was noted (e.g. the link between the contribution of aerosol (typically pollutant) material from the cities and lightning density). However, all the studies cited referred to cities in locations other than the UK. If this observation did hold for the UK, energy infrastructure in urban areas and wind turbines could be deemed to have a more elevated risk from lightning than may be otherwise expected. Current magnitude is given as high with low confidence (Table 4.37).

Table 4.37. UK-wide magnitude scores for current risks to energy from high and low temperatures, high winds and lightning (UK)	
	Present day/current risk
Risks to energy from high and low temperatures	Low (Low confidence)
Risks to energy from high winds	High (Low confidence)
Risks to energy from lightning	High (Low confidence)
Overall magnitude score	High (Low confidence)

4.11.1.2. Future risk (I9)

4.11.1.2.1. UK-wide

4.11.1.2.1.1 High and low temperatures (Future risk)

Since CCRA2, the UKCP18 projections for temperature changes have been published (Lowe *et al.*, 2018). Over land, the projected general trends of climate changes in the 21st century are similar to UKCP09, with a move towards warmer, wetter winters and hotter, drier summers. The probabilistic projections show more warming is projected in the summer than in the winter. In summer there is a

pronounced north/south contrast, with greater increases in maximum summer temperatures over south-east England compared to northern Scotland. Furthermore, considerations of the impacts of climate change on energy demand and thus on planning energy infrastructure also need to consider cold winters still occurring in addition to warmer winters and hotter summers.

Hanlon *et al.* (2021) calculated various impact metrics for the UK and its constituent countries, under different future levels of global warming from 1.5–4°C, using UKCP18. These metrics are all derived from meteorological parameters and thus are hazard-, rather than risk-, focused. Metrics potentially relevant for high-temperature energy risks included annual numbers of summer days (daily Tmax >25°C), tropical nights (daily Tmin >20°C), and cooling degree days (CDD, an indication of energy demand for cooling). Metrics potentially relevant for low-temperature energy risks included annual numbers of frost days (daily Tmin <0°C), icing days (daily Tmax <0°C), and heating degree days (HDD, an indication of energy demand for heating). Annual numbers of frost days, icing days and HDD are all projected to decrease with increasing global warming level, with summer days and CDD projected to increase. Annual numbers of tropical nights are small or zero at present but are projected to increase. The projected decreases in HDD were similar across countries but regional variations were found for all other metrics. A country-scale assessment of the high- and low-temperature metrics from Hanlon *et al.* (2021) is presented below.

Other studies have also provided relevant metrics showing similar trends. For example, Guerreiro *et al.* (2018) used climate model simulations under RCP8.5 to study future heatwaves in 571 European cities, 106 of which are in the UK. The temperature metrics provided were percentage of heatwave days and maximum temperature of heatwaves; both metrics are projected to increase, for all the UK cities studied. In addition, in a climate analogue study, Bastin *et al.* (2019) calculated bioclimatic variables for 520 global cities, 8 of which are in the UK, for the present day and for 2050 under RCP4.5. The temperature variables calculated were annual mean temperature, annual temperature range, maximum (minimum) temperature of the warmest (coldest) month, mean diurnal temperature range and mean temperature of the coldest, warmest, wettest, and driest quarters. In almost all cases the values of these temperature variables are projected to increase (increases measured in absolute terms, i.e. future value – present value). Note the contrasting approaches between these two studies and Hanlon *et al.* (2021), who computed the metrics at global warming levels rather than future time horizons.

4.11.1.2.1.1.1 England

Table 4.38 presents projected indices for England from Hanlon *et al.* (2021). The indices considered (all for annual number of days) are frost days (daily minimum temperature < 0°C), icing days (daily maximum temperature < 0°C), summer days (maximum temperature > 25°C), tropical nights (minimum temperature > 20°C), heating degree days (HDD, an indication of energy demand for heating) and cooling degree days (CDD, an indication of energy demand for cooling). The largest projected increases in summer days were found in England. England also had the largest projected increases in CDD and the largest projected increases in tropical nights.

Table 4.38 Change in a range of energy-relevant impact metrics, per global warming level, in England. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source: Hanlon *et al.* (2021)

Index	Changes in index from mean in 1981–2000: England	
	2°C global warming relative to pre-industrial	4°C global warming relative to pre-industrial
Frost Days (days)	-20 (-26 : -14)	-39 (-43 : -31)
Icing Days (days)	-2 (-2 : -1)	-3 (-3 : -2)
Summer Days (days)	+17 (+13 : +24)	+45 (+37 : +55)
Tropical Nights (days)	0 (0 : 0)	+2 (+1 : +3)
HDD (degree days)	-517 (-557 : -360)	-969 (-1074 : -845)
CDD (degree days)	+37 (+27 : +50)	+114 (+90 : +156)

4.11.1.2.1.1.2 Northern Ireland

Increases in Tropical Nights in Northern Ireland are negligible (Table 4.39).

Table 4.39: Change in a range of energy-relevant impact metrics, per global warming level, in Northern Ireland. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source Hanlon *et al.* (2021).

Index	Changes in index from mean in 1981–2000: Northern Ireland	
	2°C global warming relative to 1850-1900	4°C global warming relative to 1850-1900
Frost Days (days)	-21 (-30 : -12)	-37 (-42 : -30)
Icing Days (days)	0 (0 : 0)	-1 (-1 : -1)
Summer Days (days)	+5 (+3 : +6)	+16 (+13 : +21)
Tropical Nights (days)	0 (0 : 0)	0 (0 : 0)
HDD (degree days)	-467 (-512 : -344)	-902 (-1002 : -763)
CDD (degree days)	+9 (+7 : +12)	+32 (+26 : +46)

4.11.1.2.1.1.3 Scotland

The largest projected decreases in Frost Days and Icing Days were found in Scotland (Table 4.40). Increases in Tropical Nights in Scotland are negligible.

Table 4.40: Change in a range of energy-relevant impact metrics, per global warming level, in Scotland. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source Hanlon *et al.* (2021).

Index	Changes in index from mean in 1981–2000: Northern Ireland	
	2°C global warming relative to 1850-1900	4°C global warming relative to 1850-1900
Frost Days (days)	-32 (-42 : -18)	-62 (-67 : -53)
Icing Days (days)	-4 (-4 : -2)	-5 (-5 : -5)
Summer Days (days)	+4 (+3 : +5)	+12 (+10 : +17)
Tropical Nights (days)	0 (0 : 0)	0 (0 : 0)
HDD (degree days)	-528 (-574 : -388)	-1011 (-1113 : -891)
CDD (degree days)	+8 (+6 : +10)	+24 (+19 : +37)

4.11.1.2.1.1.4 Wales

Increases in Tropical Nights in Wales are smaller than in England (Table 4.41).

Table 4.41 Change in a range of energy-relevant impact metrics, per global warming level, in Wales. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source Hanlon *et al.* (2021).

Index	Changes in index from mean in 1981–2000: Northern Ireland	
	2°C global warming relative to 1850-1900	4°C global warming relative to 1850-1900
Frost Days (days)	-19 (-24 : -13)	-35 (-39 : -30)
Icing Days (days)	-2 (-2 : -1)	-3 (-3 : -2)
Summer Days (days)	+12 (+9 : +16)	+31 (+26 : +41)
Tropical Nights (days)	0 (0 : 0)	+2 (+1 : +2)
HDD (degree days)	-505 (-556 : -363)	-972 (-1080 : -852)
CDD (degree days)	+23 (+18 : +31)	+73 (+61 : +108)

The effect of the projected changes to these metrics on the UK energy sector would be variable. Projected decreases in frost days and icing days could reduce the risk to the electricity networks from faults related to frost and ice. Projected increases in tropical nights could also indicate increased cooling demand, as overnight there would be reduced respite from warm conditions. Similarly, projected increases in summer days could also be linked to increased cooling demand, and also to increased stress on temperature-sensitive energy system assets – both network components and supply (see Risk I9). Considering all these phenomena together implies a notable change in future seasonal energy demand profiles and therefore a potential need to change the way in which the energy system is managed. The effects of projected decreases in HDD and reduced winter energy demand, and projected increases in CDD and increased summer energy demand for cooling, are discussed in Chapter 5 in Risk H6 (Kovats and Brisley, 2021).

These statements all assume that change in risk is associated solely with change in hazard, i.e. that

there is no change in exposure or vulnerability. Given the future shape of the energy system is likely to change profoundly in the coming years and decades, in light of the UK's Net Zero aspirations, it is difficult to suggest exactly what changes in exposure or vulnerability could occur and associated magnitude.

In addition to the effects on energy networks, supply side technologies are also affected by changing temperatures (see also I6 and I9). Tobin *et al.* (2018) assessed the impacts of elevated temperatures and wind speed on PV output, stream flow and water temperature (derived from temperature, wind and precipitation climate projections) on thermoelectric power output across Europe as a result of 1.5°C, 2°C and 3°C global warming relative to 1881-1910. They project a reduction in output for PV of between 1-3% and thermoelectric generation of 5-14% relative to 1971-2000. The ramifications of the results are dependent on the future electricity generation mix as well as demand for electricity. The scale of lost revenue associated with a 5-14% reduction in outputs is of medium magnitude. Further evidence quantifying the impacts of projected temperature changes on network performance and generation would better inform an update to the CCRA 2017.

4.11.1.2.1.1 High Winds (future risk)

4.11.1.2.1.1.1 UK-wide

The limited evidence for any trend in average wind speeds due to climate change is still dwarfed by the variability of wind – the climate change ‘signal’ is very small or negligible compared to the ‘noise’. There is no information given about any possible future change in maximum wind speeds, though the limited evidence for a trend in average wind speed suggests evidence for maximum wind speed would be similarly limited. Although the evidence for how climate change will influence wind speed is limited, the anticipated growth in wind power suggests this is an important evidence gap to fill, both in terms of high winds and in light of the evidence reported in Chapter 1 (Slingo, 2021) that summer average wind speeds and thus wind outputs will reduce. A reduction in wind output during summer months could cause concern if electricity demand for air conditioning increases.

A further aspect of relevance for UK energy systems is the ‘storm track’, the path typically taken by windstorms. Any changes to this storm track could have implications for the frequency and intensity of windstorms, which impact the energy system in terms of its resilience to individual storms and, during runs of windstorms, its ability to recover between events. Murphy *et al.* (2018) show results for the end of the 21st century from the UKCP18 global projections, which suggest:

- In the 15-member HadGEM3 Perturbed Parameter Ensemble (a set of model runs just using the Met Office model), a projected increase in the occurrence of winter storms over the UK and Southern Scandinavia, with reductions to the north and south. This implies a projected strengthening of the southern fork of the winter storm track (the fork passing over the UK and Southern Scandinavia), with a weakening of the core to the north,
- In the CMIP5-13 simulations, (a set of model runs using climate models from other countries) for which storm tracking data are available, a similar pattern to that of the PPE-15, but with the band of increase in the southern fork being weaker.

There is therefore some evidence from UKCP18 that the occurrence of winter storms over the UK could increase, but the magnitude of any such increase differs between sets of climate projections. Bloomfield *et al.* (2016) assessed the weather sensitivity of power systems to climate variability. Four different wind power installation scenarios were examined, corresponding roughly to scenarios of no wind power, the present day, and two future National Grid scenarios for 2025 and 2035. As the amount of wind power installed increases, the total amount of power required from other sources decreases. The reduction is particularly pronounced for power plants expecting to operate as baseload rather than peaking (i.e. for long periods rather than short bursts). Climate variability is found to be important for the future operation of the power system; even the present-day level of wind farm installation has approximately doubled the GB power sector's exposure to interannual climate variability. This raises concerns about the robustness of any power systems planning studies which have used short time series or crude data to represent climate effects.

The main evidence emerging since CCRA2 regarding risks to the energy sector from wind are some increased understanding of the impacts of climate change on wind, reinforcing conclusions drawn from UKCP09 that the climate change signal (in the hazard) is masked by interannual noise (suggesting that current wind-sensitive sectors should focus on planning for interannual variability rather than on any potential climate change trend), the perceived possibility of increased future impacts on certain energy assets and processes from wind, and further detail on the changing vulnerability and/or exposure to wind due to the penetration of wind power supply.

4.11.1.2.1.2 Lightning (future risk)

4.11.1.2.1.2.1 UK-wide

The impact of climate change on lightning strikes is uncertain. Finney *et al.* (2018) compared two different climate model parameterisations of lightning – an existing approach based on cloud-top height and a new approach based on upward cloud ice flux – and found that in scenario of over 5°C global warming¹⁶, the newer method projected a 15% decrease in global total lightning flash rate of by 2100, which is contrary to the previously-reported global increase in lightning based on the cloud-top height approach. With both methods, however, the projected change in flash rate over the UK was not significant at the 5% level. Clark *et al.* (2017) used eight different lightning parameterisations with data from CAM5 and a range of scenarios to infer future changes in lightning flash rates. They found that the projected changes in lightning were highly sensitive to the choice of parameterisations. Two parameterisations projected a small decrease, but their spatial correlations with observed flash rates and patterns were the lowest, which reduces confidence in their projections. The remaining parameterisations projected varying increases in lightning flash rates.

The changes from CCRA2 regarding risks from lightning provide further information on the effects of climate change on lightning, including the suggestion that lightning could also decrease in future, whereas prior studies had only suggested increases. This suggests an increase in uncertainty in

¹⁶ Met Office Global Atmosphere 4.0 model driven by RCP8.5 concentrations and sea surface temperature anomalies at 2095-2105 from HadGEM2-ES, the latter model warming by approximately 5.5°C at that time relative to 1861-1890 (Betts *et al.*, 2015)

understanding future impacts compared to CCRA2.

Table 4.42. UK-wide magnitude scores for future risks to energy from high and low temperatures, high winds and lightning	
	Future risks
Risks to energy from high and low temperatures	Medium (Medium confidence)
Risks to energy from high winds	High (Low confidence)
Risks to energy from lightning	High (Low confidence)
Overall magnitude score	High (Low confidence)

* Confidence is low in both understanding of the hazard itself and in the vulnerability/exposure of the energy sector to it.

4.11.1.3 Lock-in and thresholds (I10)

The delivery of the Net Zero target will lead to fundamental changes in the energy system. It is likely to lead to a major investment in new energy generation technology, and thus involves a potential risk of lock-in if this infrastructure does not consider future climate change risks. Further evidence on the scale of potential lock-in is required, but it may arise from the climate variables used in the design specifications of new infrastructure commissioned. Different lifetimes of different energy infrastructure asset classes could affect the potential degree of lock-in in different parts of the energy system, as could the future energy mix of the UK (as a whole and for the DAs) – as different policy choices affecting energy mix (particularly the Net Zero ambition) will affect the future prevalence (or not) of particular energy infrastructure assets and thus the exposure and/or vulnerability of the energy system to different hazards. Lock-in has the potential to affect the urgency score for this risk, although it depends on how quickly a future pathway to Net Zero is defined and implemented.

There are currently engineering design thresholds above which equipment will either perform with a lower efficiency (e.g. PV, transmission lines) or cut out (e.g. wind turbines). For assets which are designed according to present-day climate (e.g. for which design specifications contain thresholds which are never exceeded at present) there is potential for issues to arise if standards are not updated, for instance to change asset operating ranges to account for the projected effects of climate change.

4.11.1.4 Cross-cutting risks and inter-dependencies (I10)

In terms of interacting risks, any loss of energy supply, in particular electricity, is likely to lead to cascade failure (see I1) due to the importance of energy supply (Interacting risks project - WSP *et al.* (2020)). This increases the magnitude of risk.

The interacting risks project identified the risks of heatwaves or very hot days leading to power and water demand increases as significant in 2020, 2050 and 2080s (WSP *et al.*, 2020). The risks arising from higher temperatures interact with the increases in energy demand for cooling (Risk H6, Chapter

5: Kovats and Brisley, 2021) and the effects of reduced water availability (Risk I9) which may further restrict the immediate availability of certain sources of electricity generation as well as potentially affecting bioenergy and hydrogen production.

From an international perspective, an increasing number of electrical interconnectors means there is an interdependency with Chapter 7 (Challinor and Benton, 2021).

4.11.1.5 Implications of Net Zero (I10)

The energy system will need to transform if the UK's Net Zero ambitions are to be achieved. Although Net Zero is primarily a mitigation policy, for the energy sector it is important to consider the balance between adaptation and mitigation, as different mitigation strategies aimed at achieving Net Zero will necessitate large changes to the UK's energy mix, and therefore to its sensitivity to weather and climate. Mitigation pathways generally require less reliance on fossil fuels and more reliance on renewables and new technologies.

