PR24 Climate Resilience Assessment

Phase A - Contextualisation

July 2022

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Executive summary

As part of their PR24, Northumbrian Water are reviewing the resilience of their systems in order to develop their AMP8 investment plan for submission to Ofwat in autumn 2023. Following recent guidance from Ofwat on long-term delivery strategies, Northumbrian Water wish to consider the potential impact of climate change on their infrastructure and operations so that adaptation options are identified, and resilience incorporated.

As an initial step to form part of the Needs Assessment, the present contextualisation work has identified the expected long-term climate changes as well as the evolution of extreme weather events impacting the North-East (water and wastewater) and South-East (water only) areas of operation. This has highlighted that:

- Droughts will intensify, above all in the South-East, where the increase in temperatures will be greater. However, annual rainfall is expected to decrease more in the North-East. This will also have an impact in soil moisture deficit.
- Heatwaves like the ones in summer 2018 will become more frequent and hotter, above all in the South-East.
- Floods will become significantly more extreme in the North-East associated with large scale storms, whereas in the South-East, summer convective rainfall will increase, potentially leading to localised flooding.
- Winter storms with associated high winds, which occurred during storms Desmond and Arwen will be more frequent and intense in the future.
- Sea level will continue to rise, in particular in the South-East, and storm surges will be more frequent, although their intensity will probably remain the same.
- Freeze-thaw events and snow will decrease with global warming.
- Lightning projections are inconclusive but there is some indication their frequency would decrease.

These changes in climate hazards have been compared to the magnitude of the consequences of past extreme weather events to establish the magnitude of the risk to Northumbrian Water. This has resulted in:

- Two very high risks in the North-East: flooding and wind, followed by droughts, water quality deterioration and soil moisture deficit as high risks.
- Three very high risks in the South-East: droughts, soil moisture deficit and wind, followed by heat and flooding as high risks.

These risks together with freeze-thaw events, which has been classified as a medium risk in both areas, will undergo further assessments in the next phase.

1 Introduction

As part of their PR24, Northumbrian Water are reviewing the resilience of their systems in order to develop their Asset management Plan (AMP)8 investment plan for submission to Ofwat in autumn 2023. In the context of climate emergency and with the understanding of the threats that climate change poses to the water sector and when they are likely to materialise, investing in climate resilience becomes one of the priorities to protecting services. Northumbrian Water have commissioned Mott MacDonald to undertake a contextualisation piece of the climate risks faced by the Company and identify those that are most relevant to its geography and operations. These will be subjected to a more detailed assessment in a subsequent phase.

1.1 Regulatory context and adaptation reporting

In 2021, Ofwat outlined their vision for Price Review (PR)24[1]. With a focus on the long-term delivery of greater social and environmental value to customers, the paper highlights the need to focus on the right long-term solutions, particularly in the context of climate change. Water companies were then asked to set out their 5-year business plan for AMP8 in the context of achieving their vision and outcomes for 2050. In order to align with Ofwat directions to incorporate climate resilience into PR24 by taking account of plausible future changes in key factors, water companies need to understand the medium and long-term climate-related challenges they are facing and review the ability of their water and wastewater systems to cope with the implications of a changing climate.

Climate uncertainty around the likelihood, magnitude and timing of potential hazards is the primary limiting factor for long-term resilience planning. Common reference scenarios have been defined by Ofwat to help focus the price review on establishing the best possible trajectory towards meeting long-term outcomes. For climate change, the selected scenarios are Representative Concentration Pathway (RCP)2.6 and RCP8.5[2], relating to the lowest and highest emission scenarios as specified by the Intergovernmental Panel on Climate Change in their 5th Assessment Report. This provides the greatest range of possible climate outcomes. Water companies are expected to use the United Kingdom Climate Projections (UKCP)18 for both scenarios to explore how these different climate futures might affect their systems. These are the latest projections available from the Met Office at the time of this assessment.

In their Third Climate Adaptation Report submitted to Defra at the end of 2021 as required in the Climate Change Act 2008, Northumbrian Water listed the main climate risks faced by the Company and the associated adaptation solutions to improve their resilience. Flooding, drought, extreme temperature and sea level rise were highlighted as the main hazards. These related to subsequent risks of flooding, subsidence, water quality deterioration and reduction in water availability, alongside cascading failure risks across systems (both intra and inter organisations and sectors).

1.2 Purpose

Building on the general findings of the Climate Adaptation Report, the purpose of this work is to identify the key climate risks with the potential to affect Northumbrian water and wastewater assets in its North-East and water in its South-East service areas.

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[1] PR24-and-Beyond-Creating-tomorrow-together.pdf (ofwat.gov.uk)

[2] RCPs specify concentrations of greenhouse gases that will result in total radiative forcing (difference between the incoming and outgoing radiation at the top of the atmosphere) increasing by a target amount by 2100, relative to pre-industrial levels. This target in expressed in $W.m^{-2}$ in the RCP name.