CCC (2019a) discusses potential approaches to meeting the Government's ambition to reach net-zero greenhouse gas emissions by 2050. The report notes possible ways in which the energy sector could evolve in order to realise the Net Zero target, which will in turn change the vulnerability and exposure of the energy sector to climate change in the relatively short term. For instance, CCC (2019b) suggests that by 2050 with respect to 2017:

- Electricity demand would almost double (despite the fact that it has been falling in recent years) as increases energy efficiencies have offset increasing population and economic activity),
- A ten-fold increase in hydrogen use would need to occur,
- Carbon capture and storage (CCS) would need to be used; it is not yet used at all in the UK.

Wind is clearly both a resource and a risk, and a balance needs to be struck to ensure that new wind generation is resilient to future changes in climate including high and low wind speeds. It is also highlighted that both wind and solar energy are weather-dependent and that even with an expansion of these renewable energy sources, other energy sources will still be needed. Furthermore, as certain renewable energy generation infrastructure is quite remote, *"additional investments in electricity networks could be required to transport this electricity [to where it is needed]"* (CCC, 2019b)

Energy Systems Catapult (2020) discusses systems modelling conducted explicitly to meet Net Zero. Such modelling considers the whole energy system, rather than individual components thereof. Two scenarios for achieving Net Zero are described, one centralised and one decentralised, with different policies driving different energy mixes and technologies in each case. The report makes the following recommendation for actions during this Parliament, including for the electricity sector:

- Government support for large-scale developments, such as nuclear,
- R&D funding and deployment support for new/emerging technologies key for Net Zero,
- Stimulating efficient demand reduction and/or flexibility,

- Improved market price signals and strengthened network price controls to support decarbonisation.

Such reports suggest approaches for achieving Net Zero and propose actions and timings for these. However, these are only possibilities; it is not yet clear what impact the UK’s choices about mitigation will have on the scale of the adaptation challenge. While the UK has good knowledge on the risks of low and high temperature on the existing stock of energy supply technologies, there is less known about new Net Zero technology.

It is also highlighted (see also H6) that climate change will affect energy demand in the UK, reducing winter heating demand, as well as increasing summer cooling demand. This will have implications for the energy system (peak, seasonal and average generation) affecting generation capacity and storage. The impact of higher temperatures on heating and cooling demand has been considered in the preparation of the UK’s Sixth Carbon Budget (CCC, 2020a; Box 1.4 and Box 3.8).

4.11.1.6 Inequalities (I10)

Outages remain more likely to customers on radial networks, (e.g. North Wales, South West of England) as well as customers towards the end of distribution networks in rural / upland regions.

4.11.1.7 Magnitude scores (I10)

Table 4.43 Magnitude scores for risks to energy from high and low temperatures, high winds and lightning.					
Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Northern Ireland	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Scotland	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Wales	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)

The new information arising since CCRA2 has provided a better understanding of how climate change will alter the wind and lightning risk, whether for the UK or globally. The current impacts of high winds and lightning do currently affect the performance of the energy system, notably the widespread power cut on 9th August 2019, in which lightning was implicated. UKCP18 has not changed the message around future projections of wind, however, in which the ‘noise’ of interannual variability is projected to still far outweigh any possible climate change ‘signal’. It is possible that – faced with this seemingly uncertain future information – decision makers might choose to delay actions to reduce wind risk, in favour of actions reducing the risks from other hazards, for which projections seem more robust. This might not be an appropriate course of action, given that the magnitude of the risk is high currently.

There is little new evidence on the impacts of high and low temperatures on the energy sector, and the relative magnitude of the impacts of climate change on the energy sector as a whole, due to high and low temperatures to change the magnitude from CCRA2. This is perhaps because these hazards (and their impact on current UK energy infrastructure) are considered to be relatively well-understood. Although there is evidence on the impacts of high temperatures on different elements of the energy sector (PV, thermoelectric generation, network equipment, demand), the magnitude of the collective impact is not clear, and is dependent on the future evolution of the UK’s energy supply. Additionally, a warming climate is commensurate with the rarer occurrence of cold spells, which itself could have resilience implications in terms of reducing the ‘memory’ of how such events were managed in the past.

There are varying degrees of risk posed by the hazards to energy presented in this section, as well as varying degrees of understanding of the future risk posed in various climate scenarios. It has been demonstrated that weather hazards have the potential to cause high magnitude impacts affecting millions of people (August 2019 power cuts). Individual scores for each hazard are set out in the sections above, however the overall risk is scored at the highest level of risk across all hazards, which is high, with low confidence for present day and for future risk. While understanding of the relationships between the energy sector and temperatures, wind and lightning and the energy sector are good, there is less confidence in the attribution of climate change to the impacts observed to date.

4.11.2 The extent to which current adaptation will manage the risk (I10)

4.11.2.1 Effects of current adaptation policy and commitments adaptation on current and future risks (I10)

The mechanisms which govern adaptation for power generators are discussed in I6 (Hydro), I9 (Thermal) and I11 (Offshore). This includes planning guidance through National Planning Policy Statements (England), Technical Guidance Notes (Wales), National Planning Framework (Scotland) and Strategic Planning Policy Statement (Northern Ireland) together with requirements under Environmental Impact Regulations for climate vulnerability assessments. Existing guidance and statements generally cover larger installations and do not cover all possible climate risks a site may be exposed to (CCC 2019b). For existing operators, they may voluntarily report their plans for adaptation through the Adaptation Reporting Powers process. Both gas and electricity network

companies are incentivised to provide a reliable service during adverse weather and enhance longer term resilience through Ofgem's RIIO price control Framework. The recent RIIO-ED2 for distribution network operators covering the period 2023-28 includes specific reference to the production of a climate resilience strategy and establishment of a climate resilience focus group.

4.11.2.2 Effects of current non-government adaptation on current and future risks (I10)

4.11.2.2.1 UK-wide

Much of the energy sector are invited to produce reports on how current and future climate will affect their organisation and to describe their proposals for adapting to climate change under the Adaptation Reporting Process (ARP) of the Climate Change Act 2008. Electricity generators, transmitters and distributors as well as gas transporters and the regulator Ofgem produce these adaptation reports. The main outcomes of the assessment of temperature impacts, from the latest reports (ARP2) published 2015-2017 (i.e. those which were not published in time to inform the last CCRA), are summarised here. Unfortunately, ARP3 reports are not available at the time of writing to provide an update on more recent activities.

4.11.2.2.1.1 High and low temperatures

National Grid Electricity Transmission (NGET, 2016) ARP2 reported that further information was required in order to assess the longer-term impacts of heat on substation equipment and change existing design standards. In National Grid Gas (NGG, 2016) ARP2 report, the highest-rated impacts related to temperature were effects on control systems / telemetry / ICT for which there are temperature limits for their operation. The maximum operating temperature of the majority of process instrumentation is between 60-80°C; telemetry outstations have a maximum temperature of 55°C and their associated communications infrastructure has a maximum operating temperature of 40°C. National Grid Gas also highlighted weather changes may increase the costs of maintenance, construction, repair and new installations.

NGG's assessment of control systems/telemetry risks includes several temperature thresholds. With future impacts in mind, considering the lowest of the thresholds mentioned (40°C) it is worth noting that Christidis *et al.* (2020) have assessed the likelihood of reaching a temperature threshold of 40°C in the UK at present and by 2100. They found that, statistically, summers which see days above 40 °C have a return time of 100s–1000s of years in the natural climate. This is reduced to 100–300 years in the present climate, and to only about 15 years by 2100 in a scenario reaching approximately 2°C global warming at the end of the century¹⁷, and 3.5 years in a scenario reaching approximately 4°C at the end of the century¹⁸. That is, although such temperatures have not been observed in the UK, they could theoretically occur now, and are projected to become more common in future, with the return time being dependent on the emissions pathway followed and the sensitivity of the climate system.

¹⁷ Central estimate for the CMIP5 ensemble driven by the RCP4.5 concentration pathway, with the multi-model mean reaching 2.4°C global warming in 2081-2100 relative to 1850-1900

¹⁸ Central estimate for the CMIP5 ensemble driven by the RCP8.5 concentration pathway, with the multi-model mean reaching 4.3°C global warming in 2081-2100 relative to 1850-1900

The other thresholds may appear high, but some assets are enclosed, or housed indoors, where the temperatures they experience could be higher than ambient temperatures. It is not clear whether this applies to the assets discussed.

4.11.2.2.1.2 High winds

Analogously to the above discussion for temperature-related impacts, NGET (2016) listed various wind-related impacts, but their own assessment of these rated them as 'green'. For instance, design standards were deemed to account for extreme weather conditions, with substation equipment being designed to a wind speed of 34 ms^{-1} (76 mph), and while access to equipment for maintenance and repairs could be constrained during extreme events (including extreme wind), it was deemed unlikely that this would have a prolonged impact on maintenance.

NGG (2016) ARP2 report listed eleven 'amber'-rated impacts related to wind arising from wind-blown debris; safety risk to personnel working on NGG infrastructure, increased wind loading on certain assets (LNG compressor stations and storage facilities), and potential for wind loading to exceed design specifications for some assets.

Projected changes in maximum average wind speeds due to climate change remain uncertain (Lowe *et al.*, 2018). Murphy *et al.* (2018) projected the occurrence of windstorms over the UK to increase in winter, though the magnitude of any such increase is uncertain. Fu *et al.* (2018) find that the electricity system is resilient to windstorms in the current climate, but a 5–10% increase in windstorm intensity and frequency is sufficient to induce a failure to meet demand. A better understanding of projected changes to wind extremes would be useful here (both in terms of frequency of occurrence and magnitude). Based on the uncertainties in maximum wind projections, the need to implement corresponding modifications to the strength design of the overhead electricity lines, poles and pylons would depend on the risk appetite of the regulator; for new infrastructure, there is an opportunity to avoid lock-in due to 'business as usual planning' (see Chapter 2: Watkiss and Betts, 2021) if evidence were to emerge in the future that maximum wind speeds could increase by 5-10% or more. Risks to the distribution system from wind are potentially greater than to transmission infrastructure and may be more resource intensive to manage. Even with the uncertainties around projected future changes to wind, the adverse impacts of high winds in the current climate could warrant a precautionary approach, at least while the evidence base remains inconclusive.

4.11.2.2.1.3 Lightning

NGG (2016) ARP2 report highlighted that while buildings and assets are protected against lightning, if an increase in lightning strikes increased power failures, more standby generators would be considered. NGG also stated that lightning may cause an increase in intermittent loss of telemetry and anticipate that "Business Continuity Management (BCM) plans and plant design provides resilience".

The CCC's 2019 evaluation of the Adaptation Reporting Power reports and wider evidence (CCC,

2019b, 2019c (England and Scotland progress reports)) is that the energy generation, transmission and distribution sector is making relatively good progress in adaptation. However, as noted by the CCC, “*CCRA2 identified risks from wind and lightning as urgent to address for the energy sector.... There is a need for better understanding of projected changes in maximum wind speeds and the frequency of such events. If maximum wind speeds were to increase, there would need to be a corresponding modification to the strength design of overhead electricity lines, poles and pylons. It is not clear whether adequate action is being taken to improve resilience to the projected increase in faults to the electricity distribution network caused by lightning strikes.*”

CCC (2019a) recommended that for England, more research is needed on the implications of increased vegetation growth rates on future risks of damage from falling trees during storms. If vegetation growth rates (and the associated risks) were shown to increase in such studies, the potential impact of this could be mitigated by changing vegetation management regimes (e.g. cutting back more often, or ensuring effective monitoring/surveying so that clearances remain sufficient).

4.11.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I10)

Fu *et al.* (2018) presented an integrated approach to assess the resilience of future electricity infrastructure networks to climate hazards. The approach considers different possible ways in which the UK electricity network could evolve depending on policy decisions and changes in supply and demand, and possible changes in the climate hazard (windstorm frequency and/or intensity) and their impact on the network’s resilience. Four scenarios were tested (the four combinations of low/high investment cost and centralised/distributed generation) in a simplified model of the power system. The analysis shows that, in this model, infrastructure policies strongly shape the long-term spatial configuration of electricity networks and that this has profound impacts on their resilience. According to the approach, the system is resilient to windstorms in the current climate, but a 5–10% increase in windstorm intensity and frequency is sufficient to induce a failure to meet demand.

Bloomfield *et al.* (2018) studied how the integration of wind power in GB is affecting the overall weather sensitivity of the power system, using three metrics: total annual energy requirement, peak residual load from non-wind sources, and wind power curtailment. The highest-impact weather conditions for the GB power system are different depending on the amount of installed wind power capacity. At the current level of wind power capacity, the total energy generation from non-wind (‘traditional’) sources is already mostly characterised by the variability in near-surface wind speed, rather than temperature. Without any wind power capacity, the peak residual load from traditional generation is associated with anomalously low 2 m temperatures. With increasing wind capacity, though, the peak residual load tends to be associated with moderately low temperatures and very low wind speeds. This suggests generation adequacy analysis should move away from wind power availability during peak load and towards peak residual load. Demand-limited curtailment events (in which wind power generation is >70% of demand) were associated with low pressure systems north of GB, leading to high wind power production. A major consequence of this study is that the past weather sensitivity of the power system may no longer be an appropriate guide for the future.

In conclusion, there could be an adaptation shortfall related to the implications of temperatures

exceeding 40°C for communications infrastructure resilience, increased vegetation growth rates and the associated future risks of damage from falling trees during high winds and storms, though this remains an uncertain area. There could also be a shortfall regarding resilience to lightning-related risks – however recent studies add uncertainty to the understanding of how climate change will affect lightning hazard. Further investigation of the impacts of climate change on future maximum wind speeds and the seasonal change of wind speeds would enable a better understanding of the extent of any adaptation shortfall associated with wind related impacts.

Several actions in the energy sector are outlined which need to occur (or continue) in the 2020s:

- Continued deployment of baseload and variable low-carbon power,
- Increased electrification of transport and heat,
- Continued improvements in system flexibility,
- Upgrading distribution networks for electrification.

Some of these changes may have positive impacts on the power network from a resilience / adaptation perspective. For instance, upgrading the distribution network has the potential to make it more resilient to weather.

As highlighted in Risk H6 (Chapter 5: Kovats and Brisley, 2021), there is a need for more consideration of the impact of climate change on energy demand, as well as consideration of the potential risks on energy supply technologies. This is important because of the potentially large future demand changes and the large differences in risks across different pathways, i.e. for pathways to 2°C and 4°C global warming by the end of the century.

4.11.2.4 Adaptation scores (I10)

Table 4.44 Adaptation scores for risks to energy from high and low temperatures, high winds and lightning			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

4.11.3 Benefits of further adaptation action in the next five years (I10)

There are benefits of additional action in the next five years. For example, further investigation on the implications of increased vegetation growth rates and the future risks of damage from falling trees. The potential for greater use of ‘soft’ adaptation solutions is identified in NGG’s ARP2 report (the specific idea mentioned being changes to working practices). Although organisations are generally already exploring this concept, it is an area where collaboration between companies and between sectors could further facilitate progress in adaptation. There could be benefits in exploring this further through existing collaborative channels.

Metz *et al.* (2016) indicate there are benefits from incorporating climate change information into the decision-making stages regarding the design of new assets and life extension of existing assets. This activity would reduce the potential for lock-in. A watching brief on the evidence regarding future wind speeds could be considered, to be reviewed if evidence suggests an increase in maximum wind speeds of 5% or more are indicated. Further investigation on activities being implemented by the energy sector on existing plans to protect assets from increased lightning strikes is needed to assess whether this should be included as an action here.

There are no regret options involved in better understanding of the potential influence of climate on future energy demand, and thus the Net Zero strategies (see H6), as these influence energy supply.

4.11.3.1 Indicative costs and benefits of additional adaptation (I10)

There is emerging information on the costs and benefits of climate smart design of energy generation including renewables. There is less evidence on the risk levels and potential costs and benefits of climate smart design for the new generation of technologies that will be developed to meet Net Zero, though there are obvious early low regret actions to further investigate these.

There are several hazards and a number of different energy generation technologies within this risk, each of which has particular adaptation responses.