The work aims to set the scene for future and more detailed investigations of the key climate risks and provide an evidence-based assessment of the risks that are of lesser relevance to Northumbrian Water, which will not warrant further studies. Mott MacDonald have been commissioned to undertake this review based on the latest UKCP18 climate projections, together with an analysis of recent incidents that have affected infrastructures and operations. This shall form the basis for a preliminary risk assessment.

1.3 Structure of the report

In response to the objectives of the work, the report is structured as follows:

- Section 2 presents an initial comparison of projected changes in key climate variables across the UK, to establish where Northumbrian Water region lies in relative terms;
- Section 3 sets out long-term changes in climate variables;
- Section 4 includes an analysis of potential changes in extreme weather events, building on past occurrences and the atmospheric conditions that led to them;
- Section 5 compiles a preliminary risk assessment based on a combination of the magnitude of the consequences associated with a variety of hazards as recorded in the past, together with the likelihood of hazards under future climate conditions; and
- Section 6 presents the conclusions of the study.

2 Regional comparison of climate change hazards

A relative comparison of changes in climatic variables associated with potential hazards (droughts, heatwaves and storms) across the UK administrative regions has been performed based on the UKCP18 regional and local projections under RCP8.5. Projections from the Met Office have been bias corrected using spatial averages of observations, consulted to estimate the expected change between future conditions (2036-2065) and baseline conditions (1991-2020) and then displayed in GIS. To note that the low emission scenario requested by Ofwat (RCP2.6) is not available for these dynamical downscaled projections. However, its potential effects in geographical relative terms are expected to be similar to the ones associated with RCP8.5. Given that variables are averaged across large areas, changes in absolute terms should not be relied on. Finally, Environment Agency climate change allowances for peak flows[3] are presented to provide a countrywide comparison of flood risk.

2.1 Droughts

Drought conditions are associated with decreased rainfall over an extended period of time, and with high temperatures that increase evapotranspiration. Although the estimation of changes in the frequency, magnitude and duration of droughts requires detailed hydro(geo)logical assessments, an indication of the potential future trends can the inferred from changes in annual rainfall, mean temperature summer rainfall and autumn rainfall. Figure 2.1, Figure 2.2, Figure 2.3 and Figure 2.4 show the changes in these variables for each UK administrative region. The Northumbrian Water North-East area of operations would experience one of the largest declines in annual rainfall, with the South-East area also presenting a significant reduction. The latter is also the region with the highest increase in average temperature. Regarding summer rainfall, the Northumbrian Water regions would be less affected by future decreases compared to the rest of the country. However, the two regions would experience the greatest decline in autumn rainfall in the country, which is likely to prolong river recessions and stress the supply systems (see Figure 2.4)

[3] Flood risk assessments: climate change allowances - GOV.UK (www.gov.uk)