The risk of wind damage to energy supply and transmission infrastructure is one area, and there may be compounding effects from increased vegetation growth. There has been some analysis of these aspects, and the potential increase in vegetation management costs, which can be considered as an impact or an adaptation) (Metroeconomica, 2004), though there are additional options, e.g. wind fences/breaks, circuit breakers, etc. The potential changes in wind regimes and wind power generation are highlighted as a watching brief above: there are technical design as well as operational management options to address potential changes should these emerge.

There is a more general approach for adaptation, with the inclusion of climate risk assessment as part of project design and financial and economic appraisal (see also the Green Book Supplementary Guidance on Accounting for Climate Change, Defra, 2020a). However, there is less evidence on the risk levels and potential costs and benefits of climate smart design for the new generation of technologies that will be developed to meet net zero: an obvious early low regret action is to further investigate these.

4.11.3.3 Overall Urgency scores (I10)

There is a need for further investigation in all four UK countries (Table 4.45), to better understand the future risks to energy from these hazards, particularly high winds and lightning. Better understanding of the implications of increased vegetation growth rates and the future risks of damage from falling trees is also required. Current and announced adaptation actions are not expected to sufficiently manage this risk. The urgency for this risk is assessed with High confidence.

Table 4.45 Urgency scores for risks to energy from high and low temperatures, high winds and lightning				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	High	High	High	High

4.11.4 Looking ahead (I10)

More research is needed on the implications of increased vegetation growth rates on future risks of damage from falling trees during storms. The evolution of research into future wind speeds and lightning frequencies hazards will enable a better understanding of the magnitude of these impacts on energy networks and appropriate adaptation responses. Studies such as the NGET assessment which include the likelihood of change as well as its impact are an example of good practice. This risk links to Risks I11, I10 I12 and H6 (Chapter 5; Kovats and Brisley, 2021) which highlight a need for more consideration of the impact of climate change on energy demand, as well as consideration of the potential risks on energy supply technologies which are reliant on weather – particularly those which capture diurnal and seasonal changes in demand and supply. It may be beneficial to increasingly consider the onshore and offshore energy generation, transmission and distribution system together to identify risks on a whole system basis.

4.12. Risks to offshore infrastructure from storms and high waves (I11)

Offshore infrastructure includes equipment used by the oil and gas industry, wind, tidal stream and wave energy as well as communications, gas pipelines and power cables on or under the seabed. Their vulnerabilities as a result of storms and high waves include destabilization or degradation of mechanical systems and structures, reduced energy yields and operating periods, loss of integrity of foundations and cabling systems caused by loading and sediment transport across the sea bed, and impeded access for maintenance and inspection activities.

In the future, the risk is allocated as medium magnitude, due in part to the increased vulnerability from the higher reliance on offshore wind for energy supply, since offshore wind capacity is planned to increase from 9 GW currently to 95 GW by 2050, under the CCC's balanced pathway to Net Zero (CCC, 2020b). In addition, a large fleet of oil and gas platforms remains in UK waters, which may be repurposed for carbon sequestration storage and thus remain operational beyond their initially intended lifespan. The length of experience of offshore wind farm operations and resilience is relatively short, due to the limited timespan of this industry to date. Therefore, long term effects are not yet fully understood.

Meanwhile, the confidence in current projections of the effect of climate change on offshore environmental conditions, including wave heights, is low according to the UKCP18 Marine Report

(Palmer *et al.*, 2018). This low confidence in the projected changes in the environment coupled with the short timescale of experience and evidence of offshore wind operations, as well as the rapid growth of this infrastructure and its importance to our energy system, leads to a medium classification of the future magnitude of risk.

Adaptation by the industry can be anticipated based on historic adaptability of the oil industry and the long-term investment in offshore energy infrastructure. The industry adheres to international design standards, which must be evolved as climate impacts on the marine environment become better understood. Current action should be sustained in the next 5 years.

4.12.1 Current and future level of risk (I11)

Note: It has not been possible to split the evidence by UK country for this risk.

4.12.1.1. Current Risk (I11)

4.12.1.1.1. UK-wide (I11)

In UK waters there is extensive infrastructure associated with offshore energy production, including both oil and gas facilities and renewable energy (mainly wind but also tidal stream and wave energy). Oil and gas facilities are in the North Sea, the Irish Sea and west of the Shetland Islands (OGA, 2020). There are ~300 offshore oil and gas platforms, of which ~140 have crew onboard, connected via a network of pipelines (Insite, 2020). This number has been stable since the previous CCRA report in 2017.

Offshore wind farms are primarily found in the southern North Sea and the Irish Sea, and the first farms have recently begun operation in new regions including the Moray Firth and the English Channel (Crown Estate, 2020). The current Crown Estate lease opportunities include zones on the south coast, the Irish Sea and into deeper regions of the North Sea. Currently there are ~3000 offshore wind turbines installed or under construction in UK waters, approximately doubling since the previous CCRA report (Crown Estate, 2018). On the seabed around the UK there is also a network of communications cables that carry telephone and internet traffic to Europe and across the Atlantic.

The oil and gas facilities contain and produce hazardous hydrocarbons and there are typically 100 helicopter flights per day to transfer crew between shore and facilities, with a total of 500,000 crew transfers annually (TSC, 2014). Wind turbines require maintenance and repair, via typically 5 visits per year, when the turbine must be boarded from a vessel in suitably calm conditions. Offshore installation operations are weather restricted and require evaluation of the expected environmental conditions to ensure that there will be adequate weather windows for the planned operations (DNV-OS-H206, 2014). The environmental limits are specified by manufacturers (IEC 61400), and owners manage operations and scheduling; for most current maintenance vessels, a crew transfer to the turbine can take place only when the significant wave height is <1.5 m.

Offshore wind farms currently provide 10% of UK domestic energy consumption (Crown Estate, 2018) and this proportion will continue to rise as new installations come online. The production of

electricity by a wind farm is intermittent due to shutdowns during periods of wind that exceed the design limit, and due to low productivity in calm periods. This leads to a requirement for ‘balancing’ of the electricity grid, particularly when wind farms cease production due to faults, and during calm conditions or excessive wind. This need for balancing is likely to increase in the future.

4.12.1.2. Future Risk (I11)

Marine climate change, including extreme storms, impacts offshore infrastructure. CCRA2 provided a short description of this risk, focusing primarily on qualitative evidence related to the structural integrity of wind turbines and highlighting uncertainty in linking these risks to climate change. For CCRA3 this section has been enlarged, with a wider review of exposure, hazards, vulnerabilities, and risks, linked to more detailed context of the UK’s future offshore infrastructure.

Marine climate change presents a changing hazard to offshore infrastructure. Meteorological and oceanographic conditions that affect the risk to offshore infrastructure from climate change include wind, waves, current and water level.

The marine climate around the UK is summarised in the UKCP18 Marine Report (Palmer *et al.*, 2018). The largest waves offshore of the UK are found off the western coasts, including Cornwall, south-west Wales, and north-west Scotland. These west-facing coasts are dominated by long swell waves that are generated far offshore, in the north Atlantic. The lowest wave heights are found in more enclosed seas, which are sheltered from long swells. In the enclosed seas, such as the Irish Sea and the North Sea, local winds with a short fetch generate short-period waves. The design of offshore infrastructure in these different locations takes account of the different conditions by allowing for the lower loads and altering the structural capacity accordingly. Design codes aim for the same reliability to be achieved, regardless of the location.

The UKCP Marine Report provides UK marine climate projections for the 21st century for three different representative concentration path (RCP) climate change scenarios, namely RCP8.5, RCP4.5 and RCP2.6. Projections for the RCP6.0 scenario are not included because the scenario exhibits a similar trend at 2100 to RCP4.5 and has poorer data availability than the other scenarios. In the UKCP18 Marine Projections, the median of the CMIP5-based RCP8.5 projections is in the upper part of the range of the CCRA3 pathway to 4°C global warming by the end of the century (see Chapter 2: Watkiss and Betts, 2021). Key results from UKCP18, for the period 2070-2099, focusing on (i) mean sea level; (ii) wave height; and (iii) wind speed are highlighted, to provide a quantitative basis for review of the offshore infrastructure vulnerabilities.

- a) *Mean Sea Level.* Global mean sea level (GMSL) increased by around 0.2 m from 1901 to 2010, at an average rate of 1.7 mm per year (IPCC, 2013), and this will continue to rise over the 21st century under all RCP climate change scenarios. Sea level projections for the UK in UKCP18 are derived from the GMSL projections, and presented in terms of time-mean sea level, which is the baseline water level upon which drivers of sea level extremes, including tides, surges and waves, need to be superimposed.

All RCP scenarios show substantial sea level rise over the 21st century. In the south, the

projected rise is on average 0.8 m to 2100 under RCP8.5 scenario, while a lower rise of about 0.5 m and 0.4 m is projected under RCP4.5 and RCP2.6, respectively. For RCP8.5, the range of projections extends up to ~1 m. A lower sea level rise is projected for the north of the UK. The lowest predicted sea level rise is in south-west of Scotland, with a rise of <0.3 m under RCP2.6, and about 0.4 m and 0.5 m under RCP4.5 and RCP8.5 scenarios, respectively. The change in time-mean sea level will dominate changes in the water level extremes during the 21st century, with negligible contribution from changes in atmospheric storminess, which is expected to range from about -1 mm/yr to about 0.7 mm/yr, but with overall zero mean.

- b) *Wave height.* Seven CMIP5-based global wave models are used in the UKCP18 Marine Report to provide future changes in mean and mean annual maximum Significant Wave Height (SWH) under RCP8.5. The significant wave height is the mean height (from trough to crest) of the largest one third of waves in a given sea state (other statistical definitions are used, but with minimal practical difference). Results for lower RCPs are not provided. On average, these models project an overall decrease in mean SWH around most of the UK coastline of 10–20% over the 21st century. However, it is stated that the projections should be treated with low confidence, due to the variation between different models. Based on the average results, the mean SWH reduces by ~0.2 m to the south west of the UK and Ireland, and by ~0.1 m in the North Sea and the Irish Sea. These changes are in the range 10–20%.

The projected changes in mean annual maximum SWH are in the range +/- 1 m or 20%, but with a more complex spatial pattern than for the mean SWH because they are affected by the passing of individual Atlantic storms. In the central and southern North Sea, a reduction in annual maximum SWH of ~0.5 m is projected. However, an increase by up to ~1 m is projected in the Irish Sea and the northern North Sea. This latter change could be related to a change in sea-ice cover due to global warming, leading to increased fetch for northerly winds in Nordic Seas. There is too much uncertainty among the models to provide a projection for offshore the south west of the UK.

To put these changes in mean and maximum SWH in context, the trough-to-crest height of the probable maximum wave during a storm, H_{\max} , is a key design parameter, and is typically double the SWH. H_{\max} rises with increasing latitude from ~20 m offshore Cornwall to ~35 m north of Scotland and west of the Shetland Isles (Santo *et al.*, 2016). The UKCP18 climate projections for RCP 8.5 to 2100 in the Irish Sea and the northern part of the North Sea represent a change in the elevation of the top of this maximum wave of up to ~2 m. This comes from an up to ~1 m rise in sea level combined with half of the 1 m rise in the *trough-to-crest* amplitude of the annual maximum SWH, doubled to represent H_{\max} . In the central and southern North Sea, the predicted reduction in annual maximum SWH of 0.5 m could compensate for the rise in sea level, leaving the elevation of the annual maximum wave unaffected.

However, these changes are affected on a decadal timescale by the strength of the North Atlantic Oscillation (NAO), which is the fluctuation of the difference between the Icelandic low pressure and Azores high pressure regions. The NAO affects the strength and direction

of westerly storm tracks approaching the UK and alters the H_{\max} to the west and north of the UK (from Cornwall up to the Shetlands) by typically +/- 3 m over a decadal period (Santo *et al.*, 2016).

- c) *Wind speed.* The mean changes in wind speed predicted by the CMIP5 climate models (Wade *et al.*, 2015) have similar patterns to changes in mean SWH discussed earlier, with a reduction to the west and south west of Ireland, and slight increase to the north of the British Isles. The differences from historical conditions to end-21st century RCP8.5 are on the order of 0.5 m/s. Changes in the mean annual maximum wind speed are spatially variable, with changes of the order +/- 1.5 m/s in places (Palmer *et al.*, 2018). Under the H++ scenario, defined as the more extreme climate change scenarios on the margins or outside of the 10th to 90th percentile range presented in the UKCP09 projections (Murphy *et al.*, 2009), the model projects a 50–80% increase in the days of strong winds over the UK by 2070–2100 compared to the period 1975–2005.

Together, these three effects of climate change create the following vulnerabilities: the stability and degradation of structures and mechanical systems (e.g. turbines), the energy yield and operating window (periods of operation) of turbines and facilities, sediment transport across the seabed, influencing the integrity of foundations of subsea infrastructure and cabling systems, the accessibility of structures for maintenance, inspection and crew transfer, and the operation of ports and coastal infrastructure for maintenance and inspection activities.

4.12.1.2.1 Effect on the stability and degradation of structures and mechanical systems (e.g. turbines)

Offshore infrastructure is designed against limit states that may be controlled by a single extreme load, or by an accumulation of many small loading events, or a combination of both. For example, the stability of a structure is primarily dependent on the largest single load, but prior cycles may weaken it. Fatigue failure of structural or mechanical components, or progressive tilt of the structure, may be controlled by both large (infrequent) and small (frequent) loads, depending on the structural form, the materials and the ground conditions. Small changes in load level can have a large effect on structural life. This is because the number of cycles to fatigue failure depends on the applied stress raised to a high power, typically 5 for high cycle fatigue modes (Bai and Jin, 2015). Consequently, a 10% change in load reduces the structural life by a factor of $1.1^5 = 1.6$.

The extreme loads on a structure are typically driven by the largest wave in an extreme storm event. Examples of smaller but more frequent loads are the cycles caused by a wind turbine blade passing the tower or by the waves in rough seas. The maximum single extreme load on a fixed structure is affected by climate change through the severity of the extreme storm event combined with the increase in sea level. As outlined above, the projected rise in the elevation of the crest of the annual maximum storm wave is up to ~2 m by 2070–2100 under RCP8.5, from the combined changes in sea level and waves. However, in some regions the effect is projected to be smaller, such as the southern and central North Sea, where the majority of current wind farms are installed.

The corresponding increase in load on platforms and turbine structures can be assessed by

extrapolating existing design approaches. The change may be only a small fraction of the total load but in some situations could be a large step increase. For example, where an ‘air gap’ is allowed beneath a platform so that extreme waves pass through the platform legs but do not impact on the structure, the rise in extreme wave elevation could bring water into contact with the platform. This threshold will cause a sharp rise in the extreme load and structural risk that is disproportionately greater than the rise in the wave crest height. A systemic design change and remediation or mitigation process would be triggered by this threshold, if reached.

Deck structures and access platforms that are not designed to resist direct wave forces are required by design codes to have an adequate air gap from the bottom of the structure to the elevation of the highest wave crest. For example, the DNVGL-ST-0126 design code for offshore wind turbines requires an air gap of at least 20% of the SWH (or 1 m at minimum) with a return period of 50 years.

Strategies to incorporate the effects of climate change into design input parameters for the stability of structures are in their infancy. The concept of considering both ‘start of life’ design inputs and also ‘end of life’ inputs, which are selected allowing for climate change forecasts, is described by Brown *et al.* (2019) using an oil and gas project in the far east as a case study. Comparable published strategies for UK waters have not been found. Some design codes for offshore infrastructure reference climate change when setting out how design values should be selected. For example, the DNVGL-ST-0126 design code for wind turbine support structures states that future changes in sea level should be considered. However, design codes do not prescribe a specific basis for this selection. Meanwhile, the National Policy Statement for Renewable Energy (2011), among its considerations for climate change adaptation, requires that applicants building offshore wind farms “should particularly set out how the proposal would be resilient to storms.”

Finally, failure or damage rates for existing infrastructure, such as wind turbines, are not publicly available. Wind farm reliability studies often rely on old data sets from onshore turbines (e.g. Martin *et al.*, 2016, Dao *et al.*, 2019). There is therefore a data gap on the current failure rates and structural performance, as well as uncertainty about potential future changes in loading and therefore stability and machine degradation.

4.12.1.2.2 Effect on the energy yield and operating window (periods of operation) of turbines

A rise in wind speed leads to increased energy production by wind farms, but this also causes an increase in wear and maintenance requirement and reduces the accessibility for crew vessel transfers. Changes in the wave and wind climate lead to a change in the capacity factor of wind turbines, i.e. the annualised electricity yield relative to their rated capacity. Based on the RCP 6.0 forecast, Hdidouan and Staffel (2017) examined the change in capacity factor for offshore wind around the UK, to 2050 and 2080. They found a small (<1%) change for farms east of England in the North Sea, with small increases in capacity factor moving further north, reaching 5% to the north and west of Scotland. These variations are comparable to the current 1-2% year-on-year variation in capacity factor across the entire UK fleet of wind farms associated with annual variability in storm events and other operational issues (Crown Estate, 2018). Chapter 1 (Slingo, 2021) highlighted recent climate modelling which suggests a reduction in average wind speeds and corresponding power output during summer periods, however this has not been quantified. The seasonal pattern

of power supply has ramifications for network management.

In addition to climate-related changes in average wind speed, a shift in the storm track paths or the strength of the driving forces due to the NAO could lead to a change in the spatial distribution of wind speeds around the country (Cradden *et al.*, 2015). There is some evidence to suggest that the paths of incoming Atlantic storms may change under future climate change scenarios (e.g. Jiang and Perrie, 2007; Woollings *et al.*, 2012; Zappa *et al.*, 2013) although confidence in such projections is low. Cut-in and cut-out wind speeds for wind turbines have remained practically unchanged as the size of devices has evolved over the past decade, with typical values of 3 or 4 m/s and 25 m/s, respectively (Gaertner *et al.*, 2020).

The changes in annual mean SWH due to climate change affect the energy available for harvesting by wave energy devices. Reeve *et al.* (2011) used Cornwall's wave hub facility and a particular Wave Energy Converter (WEC) to provide a case study of the effect of climate change on wave energy yield. Their study examined projected changes for the period 2061 – 2100 for scenarios that reached approximately 3°C and 4°C global warming at the end of the century¹⁹. Their modelling projected reductions in mean annual yield of 2-3% relative to present day conditions for both scenarios due to a combination of increased downtime and changes in device efficiency with wave steepness. These changes are small relative to the inter-annual changes in yield and also the likely improvements in the power and yield of commercial WEC systems by 2100.

Tidal stream devices, being underwater, are less susceptible to changes in sea level and SWH and are generally located in regions of shallow water.

4.12.1.2.3 Effect of sediment transport across the seabed, and the integrity of subsea infrastructure

Sediment transport can lead to the migration of small ripples or large sand waves across the seafloor, as well as the generation of deep scour holes, 2–3 diameters deep, around the legs of platforms and wind turbines. Sediment transport and scour can affect the stiffness and stability of wind turbines and can damage subsea cables. In UK waters, two wind turbines have been removed from the Robin Rigg farms due to sediment transport causing a loss of foundation support (Smith and Lamont, 2017).

The changes in annual mean and maximum SWH projected by UKCP18 may trigger sediment transport at locations where it does not currently occur, or stabilise sands that are currently mobile in other areas, so there is the potential for unexpected problems associated with sediment transport. Research has been instigated into the hazard of scour in the face of climate change (Arboleda Chavez *et al.*, 2019). However, the future change in risk level to existing and new offshore infrastructure has not been explored in published studies.

Cable failures are a particular criticality for wind farm availability because failure of a single cable can prevent production from a large part or all of a wind farm, as compared to a single turbine failure, which does not affect the other turbines. According to an insurer's analysis, 77% of the losses from a

¹⁹ SRES B1 and A1B scenarios

global analysis of wind farms are attributable to cable failures (Gulski *et al.*, 2019). A separate analysis identified that approximately 50% of subsea cable failures are attributed to environmental conditions, leading to abrasion or other damage (Dinmohaddi *et al.*, 2019). Therefore, subsea cables are notably exposed to changes in the offshore environment such as scour and sediment transport due to climate change, although currently these risks have not been quantified.

4.12.1.2.4 Effect of the accessibility of structures for maintenance, inspection and crew transfer

The projected reduction in mean SWH across the southern and central North Sea projected by UKCP18 will widen operating windows for vessels and improve accessibility to offshore installations. The availability of a wind farm – i.e. the proportion of time that it is available for power generation – is affected by accessibility when maintenance is required (Brooks *et al.*, 2020). Simulations by Dinwoodie *et al.* (2018) show that although availability can be close to 100% in summer, during winter months the accessibility falls, because of the limited weather windows for vessel access. Their study did not make predictions of the change in accessibility for specific future climate scenarios, but a variation case with 10% lower SWH showed an approximately 10% rise in availability, from typically 75–85% during the winter season.

In the future, autonomous and remote monitoring, and potentially autonomous maintenance, will reduce the influence of accessibility on wind farm availability. Coupled with the expected reduction in mean SWH in the southern and central North Sea, the expected change in accessibility risk of wind farms in this area from climate change is negligible or a reduction.

4.12.1.2.5 Effect of the operation of ports and coastal infrastructure for the maintenance and inspection activity

The operating and maintenance of offshore infrastructure requires transport by boat from coastal ports. Climate change will have an impact on coastlines and ports, and may affect the operation of the port infrastructure associated with maintenance bases.

4.12.1.3 Lock-in and thresholds (I11)

Since offshore infrastructure is designed for a 30 to 40-year life, and the consenting period plus construction is 5 years, then decisions now affect the capacity and resilience of offshore infrastructure and energy supply in 2060.

For example, offshore wind farms in locations where wind and wave loading will be increased by climate change will become more vulnerable and less available. Therefore, although the changes in vulnerability highlighted above are generally small relative to the annual and decadal variability from other effects, the risk is locked-in because adaptation is costly once structures are installed.

Oil and gas infrastructure that is currently reaching the end of production life may form part of a future CCS system. The decision to remove or adapt this infrastructure for CCS will affect whether this opportunity remains.

As wind farms move into deeper water, further from shore, there will be a progressive increase in the proportion of turbines that are supported on floating platforms rather than being fixed to the seabed. Floating wind platforms have different accessibility, availability, and reliability relative to fixed wind, so the risks highlighted above may change in severity as the proportion of offshore wind sited on floating platforms increases. The rate at which floating wind expands will depend on policy as well as technical drivers, including the approach to integrate intermittent renewable energy and energy storage across the UK's grid (Moore *et al.*, 2018). Currently the transition from fixed to floating wind is driven by economic and marine spatial planning drivers, but this threshold may also represent an adaptation that affects climate change resilience.

A further threshold highlighted above is the elimination of the 'air gap' beneath structures by rises in sea level and extreme wave elevation, causing a significant step increase in loads on structures. A systemic programme of remediation or mitigation would be triggered by this threshold.

4.12.1.4 Cross-cutting risks and inter-dependencies (I11)

The high reliance on offshore wind and subsea cables adds vulnerability to the electricity grid and the need for balancing capacity. 'Cut-out' events in storms or due to delayed maintenance caused by inaccessibility in high waves will have a greater impact in the future than they currently do. This creates an interacting risk with the overall energy system, which needs greater resilience when it is more dependent on wind energy (e.g. Bloomfield *et al.*, 2018). This risk may also have international implications due to the increased numbers of electrical interconnectors.

The installation and maintenance operations of offshore infrastructure can only be carried out under restricted environmental conditions and adequate weather windows, at both the infrastructure and the port or shore bases. As discussed earlier, climate change may impact such activities and potentially result in longer downtimes due to limited access to infrastructure during unfavourable environmental conditions. As a result, this creates an interacting risk with the need for energy storage or other back-up sources to support the electricity grid, as it becomes more reliant on offshore wind.

4.12.1.5 Implications of Net Zero (I11)

The UK's fleet of offshore wind turbines is expected to at least double by 2030 reflecting the UK Government aim to reach 40 GW of installed capacity by then. The CCC's balanced pathway to Net Zero by 2050 involves 95 GW of offshore wind capacity by then, and they recommend an aim of 75–140 GW of offshore wind being deployed by 2050 to cover different scenarios. This 95 GW target will require on the order of 10,000 turbines to be operating in UK waters in 2050, occupying 1–2% of the Crown Estate seabed. For this future fleet of ~10,000 turbines, a typical requirement of 5 visits per year to each turbine corresponds to >100 wind turbine boarding's per day, although changing monitoring and maintenance methods may reduce this requirement.

Since the UK's electricity supply will rely more heavily on offshore wind, the requirement for balancing generation and electricity storage will increase, to address the risk associated with supply variability including intermittent cut-out of wind farms. In addition, a larger proportion of UK power

will be supplied via electricity, for example through the electrification of transport. This raises our reliance on the offshore infrastructure of wind farms and subsea cables for balancing transmission of electricity to and from Europe.

The UK's operating offshore oil and gas facilities are likely to decline in number towards 2050, but when a field shuts down there are significant offshore operations associated with decommissioning works, which involve large crewed vessels operating to remove structures and also plug and abandon wells. While oil and gas production is in decline, some of the associated infrastructure will remain in place after decommissioning (RAE, 2013), and may be repurposed for carbon capture and storage infrastructure (Williams *et al.*, 2013).

4.12.1.6 Inequalities (I11)

None identified at present.

The amount of oil and gas infrastructure in UK waters has been stable since the previous CCRA report in 2017, and there is no new evidence to suggest a change in the overall hazard for the present time. Although exposure has slightly increased due to the deployment of new wind farms (currently there are about 3000 offshore wind turbines installed or under construction in UK waters, with recent wind farms in new regions including the Moray Firth and the English Channel), there is no new evidence to suggest a change in the current magnitude of risk since the last CCRA.

The UK Government has put offshore wind at the heart of the national energy future, through the Offshore Wind Sector Deal and the Net Zero roadmap. The quantity of offshore renewable energy infrastructure will therefore increase significantly over the 21st century, along with society's reliance on its electricity supply. Owing to this increasing offshore renewable energy infrastructure, and the continued presence of a large fleet of oil and gas platforms that may be repurposed for carbon sequestration and storage, and thus remain operational beyond their initially-intended lifespan, the risk exposure of offshore infrastructure will grow significantly.

The UK has historically relied on offshore infrastructure for energy production through oil and gas, but this has been imported from diverse overseas locations in addition to production in UK waters. By 2050, Net Zero projections indicate approximately 50% of UK electricity will be generated by offshore wind in UK waters (CCC 2020b), so energy security will be strongly dependent on the continued operation of around 10,000 offshore wind turbines – five times more than are currently installed.

Meanwhile, the confidence in current projections of the effect of climate change on offshore environmental conditions is low, according to the UKCP18 Marine Report. Also, the length of experience of offshore wind farm operations and resilience is relatively short, due to the limited timespan of this industry to date. Therefore, long term effects are not yet fully understood.

4.12.1.7 Magnitude scores (I11)

The projected consequences of climate change on offshore infrastructure outlined above are generally low, and in some cases represent a reduction in risk. However, the low confidence in the projected changes in the environment coupled with the short timescale of experience and evidence of offshore wind operations as well as the rapid growth of this infrastructure, its vulnerability to changes in environmental conditions, and its importance to our energy system, leads to a Medium classification of the future magnitude of risk.

Table 4.46. Magnitudes score for risks to offshore infrastructure from storms and high waves

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Northern Ireland	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Scotland	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Wales	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

4.12.2 The extent to which current adaptation will manage the risk (I11)

4.12.2.1 Effects of current adaptation policy and commitments and on current and future risks (I11)

4.12.2.1.1 UK-wide

Adaptation of offshore infrastructure design and operation to account for the changes described above is taking place via the following two routes, which manage and mitigate the risks.

The design of offshore infrastructure is highly regulated by international standards. These codes have evolved from the oil and gas industry, which is inherently hazardous and has a good framework for assessing and mitigating hazards and risk. These design codes are evolving to include requirements to allow for future effects of climate change in the selection of environmental loads

and other actions on offshore infrastructure. For example, the most recent update of ISO 19900, which is the top-level ISO Standard for offshore structures, introduced a recommendation that changes in design conditions due to climate change be considered (ISO, 2019). Similarly, the design standard that is most widely used by the offshore wind industry, states that sea level rise due to global warming must be included in extreme wave elevation calculations (DNVGL, 2016).

Government and the private sector are both heavily investing in offshore renewable energy industries. The UK government is strongly committed to a successful offshore wind industry, for example through the Offshore Wind Sector Deal (HM Government, 2019b), as Point 1 of the Ten Point Plan for a Green Industrial Revolution (HM Government, 2020b), and through its role in planning and consenting of new projects, overseen by the Crown Estate and the Crown Estate Scotland. Meanwhile, the owners and operators of offshore wind facilities are major organisations with long term commitment and investment in their wind farm projects, each of which represent a multi-billion-pound investment, with the 30 to 40-year horizon.

4.12.2.2 Effects on non-government adaptation (I11)

The oil and gas industry has historically applied adaptation as environmental conditions change or become better understood, leading to revised design assumptions. This process is continuing via the same protocols to accommodate climate change. Examples of these provisions as applied to a particular design cases are presented by Toumi *et al* (2008) and Brown *et al* (2019).

Research and development are unlocking new technologies to support the offshore renewable energy industry, providing potential adaptation routes to mitigate climate change effects. These new technologies include floating offshore wind platforms, robotic and autonomous inspection and maintenance, and tidal turbines and wave energy devices. These technologies offer alternative solutions to develop offshore energy that have different exposures to the effects of climate change. The UK has a world-leading capacity for fundamental and applied research related to offshore energy for renewable energy, legacy oil and gas infrastructure, marine science, and oceanography (e.g. BEIS, 2016, 2017).

4.12.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I11)

As outlined above, offshore energy infrastructure is heavily regulated in design and operation. The stakeholders span government, the private sector and academia, and have the expertise and resources to implement climate-related adaptations in the design and operation of new infrastructure. Meanwhile, new technologies are providing new adaptation pathways to mitigate climate change effects. The offshore renewable energy industry is relatively new and is rapidly growing in scale and moving to new offshore regions. As a result, there is currently a limited evidence base for the current risk levels and vulnerability. If the actions outlined above continue to take place, it is expected that the risk to offshore infrastructure will remain at the current levels or reduce. It is therefore likely that there will be no adaptation shortfall in the next 5 years.

4.12.2.4 Adaptation scores (I11)

Table 4.47 Adaptation scores for risks to offshore infrastructure from storms and high waves			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Yes (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)

4.12.3 Benefits of further adaptation action in the next five years (I11)

4.12.3.1 Additional planned adaptation that would address the adaptation shortfall (I11)

Adaptations are outlined in Step 1 and include changes to the design loads, extreme wave elevation and accessibility of offshore infrastructure for maintenance and crew transfer. In some regions these changes represent a rise in risk, and in others the net effect may be a reduction (i.e. a reduction in wave height counteracting the rise in sea level). Also, the expected changes in average annual energy production per unit of installed capacity by 2100 are comparable to the existing year-to-year variability. All these forecasts are predicated on the projected effects of climate change on the marine environment, for which there is currently low confidence. Given the anticipated expansion of offshore renewable energy in order to meet Net Zero and current low confidence in marine projections, further investigation into the potential changes in relevant climate metrics including wind and wave heights could better inform design and siting choices.

4.12.3.2 Indicative costs and benefits of additional adaptation (I11)

This risk is evaluated as Sustain current action. As with the previous risks, the potential changes in the offshore wind regime and implications for offshore energy infrastructure (notably offshore wind), as well as other offshore risks (e.g. wave regimes), requires periodic review (e.g. Stewart *et al.*, 2014), but there are technical designs for turbines as well as operational management options to address potential changes should these emerge, and a general recommendation on the use of climate risk assessment in new project design and appraisal. Offshore, subsea cable failures are currently the most important failure risk; these can occur from changes in tidal flows (Dinmohammadi *et al.*, 2019) and might warrant further consideration of risks.

4.12.3.3 Overall urgency scores (I11)

Based on the assessment of current and future magnitude of impact, as well as the judgement that current and announced actions should maintain or reduce this magnitude, it is assessed that current actions should be sustained. This is assessed with medium confidence. This may need to be reassessed pending developments around Net Zero and the growing importance of offshore infrastructure, especially energy generation from wind.

Table 4.48 Urgency scores for risks to offshore infrastructure from storms and high waves

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Sustain current action	Sustain current action	Sustain current action	Sustain current action
Confidence	Medium	Medium	Medium	Medium

4.12.4 Looking ahead (I11)

To support the current adaptation activities to further actions are identified:

- Improvement of confidence in projections of the changing marine environment. These projections currently have low confidence and are at a coarse regional scale,
- Improvement of baseline data documenting the performance and reliability of new types of offshore infrastructure, such as offshore wind turbines.