Figure 2.1: UK regional projected changes in annual rainfall

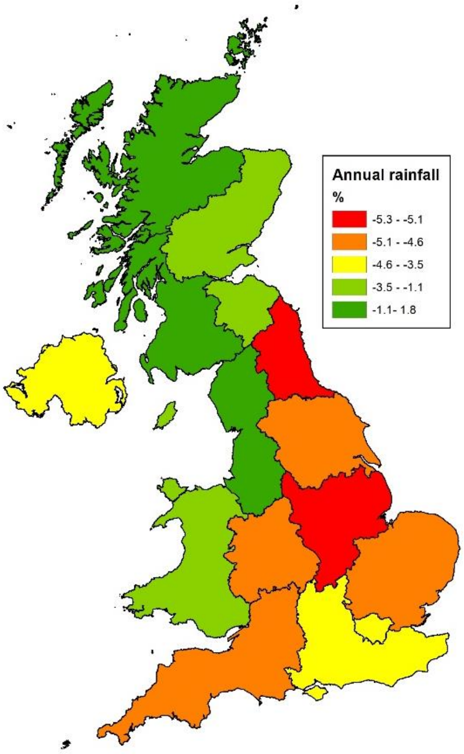


Figure 2.2: UK regional projected changes in mean temperature

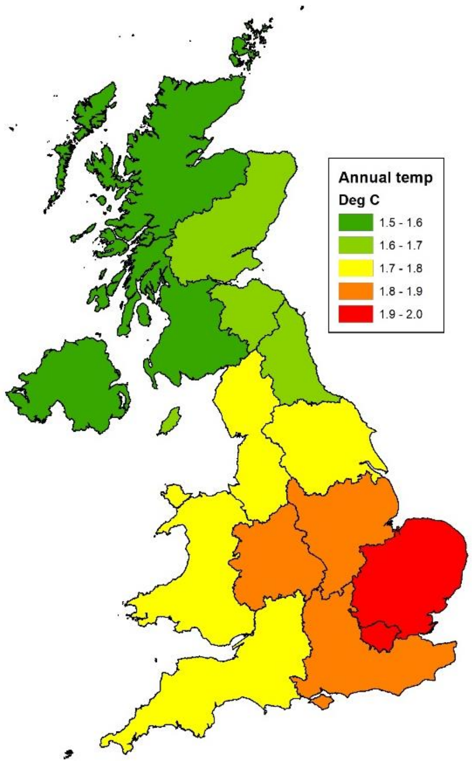


Figure 2.3: UK regional projected changes in summer rainfall

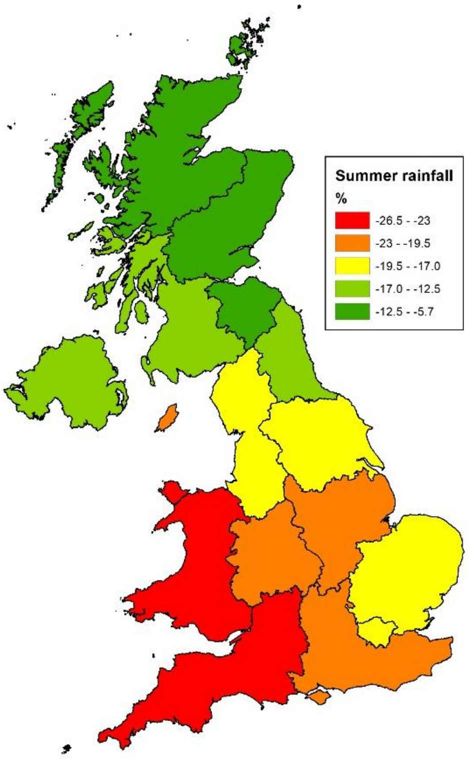
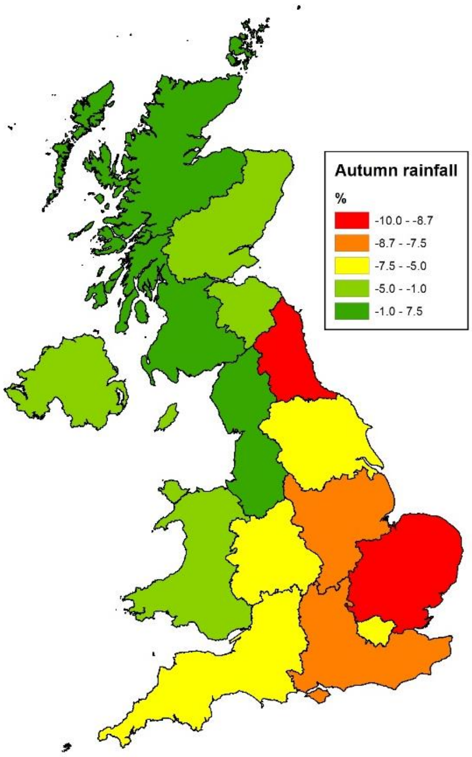


Figure 2.4: UK regional projected changes in autumn rainfall

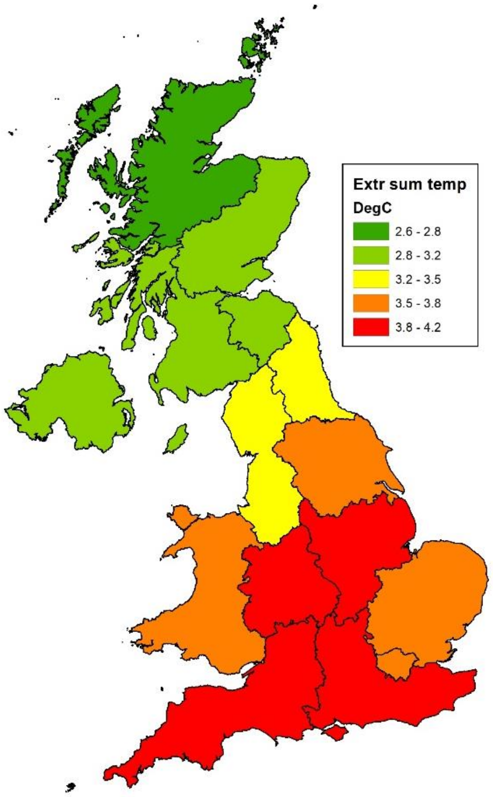


Source: Mott MacDonald analysis of UKCP18 projections

2.2 Heat waves

To understand potential changes in the intensity of heatwaves, the Q95 summer daily maximum temperature has been adopted for comparison (maximum temperature exceeded 5% of the days in summer). Projected changes in this extreme summer temperature in 2050 are shown in Figure 2.5. Compared to other UK regions, the Northumbrian Water South-East area of service is likely to be highly affected by heatwaves, although given the current summer temperatures, increases with respect to the baseline would be lower than in other southern regions. The North-East, in turn, would experience a relatively lower rise in extreme maximum temperatures.