The UKCP18 Marine Report identifies a low confidence level in projections of the future wave climate and wind conditions in offshore regions. These projects also have a coarse regional scale, so offer limited quantitative evidence for local vulnerabilities such as changes in the movement of sand banks or erosion of seabed sediment at particular locations.

The offshore wind industry is undergoing a rapid expansion and there is a limited track record of performance data available for assessing adaptation requirements. As noted previously, the available reliability and failure data is predominantly from smaller onshore wind turbines. For effective adaptation, it will be necessary for the performance of the current and new infrastructure to be monitored and analysed to determine baseline data, which can be used to improve projections of future scenarios. The international element of this risk associated with increased numbers of electrical interconnectors is an area which may benefit from further research.

4.13. Risks to transport from high and low temperatures, high winds and lightning (I12)

The current risk magnitude score for transport is medium, with high confidence. For future scenarios, the risk magnitude is high with low confidence. Heat-related rail buckling is identified as a key issue (but note that progress on adaptation in the rail sector is generally well-advanced). The urgency score for the whole UK is 'more action needed' with medium confidence, acknowledging that action will varied between modes and for different climate hazards, with further research also needed where appropriate. Although transport was included in CCRA2, it was combined with the energy and digital sectors and assessed on the basis of hazard (e.g. 'Risks to energy, transport and digital infrastructure from high winds and Lightning'), hence this precludes a direct comparison between assessments.

Assessment of planned and announced adaptation actions within the transport sector indicate that the risk is only being partially managed across the system. Although there are examples of good practice within individual transport modes and emerging activities taking place, the approach to managing climate risks across the transport infrastructure is not comprehensive and is not being undertaken from a mobility/whole-systems perspective.

As well as tackling existing issues such as avoidable uncertainty in basic asset data, reducing climate risks to transport will require the formal assessment of the future electrified transport systems that will be required to meet the UK's Net Zero commitments. This will include the identification and mapping of new interdependencies with the energy sector (electricity generation, transmission and distribution networks) and the digital/ICT sector.

4.13.1 Current and future level of risk (I12)

Note: it has not been possible to split the evidence by UK country for this risk.

4.13.1.1 Current risk (I12)

4.13.1.1.1 UK-wide

4.13.1.1.1.1 Rail (current risk)

Network Rail (2017a) reported that the impact of high temperatures on their network was responsible for over £20 million in compensation payments to Train Operating Companies (TOCs) between 2006 and 2016. Heat can cause rails to buckle, overhead cables to sag, signals to fail and prevent maintenance from being performed (RSSB, 2015). Railway assets tend to demonstrate threshold temperatures, beyond which failures manifest. For example, to maintain seasonal resilience to the average UK climate, Network Rail 'pre-stress' rail to a stress-free temperature (STF) of 27°C. In reality, once the track is laid, this resilience reduces as the ballast moves and settles, meaning STFs can be 3°C lower within a year, hence maintenance (particularly tamping) is essential to maintain resilience.

Network Rail (2015) state that failure rates for most of their railway assets start to increase notably at temperatures as low as 20°C, thereafter increasing more dramatically from 26°C. Although modernisation of certain assets such as overhead cables with auto-tensioning have reduced their vulnerability to heat, RSSB (2015) state that modern signalling is more susceptible to heat due to its dependence on electric and electronic components. Many railway components require further research to determine failure thresholds (Ferranti, 2016).

Ferranti *et al.* (2018) present a notable example of the impact of a heat event on the rail network of Great Britain. The 1st of July 2015 saw temperatures as high as 37.5°C (at Heathrow, the record for July at the time). Heat-related incidents on major routes such as London North Eastern (which connects London and Scotland) and at critical nodal points in the network, such as near Manchester Piccadilly, caused major disruption. Across Great Britain, failure and impairment of assets, as well as

emergency speed restrictions, caused 220,000 delay minutes, with all regions experiencing at least double their daily average delay minutes, costing an estimated £16 million to the national economy.

Ferranti *et al.* (2016) looked at the vulnerability of South East England's railway network to heat, particularly how the impact of a given heat event depends on its timing within the onset of the summer season. It was argued that the 'failure harvesting' phenomenon, where at-risk assets fail when they reach a critical temperature for the first time in a given year, can mean the risk profile for rail can sometime reduce during the course of the summer. Hot spots of incident occurrence were observed in urban regions such as London (owing to the concentration of infrastructure and urban heat island effects). Effects on Network Rail signalling were seen to be particularly significant, accounting for 53% of heat-related incident costs and 51% of delays in the South East of England. The conclusions around failure harvesting were borne out with the prolonged heatwave in summer 2018 which caused a 40–50% increase in asset failure rates on hot days compared with those expected on normal days, with hot days earlier in the year (April–June) seeing increases of up to 80%.

Wind accounted for approximately £145 million in compensation payments between Network Rail and TOCs between 2006 and 2016 (Network Rail, 2017a). Of the 37,820 weather related incidents in England between 2006/07 and 2017/18, 31% were attributed to wind and 23% to snow (ADAS, 2019). Wind can disrupt operations by blowing branches, trees and debris onto the line, with 2.5 million trees estimated to be growing alongside the rail network. Fu and Easton (2018) used a logistic regression model to study the contributing factors to wind-related rail incidents for the Anglia Route between 2006 and 2015. The likelihood of an incident was shown to be greatest for north-easterly winds, and decreased by more than 60% for south-westerly winds.

Network Rail (2017a) reported £40 million in compensation payments to TOCs due to the impact of lightning on their network between 2006 and 2016. Lightning can cause damage to electronic equipment, line-side trees and buildings as well as cause line-side fires. As outlined in Risk I11, the damage lightning causes to the electricity transmission and distribution system can have knock-on impacts to the railways, such as the power outages in England and Wales on the 9th of August 2019 (Ofgem, 2020a).

Between 2006 and 2016, heat caused an annual average of approximately £2 million in Schedule 8 compensation payments between Network Rail and TOCs. For lightning this was approximately £4 million and for wind £14 million (Network Rail, 2017a). These figures are for the whole of Network Rail's GB network (England, Wales and Scotland). The wider costs to the economy and society of major incidents are considerably higher than the cost to the infrastructure managers and TOCs, as exemplified by the July 2015 heat wave outlined above (estimated cost £16 million). Network Rail estimate that although the impact of weather on their business is £50-200 million (Network Rail, 2021), they estimate that this rises to £100-£300 million when considering social and economic impacts (a three to four fold rise). These figures indicate medium magnitude with high confidence.

4.13.1.1.1.2 Roads (current risk)

High summer temperatures can increase thermal loading on bridges and pavements causing

expansion, bleeding and rutting, as demonstrated during the 2003 and 2006 heatwave events (Willway *et al.*, 2008). Wildfires can lead to road closures if the fire burns next to the road or crosses it, or if large volumes of smoke obscure vision. The Swinley Forest Fire in 2011 led to closure of the A3095 for a week which cost around £229,292 (Aylen *et al.*, 2015). Cold weather (including snow and ice) caused 16% of all weather-related delays to the strategic road network in England between 2006 and 2014 (ASC, 2014). Wind impacts road operations, with high sided vehicles becoming unstable in gusts of wind over 45mph (particularly on exposed bridges). High winds can also damage roadside furniture, such as traffic signs, and blow nearby vegetation onto the road. In a notable example, the opening of the Queensferry Crossing across the Forth in 2017 has allowed key transport and supply routes to remain open between Edinburgh, Glasgow and the Central Belt and the north of Scotland, due to increased wind shielding compared to the Forth Road Bridge.

The CCC (2019) observe that the strategic road network is younger than the rail network with most of the network built since the 1950s utilising modern materials and design. They state that Highways England are meeting performance targets, with 95% of the network in good condition. The local road network is considered to be particularly vulnerable to severe weather, as it makes up 98% of the country's road network, ranging from major 'A' roads to minor country lanes. They also cover a far wider range of geographic locations, and hence more varied microclimates (CCC, 2019).

In Scotland, a combination of topography and climate can increase risk. This includes steep slopes, higher altitude and exposure, loss of original tree cover, a more extreme climate and greater exposure to winter storms (Scottish Government, 2019b). Remote areas in the Scottish Highlands and islands are often served by single routes which can lead to isolation or detours during disruption.

The DfT Resilience Review (2014) stated that roads in better condition should be better able to withstand severe weather impacts, and that higher temperatures, flooding and geotechnical movement can speed up deterioration and lessen their resilience. The DfT's Road Condition report (2019) determined that following a period of gradual improvement, condition of classified local authority managed roads has remained stable in recent years. During the same period, unclassified roads had not seen the same level of improvement. Highways England managed motorway condition has gradually improved since 2007/8 (managed 'A' roads have fluctuated).

There is a general lack of quantified data on the impact of high and low temperatures, wind and lightning on road infrastructure, hence the score of 'low' for confidence.

4.13.1.1.1.3 Air Travel (current risk)

Higher temperatures can cause problems with runway conditions and the flashpoint of aviation fuel. These factors, combined with changes in air density, would result in greater fuel usage and potentially longer runways for take-off (Heathrow Airport, 2016). Overheating of standing aircraft occurs at temperatures above 25-30°C and requires the use of aircraft Auxiliary Power Units (APU) or preconditioned air (PCA) to cool aircraft (Stansted Airport Ltd, 2016). Snow and ice can cause severe disruption to operations, as demonstrated by the heavy snow of December 2010 (Begg Report, 2011). Finally, Time Based Separations (TBS), such as those introduced in 2015 at Heathrow, can be

used to reduce delays and cancellations due to strong headwinds. This can add four plane movements per hour on strong wind days, leading to a 50% reduction in annual delays attributable to strong winds (Heathrow Airport, 2016).

4.13.1.1.1.4 Water (current risk)

High wind speeds can lead to the suspension of port operations. For example, sustained wind speeds of 22 m/s or greater will result in the suspension of vessel operations at the port with any stoppages greater than four hours in duration being considered 'major stoppages' (Milford Haven Port Authority, 2015). It was particularly noted that 2014 had been a difficult year in respect of crane stoppages due to high winds. The Port of Dover (2015), reported a number of wind-related thresholds for different operations. For instance, the port is closed during sustained wind speeds above 55 knots from a South South Westerly and West South Westerly direction. A wind speed of 37 knots and above was given as a threshold for overtopping at Admiralty Pier. Lightning strikes were reported to cause temporary dips in power, causing failure of quay crane equipment (Felixstowe Dock and Railway Company, 2016).

Table 4.49 UK-wide magnitude scores for current risks to transport from high and low temperatures, high winds, lightning	
Risks to rail from high and low temperatures, high winds, lightning	Medium (High confidence)
Risks to roads from high and low temperatures, high winds, lightning	Medium (Low confidence)
Risks to air travel from high and low temperatures, high winds, lightning	Low (Medium Confidence)
Risks to water from high and low temperatures, high winds, lightning	Low (Low confidence)
Overall magnitude scores for current risks	Medium (High confidence)

4.13.1.2. Future risk (I12)

4.13.1.2.1. UK-wide

4.13.1.2.1.1 Rail (future risk)

Evidence collected during CCRA2 indicated an eight-fold increase in the annual cost of buckling by the 2080s under a high emissions scenario using the UKCIP02 projections (Dobney *et al.*, 2009). Temporary speed restrictions were expected to quadruple from 0.5 to 2 days per summer season. In a scenario of 4°C global warming by 2100²⁰, more frequent extreme temperatures are projected to reduce the number of days when track maintenance can be undertaken across the UK, with the greatest (threefold) increase in Scotland by the 2040s (Palin *et al.*, 2013). The exposure of staff working outdoors to heat stress is also projected to increase, most significantly in the south and east

²⁰ UKCP09 HadRM3 regional climate model 11-member perturbed parameter ensemble driven by the SRES A1B scenario.

of England where events could be 2–9 times more frequent by the 2040s (Palin *et al.*, 2013). However, there are projected to be opportunities arising from fewer snow and ice days to reduce winter maintenance costs (Dora, 2015).

Arnell *et al.* (2021) present a consistent set of policy-relevant indicators of changing climate hazards for the UK. For the rail sector temperature thresholds of 26°C and 30°C were identified in the literature as relating to rail buckling risk. The study also used Network Rail's adverse weather warnings thresholds which are set for sustained wind speed above 40mph, maximum temperatures above 25°C, minimum temperatures below 3°C, daily rainfall > 40 mm, snow depth > 50 mm or a diurnal temperature range of > 16°C. Projections for two of these indicators using scenarios of 2°C and 4°C global warming at 2100²¹ is presented in Figure 4.12. The greatest increase in the transport indicators is seen in England and Wales. Scotland and Northern Ireland see shallower increases in heat-related transport indicators (although the indicators do not account for differences in the resilience of the networks in the UK and potentially lower thresholds / critical rail temperatures) and an initial decrease in adverse weather warning days as a result of reduced cold weather impacts (it must be noted this indicator includes hazards outside of the scope of this risk).

In a scenario of 4°C global warming by 2100²², the heatwave season is expected to expand from July–August to May–September by the 2040s, and by the 2080s over half the UK is projected to experience heatwave conditions at some point every year (Sanderson and Ford, 2016a). The advent of digital signalling systems such as the European Railway Management System (ERTMS), in the long-term (2050s), may remove a significant quantity of trackside signalling equipment (Ferranti *et al.*, 2018), potentially reducing heat-related risk to railway operations. The extent of impacts will also be mediated by future freight and passenger numbers and the availability of alternative modes of transport (cross-modal substitution is important across all components of the transport system). In the 2050s under the UKCP09 high emissions scenario, which warms faster than the CCRA3 higher scenario, all deep London Underground lines are projected to experience near complete passenger discomfort during the summer (Jenkins *et al.*, 2014).

Longer growing seasons were judged to increase vegetation growth rates, increasing the number of tree-related faults and disruption. However, large uncertainties surround the impact of climate change on vegetation making the possible outcomes for growth rates, species, and leaf fall difficult to ascertain (Carey, 2015). No projections existed for future storm or lightning damage to rail services. CCRA2 noted the need for better understanding of projected changes in maximum wind speeds and the frequency of such events.

²¹ Subsets of the UKCP18 probabilistic projections for which the global mean temperature anomaly reaches 2°C or 4°C above 1850-1900 in 2100.