Figure 2.5: UK regional projected changes in extreme summer temperature



Source: Mott MacDonald analysis of UKCP18 projections

2.3 Storms

Storms can bring high winds and extreme rainfall. Depending on the season, their effects can be more or less widespread, with winter storms more likely to impact larger areas and be windier. In order to establish potential changes in their magnitude, Q99.9 values (exceeded 0.1% of the days in the season) of daily precipitation in winter and summer as well as of average wind speed in winter have been derived from regional projections. In addition, Q99.9 wind gust values have been extracted for winter from the local projections. Whereas wind speed is likely to diminish slightly or remain similar in the South-East, the North-East stands out as an area where the intensity of extreme winds would increase significantly, more than in other England regions (see Figure 2.6 and Figure 2.7)

Figure 2.6: UK regional projected changes in high winter daily mean wind speed

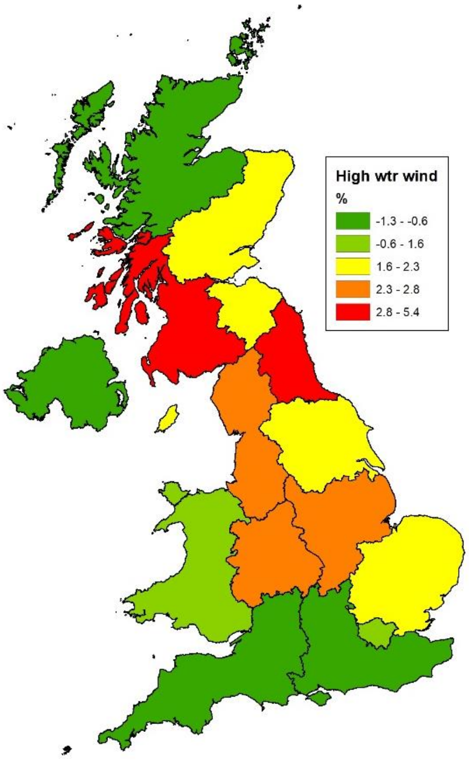
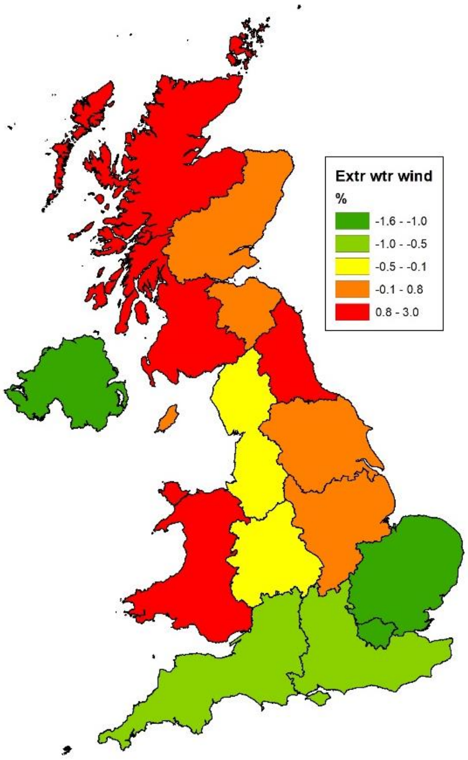


Figure 2.7: UK regional projected changes in extreme winter wind gust



Source: Mott MacDonald analysis of UKCP18 projections

Projected changes for extreme winter and summer rainfall are shown in Figure 2.8 and Figure 2.9 respectively. Northumbrian Water areas of service seem to be less affected by extreme winter rainfall given their eastern location, which reduces the impact of Atlantic storms. However, there would still be noticeable increases in rainfall intensity during this season, in particular in the North-East (see Figure 2.8). In turn, the two areas are likely to be impacted by more intense convective storms in summer, with the North-East standing out (see Figure 2.9). The combination of stronger extreme wind and more intense rainfall in the winter and summer indicates that the North-East Northumbrian Water region might be particularly susceptible to storms in the future. This is in line with the recent records of increased flooding incidents in summer, where intense rainfall followed extended periods of dry spells leading to blockages.

Figure 2.8: UK regional projected changes in extreme winter daily rainfall

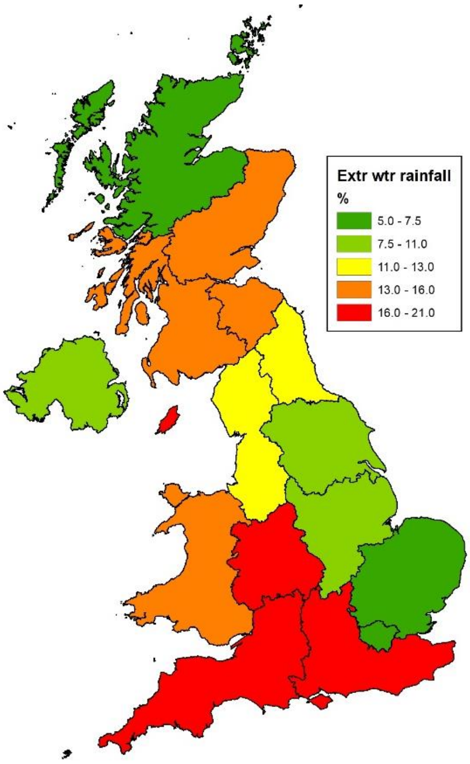
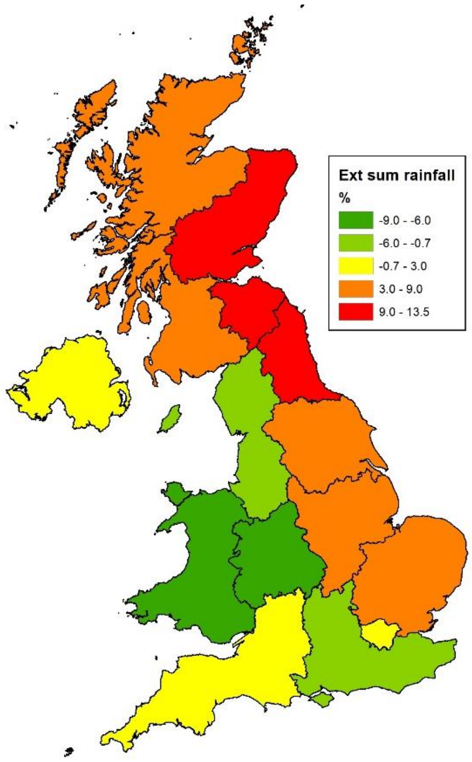


Figure 2.9: UK regional projected changes in extreme summer daily rainfall

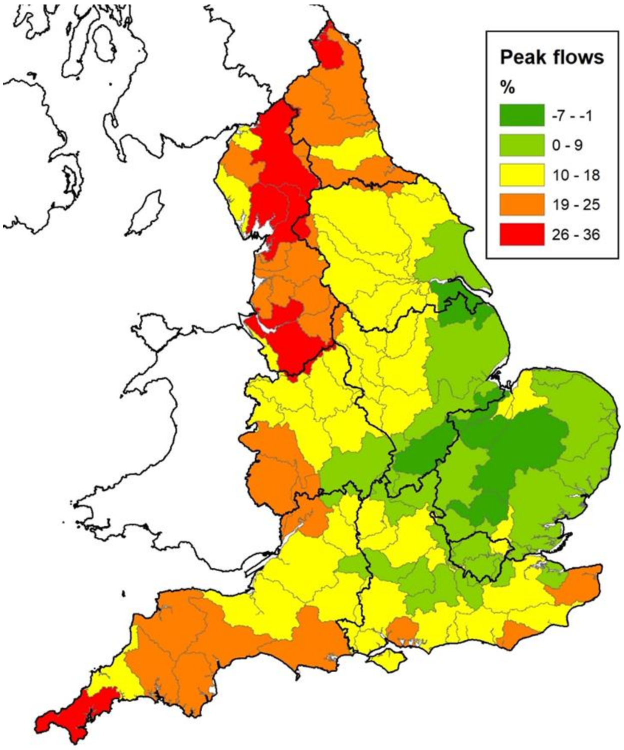


Source: Mott MacDonald analysis of UKCP18 projections

2.4 Floods

Projected changes in flood peak flows for EA management catchments are shown in Figure 2.10. They have been obtained by coupling the regional projections for RCP8.5 with rainfall-runoff models. Given this, the EA dataset accounts for not only changes in rainfall but also for the particular features of the different catchments, such as topography, geology, soil types and land cover. Likewise, as the rainfall-runoff simulation was undertaken continuously, the analysis also considered changes in the frequency of storms as well as seasonality, which is relevant to represent soil moisture conditions before the events. The combination of all these factors makes the North-East Northumbrian Water area very susceptible to changes in floods in the future in comparison with other regions. The South-East, in turn, would experience modest increases in peak flows or even decreases.

Figure 2.10: EA management catchment projected changes in peak flows



Source: Environment Agency

2.5 Summary

Table 2.1 presents a summary of how the two Northumbrian Water area of services compares with the rest of the country in terms of expected changes in climate change hazards.