²² SRES A1B scenario

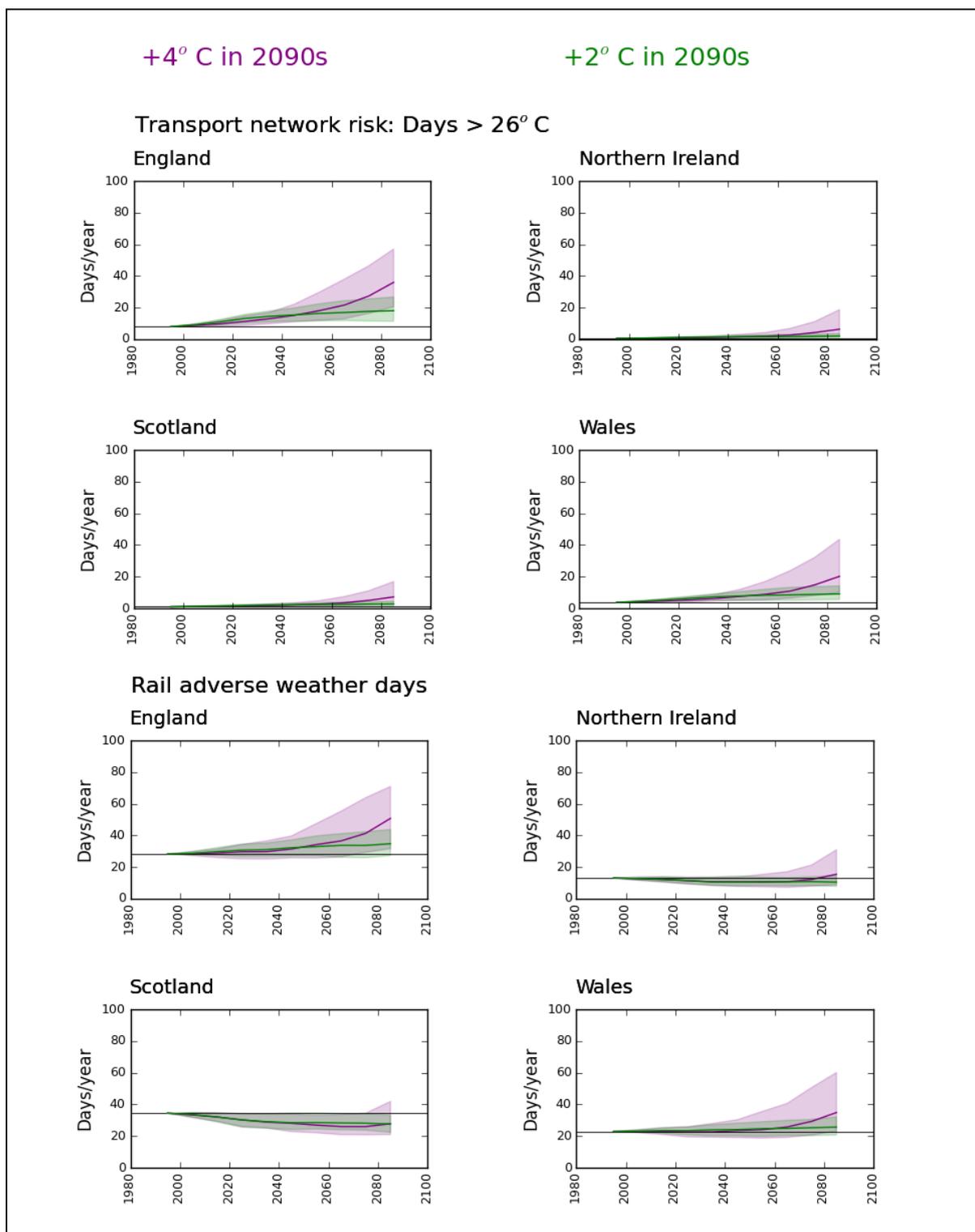


Figure 4.12. Climate Risk Indicators for rail by nation projected for pathways to 2°C (green) and 4°C (purple) global warming in 2100. Top 4 panels show days per year with temperatures exceeding 26°C, associated with rail buckling risk. Bottom 4 panels show number of days per year with either wind speed, rainfall, snowfall, maximum temperature, minimum temperatures or diurnal temperature range passing specific thresholds either individually or in combination, all of which are associated with disruption to rail travel. Plumes shows the median and 10th to 90th percentile ranges of 30-year means plotted at the middle year of the period. Modified from Arnell *et al.* (2021).

4.13.1.2.1.2 Road (future risk)

Highway's England's Climate Change Risk assessment (2016) uses a scenario compatible with the CCRA3 pathway to 4°C global warming by the end of the century²³ to identify vulnerabilities. Using these projections, and research from the Conference of European Directors of Roads (CEDR), Highways England highlighted climate change hazards with potential to impact their services and network users. Amongst the risks highlighted with high importance were increases in maximum temperature with associated extreme summer temperatures and increased wind speed for the worst gales, leading to wind speeds more frequently exceeding operational limits. They also identify a number of operational or other thresholds for action including incidence of ground frost, temperatures above which asphalt surfaces rut or stripping occurs and the length of the frost-free season (allowing reduction in winter maintenance standby requirements). Although snow and cold temperature events may decrease, any associated reduction in preparedness or increased complacency may reduce the extent of any benefits. Weather conducive to wildfire is projected to occur more frequently in all UK countries (Arnell et al., 2021), so if this results in more frequent or severe fires near roads then disruption from reduced visibility due to smoke or direct threat of fire could occur more often. There is currently a lack of quantified projections for the impact of climate change on road infrastructure and operations.

4.13.1.2.1.3 Air Travel (future risk)

It was stated in CCRA2 (Dawson *et al*, 2016) that the impacts of climate change on UK aviation were expected to be the least significant of all transport modes. Clear-air turbulence during the cruise phase of flights is projected to increase due to climate change, increasing journey length and fuel consumption. Williams and Joshi (2014) examined the effects on clear air turbulence at approximately 3°C global warming²⁴, in December, January and February in the North Atlantic flight corridor between Europe and North America. They found a 10–40% increase in the median strength of turbulence at typical cruise altitudes, but with up to a 170% increase in the frequency of greater than moderate turbulence. Williams (2016) studied transatlantic crossings and projected that a strengthening of prevailing jet stream winds would cause eastbound flights to significantly shorten and westbound flights to significantly lengthen in all seasons, with round-trip journey times increasing.

Anticipated increases in temperature in UK airports and associated impacts are well within the range experienced by other international airports and can be managed operationally. Birmingham, Gatwick, Glasgow, Heathrow, Manchester Group (including East Midlands), and Stansted Airports all reported for ARP2. All used broad UKCP09 scenarios and a workshop approach to arrive at risk registers for key assets and functions. Gatwick used low, medium, and high scenarios at the 90% probability level at the 2020s and 2050s, with the medium scenario reaching 4°C global warming by the end of the century. However, no mention is made of heat, high winds or lightning in the identified risks or adaptation measures. Take-off weight restrictions for aircraft may be lowered, as warmer air reduces the lift force on the wings (Coffel and Horton, 2015).

²³ SRES A1B scenario

²⁴ Projected with the GFDL CM2.1 climate model with CO₂ concentrations at double the pre-industrial level

4.13.1.2.1.4 Water (future risk)

It is recognised that projections of wind events are extremely uncertain, with no strong trend discernible (Met Office 2019b), acting as a barrier for their use to project future impacts (Milford Haven, 2016). The DfT’s 2018 port connectivity study highlights the importance of interdependencies with other infrastructure, particularly the preparedness of the road and rail networks for climate change.

Table 4.50 UK-wide magnitude scores for future risks to transport from high and low temperatures, high winds, lightning	
Risks to rail from high and low temperatures, high winds, lightning	High (Medium confidence)
Risks to roads from high and low temperatures, high winds, lightning	Medium (Low confidence)
Risks to air travel from high and low temperatures, high winds, lightning	Low (Low confidence)
Risks to water from high and low temperatures, high winds, lightning	Low (Low confidence)
Overall magnitude scores for future risks	High (Low confidence)

4.13.1.3 Lock-in and thresholds (I12)

New linear infrastructure and ports planned for development have a long life-time and thus could be locked in to being at risk from future high temperatures, wind and lightning if climate change projections are not used to inform the location / route and design of these assets. Upgrades of existing infrastructure could lock in vulnerabilities associated with their location and/or choice of materials and equipment if climate projections are not considered as part of these plans.

Railway assets tend to demonstrate threshold temperatures, beyond which failures manifest. For example, Network Rail ‘pre-stress’ rail to a stress-free temperature (STF) of 27°C. Similarly, road surface coverings are also specified to certain range of temperature exposure. Any future increase in high wind speeds may also reduce the capacity of certain bridges and upland roads where high sided vehicles are at risk of toppling, increasing the case for alternatives.

4.13.1.4 Cross-cutting risks and inter-dependencies (I12)

WSP (2020) assessed impacts that are affected by a number of risks further up the chain of interactions. Travel and freight delays were found to have the largest number of upstream interactions, and the largest number of interactions across all the sectors analysed (infrastructure, built environment and natural environment). This indicates that risk emanating from other sectors

are more likely to cause travel delays. The most significant interaction contributing to travel delays was found to be the impact of heatwaves or very hot days leading to transport overheating and/or ICT services being disrupted, both in turn leading to transport delays and damaged infrastructure. This pathway was assessed as low risk in 2020 but becoming medium in 2080 under a pathway to approximately 4°C global warming in the late 21st Century, with large uncertainty²⁵.

Other examples of interactions modelled in the interacting risks project include:

- Extreme summer temperatures and/or reduction in summer rainfall leading to wildfires, poor visibility and travel delay,
- Lightning, high winds, hail and ice, heavy snow, cold, and poor visibility, all leading to transport infrastructure or hub disruptions, leading to travel delay,
- Travel delays and disruption can have subsequent knock-on impacts to the built environment, for example through loss of productivity as people are unable to get to work, and impact on health and welfare if emergency personnel and services are unable to use transport.

4.13.1.5 Implications of Net Zero (I12)

The Net Zero target is likely to have a large impact on the transport sector, both in terms of fuel substitution and modal shift. Increased electrification of rail will increase the risk of disruption caused by overhead line-sag and direct and indirect damage to lines during high wind events. However, alternative decarbonisation routes such as the introduction of hydrogen-fuelled trains would reduce exposure to these risks. A shift to more active modes of transport such as cycling may expose the public to a different set of weather-related risks when travelling (e.g. high winds).

4.13.1.6 Inequalities (I12)

Access to transport infrastructure provides access to jobs and employment, key services and education opportunities. Those living in areas of transport poverty are likely more at risk from disruptions to individual transport modes, as they do not have the choice to use alternatives, exacerbating existing problems associated with poor accessibility. A particular problem is with islands, where any disruption to passenger and freight transport via air and sea can leave these communities and economies isolated.

4.13.1.7 Magnitude scores (I12)

There are varying degrees of risk posed by the hazards presented in this section, as well as varying degrees of understanding and spatial disaggregation of the current and future risks between the different modes. Rail has the strongest evidence base for current risk. In England, Scotland and Wales, quantified costs to Network Rail run into the £10s of millions annually for the hazards under consideration (full social and economic costs are estimated in the high £10s of million). Current

²⁵ UKCP18 probabilistic projections with RCP8.5 emissions, with the 5th, 50th and 95th percentiles reaching global warming of 3.0°C, 4.2°C and 5.8°C respectively in 2070-2099.

magnitude is given as medium with high confidence (Table 4.51). Given the high financial costs of infrastructure failure (particularly heat-related infrastructure failure on the rail network), this increase translates into a revised magnitude score of high across the UK. Confidence on future magnitudes is low as the assessment of impact of risks is variable across the different transport modes.

Table 4.51 Magnitude scores for risks to transport from high and low temperatures, high winds, lightning

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium	High	High	High	High
	(High confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)
Northern Ireland	Medium	High	High	High	High
	(high confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)
Scotland	Medium	High	High	High	High
	(high confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)
Wales	Medium	High	High	High	High
	(high confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)

4.13.2 The extent to which current adaptation will manage the risk (I12)

4.13.2.1 Effects of current adaptation policy and commitments on current and future risks (I12)

Each UK nation has cross-sector adaptation plans for transport. For example, the Future Wales: National Plan 2040 (Welsh Government, 2021a) and Llwybr Newydd: Wales Transport Strategy (Welsh Government, 2021c) provide an opportunity to build adaptive management approaches in Wales to road, rail, air and water-based transport planning and investment. Each has high-level commitments to develop the resilience of transport infrastructure to the effects of climate change. Similarly, the Wales National Infrastructure Commission has recognised the importance of this issue. In Scotland, the new National Transport Strategy for Scotland (2020) guides improved resilience for the road network. The Perceptions of Trunk Road Networks in Scotland survey continues to collect data on disruptions to journeys by road due to severe weather.

4.13.2.2 Effects of non-governmental adaptation (I12)

4.13.2.2.1 Rail

Network Rail produces regional Route Weather Resilience and Climate Change Adaptation Plans for each of their operational routes in England, Wales and Scotland. These identify priority resilience measures using the UKCP09 medium emissions scenario at the 90th percentile (equivalent to a 4.2°C global temperature increase by 2100). The high emission scenario is used for assets with longer operational lifetimes. These are being updated for the next Control Period (2019–2024). The CCC gave Network Rail's adaptation plans and progress to date a high score in their progress report (2019). They state that the plans set out actions, timeframes, accountabilities, and responsibilities for implementing resilience measures, and that they act as a good starting point for a framework to embed adaptation and resilience into policies, standards, decisions and investment.

The CCC (2019) report that Network Rail is undertaking further adaptation actions beyond those set out in NAP2. These include the requirement to consider climate change risk in new infrastructure projects and embedding adaptation requirements within business as usual activities through guidance, data and tools (updated to take into consideration UKCP18 projections). It is also reported that asset teams are conducting climate change risk assessments and developing strategies and action plans from an asset management perspective which will lead to updated design, operation and maintenance standards. Results of these undertakings will feed into ARP3 reports. Network Rail are also conducting research projects to assess the vulnerability of assets and prioritise action (this includes improving understanding of the real cost of weather resilience and climate change adaptation). Other plans include the development of resilience metrics and the development of improved understanding of the interdependencies within Network Rail and wider UK infrastructure systems.

Train Operating Companies are encouraged in Rail Delivery Group's Key Train Requirements document to improve the resilience of their rolling stock. This guidance informs train design franchise specifications, and specifically references lifetime resilience of rolling stock to a range of climate conditions (although it doesn't utilise scenarios).

The (London) Mayor's Transport Strategy (2018) includes an aim to improve the evidence base for cost-effective long-term climate adaptation in Greater London. Identified risks will be addressed through construction and asset renewal, ensuring major projects are climate-proofed for their intended lifetime, and identifying high-priority locations for resilience interventions.

The CCC (2019) conclude that the actions in NAP2 are likely to be reducing vulnerability in some areas in England. However, without better indicators available it is hard to assess their impact. It is also mentioned that actions are currently focussed on flood risk, slope stability and bridges.

In Northern Ireland, Translink (DAERA, 2019) have committed to carry out a detailed tree survey which will examine the risk of tree related incidents due to high wind events. Translink have also committed to carry out a project to update the Stress-Free Temperatures records for rail and to identify locations that could be at risk during extreme heat.

There are a number of policies in the Scottish Climate Change Adaptation Programme (Scottish Government, 2019b) related to adaptation of rail infrastructure. The new National Transport Strategy for Scotland (Scottish Government, 2020) includes a Policy to 'Ensure the transport system adapts to the projected climate change impacts'. Network Rail has produced a Route Weather Resilience and Climate Change Adaptation Plan for Scotland which incorporates a number of programmes and initiatives designed to increase resilience of the railway in Scotland to effects of weather and climate change including sub-programmes focussed on infrastructure resilience against extreme temperatures and high winds. The plan includes an assessment of current and future vulnerability of the rail network to climate impacts.

Quarterly monitoring of Network Rail and ScotRail services includes disruption due to the impacts of severe weather. The Office of Rail Regulation continues to publish a Quarterly Monitor on National Rail performance and Transport Scotland manages the performance of ScotRail across all areas including disruption due to the impacts of severe weather. Scottish Ministers also require Network Rail to work with the rail industry to develop and apply suitable KPIs for monitoring the impact and mitigation of climate change upon network disruption and the means of measuring the benefits of adaptation interventions.

4.13.2.2.2 Roads

The UK Roads Liaison Group's 2016 'Code of Practice: Well Managed Highway Infrastructure' (UKRLG, 2016) asks local authorities to utilise the UKCP18 projections for future risk and vulnerability assessments to ensure that infrastructure is located, planned, designed and maintained to be resilient to climate change.

Highways England (2017) high-level strategy document on Environment contains the ambition to ensure climate resilience is embedded in business-as-usual activities, taking into account evidence from UKCP18. The report highlights actions to mitigate increases in mean temperature (such as reviewing design standards for pavement construction) and increases in wind speeds (including monitoring the potential impact of wind on structures such as gantries to ensure design standards are appropriate). The CCC (2019) rated the strategic road network's adaptation plans as high and risk score as medium. Highways England's assessments use a high emission scenario (over 4°C global warming by the end of the century) and identify network vulnerabilities, with this information being used to update operational procedures and adaptation plans. Highways England look across all climate hazards including precipitation changes, increases in mean temperature and increases in wind speeds.

The CCC (2019) make reference to the Government's resilience Incentive Fund, which local highway authorities in England outside of London can apply for if they can show they have processes to manage extreme weather. Local road's adaptation plan and risk were both rated as medium (CCC, 2019). It is not clear from the available evidence whether there has been a systematic evaluation of climate change risks to either the local road network or to local highway bridges. Better indicators are needed to assess progress in managing the impact of climate risks on local roads.

4.13.2.2.3 Air Travel

Apart from Gatwick and Heathrow airports, which have economic licence conditions mandating the preparation of resilience plans and are therefore incorporated into their business plans, the CCC (2019b) notes that work on reducing vulnerability at most airports has mostly been reactive and the Government does not have a way of mandating resilience actions. CCC (2019b) highlights that the draft Aviation 2050 Strategy consultation proposes that Government work with the aviation industry to improve resilience to weather and refers to climate change in terms of reducing emissions but not adaptation to scenarios of 2°C or 4°C global warming.