Table 2.1: Summary of regional comparison

Hazard	North-East	South-East
Droughts	Average	Higher
Heat waves	Average	Higher
Windstorms	Higher	Lower
Winter extreme rainfall	Average	Lower
Summer extreme rainfall	Higher	Higher
Floods	Higher	Lower

In comparison with other regions, the North-East of England, broadly overlapping Northumbrian Water area of service, would be particularly susceptible to climate change impacts on wind and extreme summer rainfall. Extreme winter rainfall would increase as well, which together with the physical properties of the valleys (steep catchments draining westwards from the Pennines, loamy and clayey soils with impeded drainage that are seasonally wet and impermeable geological superficial deposits), would mean that the magnitude of floods would increase more than in other parts of England. Annual rainfall is expected to decrease significantly, above all in autumn when compared with other areas.

The South-East would not be as impacted by storms, with modest or no increase in large-scale flood magnitudes. However, extreme summer rainfall associated with convective storms is expected to increase more than the UK average, potentially leading to more frequent or intense localised floods. In this area droughts are a particular concern, and the increase in temperatures and the reduction in rainfall would stress the supply systems more than in other parts of the UK. Although not reported in this section, sea level rise would be greater in the South than the North as a result of tectonic plates movements. Together with the low-lying nature of the area, this would exacerbate the risk of coastal flooding and saline intrusion.

3 Long-term changes in climate

The increasing concentration of greenhouse gases in the atmosphere is leading to a gradual global warming that is altering and will further alter the average climate conditions. Changes in climate will be progressive but they will be punctuated by episodes of extreme weather. In this section, the expected long-term changes of climate variables in the 2050s are reported. In order to exclude the natural variability of climate and capture the long-term trend, a period of 30 years in the future, around the 2050s, has been adopted and projections compared with a 1991-2020 baseline, so that only the additional change in climate, over that already realised, is estimated. Where possible the two emission scenarios specified by Ofwat are included:

- RCP2.6 corresponding to a stringent scenario, where mitigation of greenhouse gas emissions are in line with the Paris agreement to keep global temperature well below 2°C above pre-industrial levels.
- RCP8.5 corresponding to a business-as-usual scenario with little mitigation efforts, leading to a global warming of 4°C above pre-industrial levels at the end of the century.

3.1 Rainfall

UKCP18 probabilistic projections of rainfall anomaly for the 2050s at 25km resolution were used to derive the 50th percentile (median or most likely) of anomalies for a number of representative grid-cells in the North-East and South-East areas. The spatial averages of the grid-cells in each area are reported below.

Mean annual precipitation is projected to slightly decrease in the North-East region (-0.9% and -0.7% for RCP2.6 and RCP8.5 respectively). The projected seasonal changes are much more pronounced, as indicated by a substantial increase in winter precipitation (8.4% and 11.6% for RCP2.6 and RCP8.5 respectively) accompanied by a larger decrease in summer precipitation (-11.3% and -13.8% for RCP2.6 and RCP8.5 respectively).

For the South-East region, projections show more pronounced decreases in mean annual precipitation (-3.3% and -4.3% respectively for RCP2.6 and RCP8.5). These are primarily driven by large decreases in mean summer precipitation (-16.1% and -21.6% respectively for RCP2.6 and RCP8.5), while mean winter precipitation is projected to increase in a similar way as that of the North-East region (7.8% and 10.4% respectively for RCP2.6 and RCP8.5).

To note, that these reductions differ from the ones indicated in Section 2.1 because they have been derived from different products, with the ones included here combining a larger set of general circulation models, thus incorporating wider uncertainty. Probabilistic projections are the only ones offering results for RCP2.6 and are also suitable for capturing long-term trends, whereas regional projection used in Section 2.1 are more adequate for assessing changes in extremes.

Projected precipitation changes for each month are shown in Figure 3.1 and Figure 3.2, respectively for the North-East and South-East regions. A similar seasonal pattern is observed for the two regions, with the most pronounced decreases occurring in July and August, and the highest increases in the winter months. A similar profile is reported for the two RCPs, with the higher emission scenario RCP8.5 showing higher increases and lower decreases. To note that while compared with the UK average, the South East region would experience drier summers, whereas in the North-East winters would be wetter than nationwide average.

Figure 3.1: Predicted monthly changes in precipitation (North-East region)

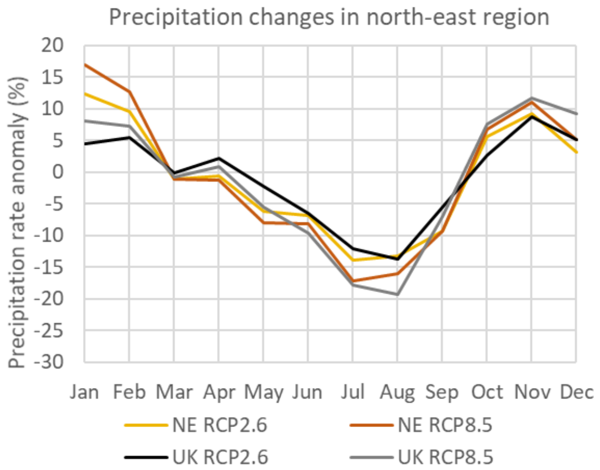
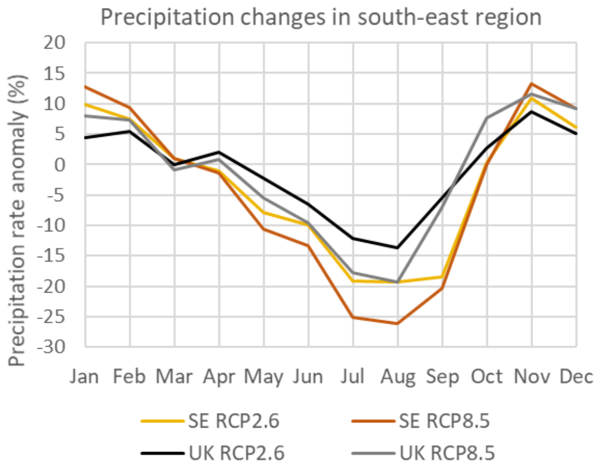


Figure 3.2: Predicted monthly changes in precipitation (South-East region)



Source: Mott MacDonald analysis of UKCP18 projections

UKCP18 probabilistic projections of extreme precipitation (100 years return period of 1-day total precipitation) for one representative 25km x 25km grid-cell of each area were processed to derive the change in the 2050s (relative to the baseline of 1990-2020) for the 50th percentile of projections. An increase in extreme precipitation is projected for both regions across both RCPs. The increases for the North-East region are 5% and 9% for RCP2.6 and RCP8.5 respectively. For the South-East region the increases in extreme precipitation are slightly more pronounced (6% and 11% for RCP2.6 and RCP8.5 respectively). To note that the expected decrease in mean summer rainfall would be compatible with an intensification of short convective storms, causing the increase in extreme rainfall indicated in Section 2.3.

3.2 Temperatures

UKCP18 probabilistic projections of average, maximum and minimum temperature anomalies for the 2050s at 25km resolution were used to derive the 50th percentile of anomalies for the same grid-cells in the North-East and South-East areas as in the case of rainfall. The spatial averages of the grid-cells in each area are reported below.

Overall, projections show an increase in mean temperature in all seasons for both North-East and South-East regions. Future increases are greater in summer than in winter. For example, for the North-East region under RCP8.5, winter temperature would increase by 1.5^{o}C compared to 2^{o}C in summer. The South-East region is facing higher increases in annual, winter and summer temperatures. For example, under RCP8.5 winter temperature is projected to increase by 1.7^{o}C and by 2.4^{o}C in summer. Projected temperature changes for each month are shown in Figure 3.3 and Figure 3.4 respectively for the North-East and South-East regions. RCP8.5 shows higher increases (between 0.5^{o}C and 1^{o}C more) compared to RCP2.6. In addition, the North-East region would be in line with national average, whilst the South-East region would experience larger increases than average.

Similar patterns are observed in maximum (Figure 3.5 and Figure 3.6) and minimum temperature (Figure 3.7 and Figure 3.8) For both regions and RCPs, maximum and minimum temperature increases are higher in summer and autumn.

Figure 3.3: Predicted monthly changes in average temperature (North-East region)

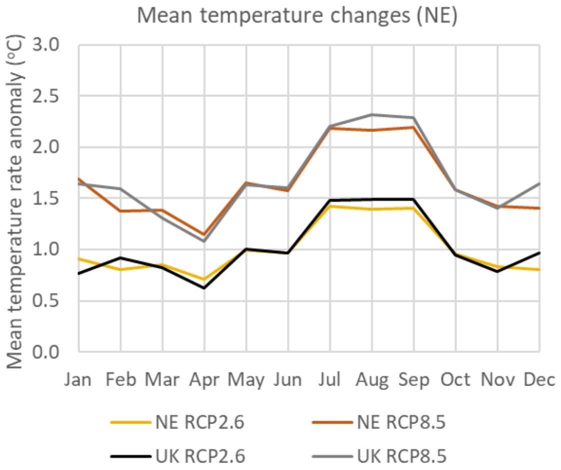


Figure 3.4: Predicted monthly changes in average temperature (South-East region)