Glasgow Airport (2016) identifies several barriers to implementing possible climate change adaptation measures. These include environmental fiscal taxes, difficulty in justifying the business case in terms of internal rates of return, regulatory constraints (evolution of new/tighter financial controls potentially restricting airports' ability to invest in measures that are not integral to meeting compliance requirements). In contrast, Heathrow Airport (2016) has begun the planning process for the next regulatory period (2019–2023). This includes a climate change adaptation risk register and incorporating climate change adaptation into business planning process.

CCC (2019b) identifies that NAP2 includes only one action for airports. This is focused on improving the understanding of risk rather than reporting on reducing vulnerability or exposure. The ARP3 reports will include climate risk assessments and steps to increasing resilience, but these are not mandatory for all airports.

4.13.2.2.4 Water

Ports are not subject to economic regulation. As a result, there is a general lack of data regarding the overall resilience of ports compared to most other regulated sectors. This means it is difficult to tell whether lessons from the winter of 2013/14 have now been learned and whether the disruption witnessed is likely or not to be repeated. Equipment in ports typically has a 20 to 100-year design life. Several ports are collaborating with other local partners to co-fund adaptation options to the benefit of ports and surrounding areas. Felixstowe port is installing equipment capable of monitoring lightning strikes which may impact on power supply continuity. This will allow the port to react, thus limiting down time / damage to equipment (Felixstowe Dock and Railway Company, 2016). Tarmac is also being replaced by more heat resilient surfaces. Most hard surfaces are covered by material that is more heat resistant than tarmac. In 2019, the CCC found that there presently isn't data to assess whether steps are being taken by ports in Scotland to manage the increase in severe weather impacts and disruption to services in future. Information that would enable an evidence-based assessment of the vulnerability might include time-series data on the number of disruptions caused by extreme weather events and the level of investment being made in improving standards of resilience.

4.13.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I12)

The risk is only partially being managed. Although there are examples of good practice within individual transport modes such as road and rail and emerging activities taking place, the approach

to managing climate risks across transport infrastructure is not comprehensive.

4.13.2.3. Adaptation scores (I12)

Table 4.52 Adaptation scores for risks to transport from high and low temperatures, high winds, lightning			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

4.13.3 Benefits of further adaptation action in the next five years (I12)

4.13.3.1. Additional planned adaptation that would address the adaptation shortfall (I2)?

In a study on the influence of uncertain asset stock data on the assessment of climate risks for railways in Great Britain, Dikanski *et al.* (2018) found that avoidable uncertainty in basic asset data (in this case related to bridge scour), can outweigh uncertainty in climate projections by an order of magnitude. They identify better asset information collection by infrastructure managers as a quick win for effect climate adaptation.

Heat-related rail buckling (and other heat-related asset failures) is a clear risk to future rail operations. CCC (2019) report that planned levels of future activity are appropriate and should continue to be implemented to ensure risk is managed. Moreover, the CCC report that actions being taken to reduce risk by the rail industry are likely reducing vulnerability in some areas, but evidence is currently lacking. This may be due to the current indicators of resilience (delay data), which may not directly indicate how the physical vulnerability of assets is changing. The Tomorrow’s Railway and Climate Change Adaptation (TRaCCA) project (RSSB, 2016b) made a number of recommendations to Government including enhanced weather incident reporting and asset condition monitoring and revised standards (for instance, increasing the stress-free temperature of steel rail in line with future climate projections). The CCC (2019) observe that although Network Rail’s route plans contain relevant actions and consider a scenario of 4°C global warming by 2100, the strategy provides guidance to prepare for future action rather than specific measurable goals to reduce risk.

For local roads, the CCC (2019) conclude that it is not clear whether there has been a systematic evaluation of climate change risks. Similarly, to rail, it is recommended that better indicators of climate resilience for roads are developed.

For ports and airports, it is clear from the CCC (2019) report that lack of engagement with the ARP process may be a barrier to adaptation. Although 16 ports and airports submitted to ARP2, another six declined to participate. The CCC argue that without making the Adaptation Reporting Power mandatory, it is hard to be assured that risk is being managed in the sector as a whole. Similarly to

road and rail, improved data on disruption to ports and airports would assist in assessing current and potential future risk.

4.13.3.2 Indicative costs and benefits of additional adaptation (I12)

In general, there are a set of no regret options in the form of improved weather and climate services, including early warning systems, for extreme risks for transport, which have been found to have high benefit to cost ratios across modes from the avoided damage and thus value of information (Clements *et al.*, 2013). There are further opportunities for these options, and general management of weather related risks through digital platforms, remote sensing, etc., and their use in real time network management (EEA, 2014), which can be considered no-regret because of the reduced costs of disruption and thus economic benefits in terms of travel time (ToPDAd, 2015).

The potential risks of high temperatures on the rail networks, and the potential economic costs of rail buckling risks under climate change have been previously estimated in the UK (e.g. Dobney *et al.*, 2009, Alvater *et al.*, 2012). The reactive adaptation response to these has been speed restrictions, although these have important travel time costs. There has been some analysis of the cost-effectiveness of options to address these risks, though these are mostly focused on improved risk assessment and monitoring (RSSB, 2016). There are potential rising risks from wind and vegetation growth, which are likely to mean increased vegetation management costs (which can be considered an impact or an adaptation).

There has also been analysis of the potential economic costs of heat on highways (including rutting and user delay costs, as well as additional capital maintenance costs) and the costs and benefits of addressing heat risks to highways (Atkins, 2013a). This considers technical surfacing options and found a modest positive net present value and cost-benefit ratio of slightly greater than 1. Alvater *et al.* (2012) also investigated the additional costs of using better asphalt for roads in the UK, and found the costs generally outweighed the benefits. There is also a large international literature in this area (from warmer countries), which highlight improved maintenance practices, risk assessments, early warning, and enhanced design standards for roads (e.g. EEA, 2014, Ecofys, 2016). There are other approaches, e.g. with greater redundancy in road networks, but these involve significant extra costs. There is also emerging focus on focusing adaptation investments on the vulnerability hot spots on networks, i.e. to identify the points on the system where greater resilience would be most cost-effective (as part of network level analysis rather than for individual assets). While this has mostly focused on flooding (Oh *et al.*, 2020), the same approaches could apply to other risks.

For existing infrastructure, improved monitoring and information, and also improvement of maintenance practices and operations, are considered low-regret adaptation options. For new infrastructure, there are opportunities for mainstreaming climate change adaptation into planning and design, to avoid retrofitting later. The balance of costs and benefits for such approaches depends on the costs, the timing and level of discounted future benefits, as well as the costs of retrofit later. This means some, but not all measures are likely to have positive NPVs and these may be site specific. There is the potential for decision making under uncertainty approaches for new transport infrastructure (e.g. considering flexibility, robustness, adaptive management) but these have important time and resource implications. The main risks of lock-in, and thus main role for such

approaches, are for new roads, rail, etc. (rather than refurbishment or upgrades) due to siting decisions.

4.13.3.3 Overall urgency scores (I12)

The understanding of current and future risk from climate impacts is varied across different transport modes and climate hazards. While there are examples of good practice within individual transport modes such as road and rail and emerging activities taking place, the approach to managing climate risks across transport infrastructure is not comprehensive. Action is also needed to avoid locking in new climate vulnerabilities in the shift to electrified and other lower carbon forms of transport. It is acknowledged that the split between more action and further research will vary between modes, climate hazard and nation.

Table 4.53 Urgency scores for risks to transport from high and low temperatures, high winds, lightning				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	Medium	Medium	Medium	Medium

4.13.4 Looking ahead (I12)

There is a need for the transport system to be assessed on a whole-system basis, both within modes and between modes. By treating mobility as a whole system (and considering the full range of climate-related risks to transport identified, such as those in risks I1, I2, I3, I4, I5 and I7), targeted, cost-effective adaptation measures can be taken which will ensure the movement of people and goods. This will require a greater level of understanding on how individual components within the individual transport networks respond to weather in the present day and how climate change may affect failure rates of these assets. Solving the problem of avoidable uncertainty in basic asset data (Dikanski *et al.*, 2018) is essential to achieving this. Asset condition monitoring and a greater use of sensors and localised weather stations will help build this understanding, which can be fed through into climate impact studies. The progress report on adaptation (CCC, 2019) states that there is a need for better understanding of projected changes in maximum wind speeds and the frequency of such events.

The resilience of future electrified transport systems needs to be formally assessed to identify and map new interdependencies with the electricity generation, transmission and distribution network, the digital/CT sector, as well as within the wider supply chain. Similarly, risks to transport from intense periods of heavy rainfall, and implications for visibility were not considered within this CCRA and could warrant further consideration particularly for aviation, shipping and road transport. Further information on the activities of the Airport Operators Association and the British Ports Association on adaptation would be useful to determine any current adaptation shortfall.

There is currently a lack of evidence on the potential impact of climate change on rivers and

waterways. This has links with Net Zero considerations, such as plans to encourage use of water-based travel such as London's Blue Ribbon Network.

4.14. Risks to digital from high and low temperatures, high winds and lightning (I13)

The current risks to digital are assessed to currently be of medium magnitude and will increase to 'high' under the most extreme scenario considered in this assessment. However, the evidence to support this is of low quality. While there is a general understanding of the interactions between ICT infrastructure and weather, quantitative projections assessing how climate change will affect the frequency and magnitude of these interruptions are lacking. This makes it difficult to assess the exact level of risk to the sector and is compounded by little information on the location or specification of assets being in the public domain for interests of security and commercial sensitivity. ICT is critical to the operation of wider infrastructure networks as well as underpinning business activities, access to key services and wider communication. Outages can therefore have significant effects on the locality and more broadly via interdependent infrastructure. While there exist different levels of access to both the internet and mobile phone coverage across the UK, the evidence is insufficient to establish with confidence any difference in risk between the devolved administrations. Reliance on ICT for the operation and control of components in the infrastructure system in isolation and as a whole is increasing, meaning the potential risk to infrastructure from ICT failure will increase in the future. Overall, further attention to the climate resilience of this sector and quantitative information on current and future risks under climate change is needed to better assess its vulnerability and exposure to climate change.

4.14.1 Current and future level of risk (I13)

Note: It has not been possible to split the evidence by UK country for this risk.

4.14.1.1. Current risk (I13)

4.14.1.1.1. UK-wide

Climate-related risks have the potential to disrupt the availability and reliability of the ICT sector and consequently push up operational costs for users (ITU, 2014). Increasingly, infrastructure such as water, power and transport are controlled over the telecommunications networks. Failure of telecommunications can lead to reduced capacity in a wide range of other essential services. Cross-sector resilience issues, and the reliance of telecommunications on the electricity network, was considered by the UKRN (2016).

The mass production, standardisation and the relative ease of transportation of many ICT infrastructure components, means disruptions are typically localised and short-lived. Components are made for a global market and so designed for weather much more extreme than that experienced in the UK.

Increasingly the user instrument is a smartphone relying upon radio access to a base station. Mobile base stations are typically sited closer to the customer than fixed line exchanges. They are also less likely to have power back-up. This increases vulnerability to local threats such as mains electricity interruption and weather impacts such as flooding (Ofcom, 2015).

ICT networks also typically exhibit considerable resilience due to the diversity of suppliers and associated network topology and redundancy. Failure of part of a network is likely to have little, or no, effect on communications outside the area directly serviced by the failed component. However, this could still be significant locally were an event to require emergency services response, hampering communication as well as members of the public who may be at risk. As businesses and members of the public increasingly rely upon ICT systems for work, accessing services, leisure and social support, even local outages can cause significant disruption to those affected.

Data from Ofcom identifying outage incidents to networks and services between 2016 and 2017 showed that 1% (5 out of 648) of incidents were caused by severe weather (flood, storms or snow). In particular, the edges of networks where diversity is at its least are at risk of failure – typically near sparsely populated areas, or remote locations, such as islands, where loss of ICT for communication or control of other systems can cause significant problems. The implications of outages caused by weather for loss of emergency services communications, business revenue and social disruption indicates medium magnitude.

The accessibility to both internet and mobile network coverage vary between Wales, England, Northern Ireland and Scotland with 3, 2, 5 and 4% of premises respectively without access to download speeds of 10Mbit/Sec and 5, 1, 1 and 13% respectively without mobile call service. If this is taken as an indicator of the potential numbers of customers currently on the edges of networks and so more liable for disruption; the magnitude is higher for Scotland in particular, as well as Wales and Northern Ireland, compared to England. Without a better understanding of the exposure of ICT infrastructure across the UK it is difficult to differentiate the magnitude between the devolved administrations.

Over the last decade, the direct effects of climate change on radio propagation have become clearer. A large proportion of communications is over radio links, to mobile or nomadic devices, on fixed links as part of backbone networks or last-half-mile connections to a fibre network, or via satellites. All radio systems experience periods of unavailability due to variable attenuation associated with weather parameters. Changes in several weather parameters have already been observed, potentially attributable to climate change, affecting different frequency ranges. For example, the availability of fixed links operating at frequencies above 5 GHz is limited by the incidence of moderate or heavier rain. Over the last 25 years in the UK, trends have been observed in the incidence and characteristics of rain that directly affect the performance of these radio systems. The incidence of moderate or heavier rain is increasing and there is evidence that the spatial extent of these rain events may be decreasing (Paulson, 2016). These changes partially cancel but may lead to increased rates of outage on these links (Ofcom, 2012). This may require a future reduction in link densities or the retrofitting of systems for interference cancellation.

4.14.1.2. Future risk (I13)

4.14.1.2.1. UK-wide

International design standards for equipment embed a resilience to a changing climate in the sector. For example, most cables are designed to operate in global extremes of temperature, and so current and projected changes to UK temperature extremes are unlikely to have detrimental effects. The communications industry also has to deal with problems caused by severe weather conditions on a regular basis. The most serious issues for telecoms providers during periods of severe cold, snow or flooding, is the denial of access to affected sites, or loss of power (EC-RRG, 2018). These risks decline as more robust, underground, fibre optic cables parallel or replace aerial cables and wireless links. Fibre and cables are vulnerable to flooding damage where they use bridges to cross rivers.

The national optical fibre networks carry the bulk of telecommunications data. Closer to the user, fixed line calls and broadband data services rely on a root and branch network comprising trunk cables and exchanges, telephone lines strung between telegraph poles, and street cabinets that serve individual areas. An increase in the frequency or intensity of storms would increase the risk of wind, ice and snow damage to overhead cables and damage from wind-blown debris. These fixed line services are being replaced by wireless services (4G and 5G) from the nearest fibre node, and direct connection to fibre networks.

More intense or longer droughts and heatwaves can affect a range of ICT infrastructure because ground shrinkage can lead to failure of electrical, gas and water pipes, thereby damaging co-sited ICT infrastructure (CCC, 2019). Similar climatic conditions, further aggravated in cities by the urban heat island effect, place additional demands for cooling on energy networks increasing the risk of 'brown out' due to a reduction or restriction in power (Chapman *et al.*, 2013). High summer temperatures, as well as rapid fluctuations in temperature and humidity, pose challenges particularly to data centres, which need to be kept cool to operate (CCC, 2019). Data centres are also vulnerable to floods, high winds, wildfire and droughts as well as loss of supporting power supply (Uptime Institute, 2020). Data centres are increasingly critical to the function of organisations that operate on the cloud. The knock-on impacts of data centre outage may be national and international in nature.

There is limited information on the location of UK ICT infrastructure, making it difficult to make a rigorous and quantitative assessment of risks to ICT networks and services. The ownership of a large proportion of ICT infrastructure, particularly data centres, base stations and network connections are spread across the private sector. Information on location and connectivity is not publicly available, for commercial or security reasons, and so it is difficult to assess vulnerability to extreme events.

A warming climate will lead to changing experience of mixed phase hydrometeors (sleet) on many links that could lead to dramatic changes in availability rates, either for the better or worse. The increasing altitude of the boundary between liquid and solid hydrometeors leads to greater rain attenuation on links to satellites (Paulson and Al-Mreri, 2011). At lower frequencies, changes in interference due to ducting has been postulated. Higher temperatures are associated with stronger atmospheric ducts near the sea surface caused by water vapour from evaporation, but less ducting

at higher altitudes. Ducts over the North Sea and English Channel lead to higher levels of unwanted signals coming from Continental Europe that interfere with signals originating from the UK. Projected increases in sea surface temperatures are likely to lead to stronger ducting effects and communications disruption (Mufti and Siddle, 2013), including increased interference with VHF/UHF systems.

4.14.1.3 Lock-in and thresholds (I13)

The short life span of some ICT/digital communications equipment should act to limit lock-in. However, towers and buildings such as data centres, have multi-decadal life spans and their location determines their exposure to extreme events such as flooding or wildfire.

Networks are sized to meet peak capacity levels; if these are exceeded, outages can occur. There are also thresholds related to operating temperatures of ICT equipment, additional cooling may be required to continue to maintain equipment at operational temperatures during heat waves. The choice of cooling equipment is important to avoid lock-in to high energy and/or carbon intensive provision or cooling systems which are unsuited to future climate. Furthermore, some cooling equipment may create further vulnerabilities to climate change such as the effects of water restrictions, or high humidity levels on evaporative cooling systems (Uptime Institute, 2020).

4.14.1.4 Cross-cutting risks and inter-dependencies (I13)

In terms of interacting risks, access to sites during disruption is important. Maintenance and repairs rely on the transport sector and WSP (2020) highlighted the implications of a heatwave event causing disruption on IT networks leading to transport delays (which could also be associated with overheating risk to passengers). This pathway was assessed in the project as having a low risk in 2020, increasing to medium in 2080 under in a scenario of approximately 4°C global warming in the late 21st Century, with large uncertainty²⁶. Data centres and wider network infrastructure are also dependent on electricity supply; any disruption to supply through flood, wildfire and heat waves may cause loss of service.

Other infrastructures may currently be less vulnerable to ICT disruption, but increased pervasiveness of ICT, particularly as a result of the increased uptake of 'smart' systems, is altering the interdependent risk profile of many infrastructure sectors and little is understood about the longer term implications of this for climate change risks. WSP (2020) highlighted disruption to IT and communication services as the second highest number of knock-on impacts in the infrastructure sector (second to power supply disruption). IT and communications disruption was also found to be significant based on impacts and likelihood meaning it is one of the most important contributors of risk through the different interacting pathways. Fundamentally, ICT is a major driver for productivity as people are unable to work, travel delays, water supply and sewage treatments.

There are potentially high levels of interdependency and vulnerability to ICT disruption in many

²⁶ UKCP18 probabilistic projections with RCP8.5 emissions, with 5th, 50th and 95th percentiles reaching global warming of 3.0°C, 4.2°C and 5.8°C respectively in 2070-2099.

areas of industry, which is considered in Chapter 6 (Surminski, 2021). This is particularly the case in industries operating processing plants and equipment (such as oil refineries, gas processing plants, chemical and petrochemical plants, food processing facilities, etc.) which have high reliance on ICT for plant operations, monitoring, remote diagnosis of faults, etc. These industries are vital to the economic well-being of the UK and their disruption can have significant national and local economic and social implications.

4.14.1.5 Implications of Net Zero (I13)

Building and maintaining ICT infrastructure requires energy. Much of a data centre's energy consumption is used for cooling and there is a risk to Net Zero of lock-in of mechanical cooling equipment that uses high GWP refrigerants, resulting in Greenhouse Gas emissions. Although equipment is becoming more energy efficient, the amount of equipment is growing quickly. ICT electricity use is predicted to double to 10–20% of global generation by 2030. This electricity will need to come from low-carbon sources or ICT growth could make Net Zero more difficult to achieve. ICT also has a large contribution to make in reaching Net Zero through the growth of smart grids, smart buildings, smart metering, logistics, real time navigation, e-commerce, e-learning, telepresence, and environmental monitoring. These reduce the need to physically move goods and people and reduce the use of fossil fuels. Adverse effects on ICT due to climate change will have a significant detrimental effect on these sectors ability to deliver Net Zero.

4.14.1.6 Inequalities (I13)

Inequalities are predominantly linked to geographic location and associated risks of wind damage, flooding and cascade risks. Sites near the edges of networks have the least redundancy and are often in remote areas, sometimes with rough terrain and limited access. These sites take longer to reach and repair after failures. Existing network access can be low in remote rural communities. There remain a significant number of premises unable to access download speeds of 10Mbit/s: 3, 2, 5 and 4% and without mobile (2G, 3G or 4G) coverage of 5, 1, 1 and 13% for Wales, England, Northern Ireland and Scotland (National Infrastructure Commission for Wales, 2019).

4.14.1.6 Magnitude scores (I13)

In an analysis of interacting risks for CCRA3, WSP (2020) highlighted disruption to IT and communication services as having the second highest number of knock-on impacts in the infrastructure sector (second to power supply disruption). The impact of other hazards such as flooding has been observed to cause significant disruption, both through cascading failure from other systems such as power loss, leading to mobile base station outages in Lancaster following Storm Desmond in 2015 (reported in I1), as well as directly such as the flooding of a datacentre in Leeds in 2015 (reported in CCRA2: Dawson *et al.*, 2016). However, the evidence base on the specific impacts of high and low temperatures, high winds and lightning on ICT infrastructure is limited. The authors found no current evidence of significant disruption caused by these hazards on UK ICT infrastructure, hence a score of low but with low confidence owing to the limited evidence base in this area (Table 4.54).

Table 4.54 Magnitude scores for risks to digital from high and low temperatures, high winds, lightning.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Northern Ireland	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Scotland	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)
Wales	Low (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)	Medium (Low confidence)

The need for datacentres to be kept cool to operate, as well as the potential impact of longer droughts or heatwaves causing ground shrinkage and failure of co-sited electrical, gas and water pipes with associated knock-on impacts to ICT, indicates a potential increased source of risk in all future scenarios in this assessment. The authors consider that the increased hazard profile combined with the increased pervasiveness of ICT and the observed magnitude of impacts of ICT failure caused by other hazards justifies a score of medium in all future scenarios in this assessment. The confidence in this assessment is low due to the lack of evidence base in this area. Quantitative projections assessing how climate change will affect the frequency and magnitude of interruptions to digital services are lacking (at least in the public domain). Without a better understanding of the exposure of ICT infrastructure across the UK it is difficult to differentiate the magnitude between the nations of the UK.

4.14.2 The extent to which current adaptation will manage the risk (I13)

4.14.2.1 Effects of current adaptation policy and commitments on current and future risks (I13)

Currently adaptation appears from the evidence to be reactive or unplanned due to the short life span of equipment. The most vulnerable assets requiring protection are masts, cables and buildings (including data centres in particular which are vulnerable to any disruption to cooling systems).

4.14.2.1.1 England

The second National Adaptation Programme (Defra, 2018) states that the Department for Culture, Media and Sport are working with the telecoms industry via the industry-run Electronic Communications Resilience and Response Group, which leads on resilience in the sector. The actions mentioned in the NAP only relate to flooding however, and it remains unclear how far other hazards are being considered.

4.14.2.1.2 Northern Ireland

The risks to digital from extreme heat, high winds and lightning are acknowledged in the Northern Ireland Climate Change Adaptation Programme 2019-2024 (DAERA, 2019), though there are no specific actions listed that relate to improving resilience of digital infrastructure specifically. The programme also states that digital infrastructure services in Northern Ireland operate independently from the Government with providers having their own responsibility to develop and monitor their own climate change resilience strategies. This includes business continuity measures in relation to climate change impacts, such as the provision of essential services which enables them and their customers to function.

4.14.2.1.3 Scotland

The Scottish Government Climate Change Adaptation Programme 2019–2024 includes recognition of the climate risks to digital ICT infrastructure and its importance in delivering resilience (Scottish Government 2019b). ‘Keeping Scotland Running’ has been designed to support critical infrastructure owners and operators, emergency responders, resilience partnerships (RPs), industry groups and relevant government departments in working together to improve the resilience of critical infrastructure and essential services provision in Scotland. Digital infrastructure is considered an essential service. The ‘Keeping Scotland Running’ Guidance Suite seeks to support the delivery of Scotland’s Critical Infrastructure Resilience (CIR) Strategy and includes guides on Cyber Security and Critical Infrastructure, Resilience to Natural Hazards and Building Resilience to a Changing Climate (Adaptation)

4.14.2.1.4 Wales

The Welsh Government climate change adaptation plan, Prosperity for All: A Climate Conscious Wales (Welsh Government, 2019b) and associated consultation (Welsh Government, 2019c) refers to resilient digital infrastructure as a key cross-cutting interdependency. The Welsh Government has committed to strengthen preparedness against multiple risks to interdependent infrastructure networks via pilot emergency response exercises, local resilience for an emergency response, and working with utility companies on electricity transmission network failure (Welsh Government, 2019b; 2019c). The National Infrastructure Commission for Wales should be considering this as part of their call for evidence and work on national approaches to digital infrastructure. There is no evidence on the level of engagement within the industry, or for SMART objectives to manage risk.

4.14.2.2 Effects on non-government adaptation (I13)

There is no clear plan or process by the industry or Government with actions to manage long-term climate risks to the sector. CCC (2019) identify the lack of available data to assess vulnerability as a key barrier to adaptation, although some progress has been made on flooding (not covered in this risk but covered in I2 and I3). It also stated that although Ofcom provides guidance on maintaining services during flood events, guidance is not given on adaptation to climate change.

4.14.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I13)

While the risks to digital networks are recognised as an issue in all of the UK national adaptation programmes, there is a lack of evidence in the public realm of specific adaptation actions that will manage the specific risks of high and low temperatures, high winds, lightning down to low magnitude levels. It is acknowledged that the short generation times of particular components may by default manage risk in certain areas, but there is no evidence that non-government adaptation for longer-life infrastructure such as data centres will manage the risk. It is therefore considered the potential risk identified in Step 1 of this assessment is not currently being managed.

4.14.2.4 Adaptation scores (I13)

Table 4.55 Adaptation scores for risks to digital from high and low temperatures, high winds, lightning			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
No (Low confidence)	No (Low confidence)	No (Low confidence)	No (Low confidence)

4.14.3 Benefits of further adaptation action in the next five years (I13)

4.14.3.1. Additional planned adaptation that would address the adaptation shortfall (I13)

Further adaptation would include incorporating digital infrastructure into existing infrastructure climate adaptation plans recognising the criticality of ICT provision for wider infrastructure and society. Further information is also needed to identify and protect assets at risk of flooding and wildfires together with a better understanding of future impacts on radio communication VHF/UHF systems.

4.14.3.2 Indicative costs and benefits of additional adaptation (I13)

While there is some information on adaptation options for the digital and ICT sector (Horrocks *et al.*, 2010), there does not appear to be a large literature on the costs and benefits of adaptation. There is a general low regret option to ensure better information on such risks, as well as to ensure climate risk assessment is included in design (and financial and economic appraisal, see also the

supplementary Green book Guidance on accounting for climate change, Defra, 2020a). It is noted that the sector typically has short design lifetimes, and thus there is the potential to consider the management of some risks (e.g. equipment) as part of upgrades rather than through designing for future climates. However, there may still be cost-effective actions for critical digital infrastructure, given the cost of downtime from failures is often high; evidence from companies that report that the cost of downtime could be as high as £thousands per minute (Ponemon Institute, 2016).

Warmer temperatures are likely to mean higher cooling needs and associated energy costs (Lee *et al.*, 2013; Capozzoli and Primiceri, 2015; Song *et al.*, 2015). There are a range of adaptation options from early warning and emergency planning through to back-ups to address heat extremes. These issues are linked to the general increase in cooling demand (see Chapter 5: Kovats and Brisley, 2021) and the potential role for energy efficiency standards.

The consideration of network risks, and more focused adaptation strategies to key vulnerabilities, can be a more efficient use of available adaptation resources. Adaptation can also be achieved by enhancing network redundancy and introducing back-ups. Pant *et al.* (2020) investigated the economic impacts of failure events in the telecoms network and estimated that direct losses for the top 50 events could vary between £220,000–£3.6 million/day and total losses vary between £0.34–£7.0 million/day. However, as the degrees of connections are increased, the economic impacts were found to decrease. The authors also show the benefits of introducing backup supply for the electricity sector in delaying and thereby decreasing the disruptions in the ICT sector by up to ~90% compared to a scenario with one connection and no back up (though note the study does not assess costs, and thus the overall economic net benefit).

It is also highlighted that ICT and digital solutions can help reduce risks or realise opportunities in other sectors, i.e. they have considerable potential as part of adaptation across many areas (ITU, 2014).

4.14.3.3 Overall urgency scores (I13)

Further investigation is needed to assess how climate change will affect the frequency and magnitude of interruptions to digital services across the four countries of the UK and whether more action is needed. While National adaptation programmes acknowledge the risks to the digital sector, there is no evidence of specific actions to ensure the resilience of digital infrastructure to the specific hazards of high and low temperatures, high winds and lightning.

Table 4.56 Urgency scores for risks to digital from high and low temperatures, high winds, lightning				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	Low	Low	Low	Low

4.14.4 Looking ahead (113)

Data are not available to assess the vulnerability of the telecoms, digital and ICT sector to climate risks, though actions should reduce the vulnerability of some assets. A useful indicator would be to monitor the number of weather and climate related disruptions across the sector. There is also limited information on the location of UK ICT infrastructure, making it difficult to make a rigorous and quantitative assessment of risks to ICT networks and services. The ownership of a large proportion of ICT infrastructure, particularly data centres, base stations and network connections are spread across the private sector. Information on location and connectivity is not publicly available, for commercial or security reasons, and so it is difficult to assess their potential exposure to extreme events. Improved data availability and sharing would allow the creation of digital twin ecosystems, which would aid in identifying exposure and vulnerabilities. However, it is essential to highlight the pivotal role that digital infrastructure has in underpinning the operation of most other forms of infrastructure, and this role is likely to increase in the future. It is therefore imperative that the resilience of ICT to climate impacts is further scrutinised to mitigate interacting risks across the infrastructure sector.

4.15 Case Study - Toddbrook Reservoir

In light of current climate change projections, the periodicity of flood events continues to change significantly. The last independent review, commissioned by DEFRA, used UKCIP02 data and concluded that to a 2050s time horizon that no regional pattern of risk to reservoirs (from climate change) was evident (Defra, 2002). The incident at Toddbrook, although providing a stark reminder of the potential implications of a dam failure, in itself does not change this view, but does demonstrate that a new review based on the latest climate projections is overdue, as is engagement with Adaptation Reporting Power requirements by infrastructure owners. Overall, the incident underlines the need for a watching brief on the future impacts of climate change on dam infrastructure, particularly in light of ongoing maintenance regimes which need to be specifically tailored to the dam type and age.

Designed to supply water to the Peak Forest and Macclesfield Canals, the Toddbrook reservoir, located in the Peak District, hit the headlines in 2019 after heavy rain over a 6 day period between 27th July and 1st August, following a period of record summer warmth, caused significant damage to the auxiliary spillway. As a precaution, nearby roads and businesses were closed and 1500 residents were evacuated from the nearby town of Whaley Bridge. Fortunately, an urgent response consisting of a rapid lowering of the water level, accompanied by emergency bolstering of the spillway, was sufficient to avert disaster with residents able to return to their homes 6 days later.

As a result of the incident, an independent review was commissioned by the government to identify what might have led to the damage, whether it could have been prevented or predicted and identify any lessons learned. The report concluded that the most probable cause of the failure was poor design followed by a gradual deterioration / erosion of the slipway via seepage flows, as

a result of intermittent maintenance over the years (Balmforth, 2020). Temporary resilience work commenced in January 2020 to further reinforce the dam and spillway by means of waterproof nibs to prevent seepage flows undermining the spillway. However, a longer-term repair is required, which is estimated to cost in the region of £10m and will take several years to implement (Canal and River Trust, 2020).

The heavy rainfall of August 2019 is yet to be attributed directly to climate change, but it is inevitable that some links will be drawn between increasing levels of precipitation in a changing climate and the stability of aging dam infrastructure. Indeed, the need to keep pace with the impacts of climate change is mentioned in the foreword of the independent report (Balmforth, 2020), as CCRA2 had highlighted a potential risk with this type of dam. The rain that fell during the preceding 6-day period consisted of two rainfall events, the latter (between 30th July and 1st August) being the most significant and classified as a 1 in 100-year event. Although rare, this needs to be considered in the context that Category 1 dams are currently engineered to withstand a 1 in 10,000-year flood event and therefore rainfall events of this magnitude should not have been a key factor in the failure of the asset. Furthermore, the spillway had coped without issue with previous floods in 1998 and 2007. It had also recently been inspected and declared compliant with current legislation (Balmforth, 2020).

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