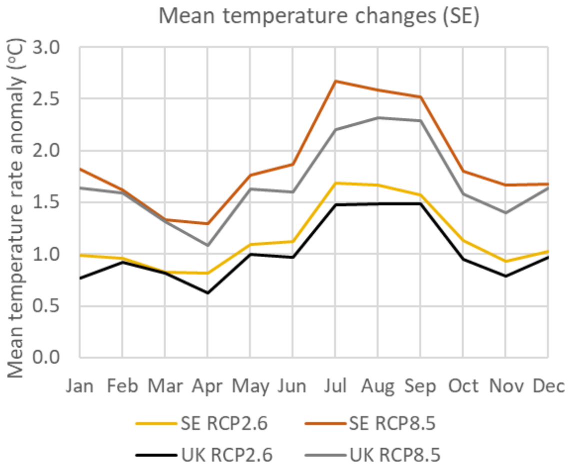


Figure 3.5: Predicted monthly changes in maximum temperature (North-East region)

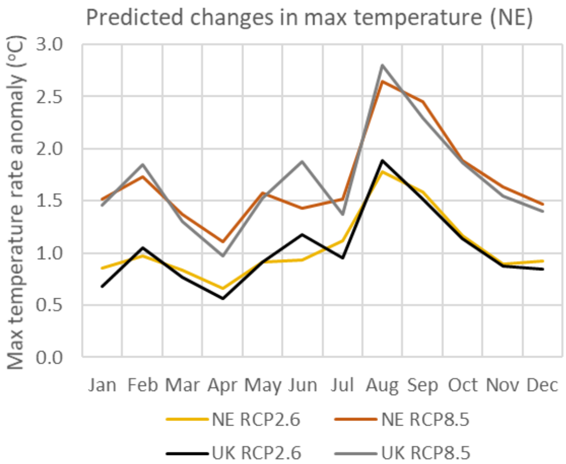


Figure 3.6: Predicted monthly changes in maximum temperature (South-East region)

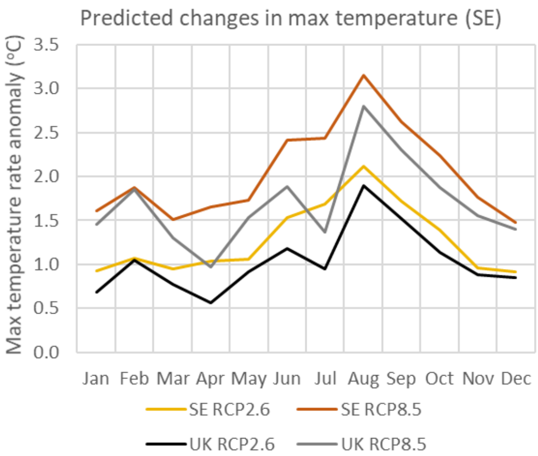


Figure 3.7: Predicted monthly changes in minimum temperature (North-East region)

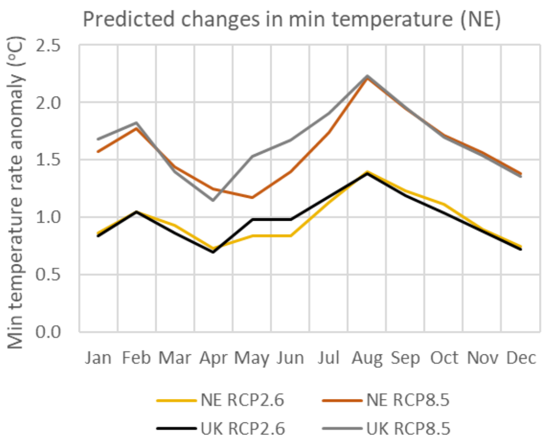
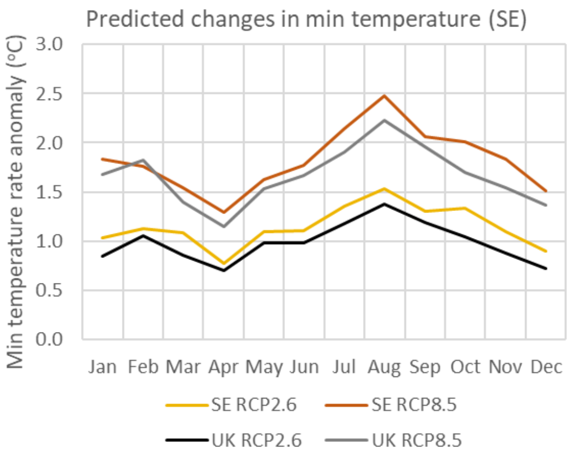


Figure 3.8: Predicted monthly changes in minimum temperature (South-East region)



Source: Mott MacDonald analysis of UKCP18 projections

UKCP18 probabilistic projections of extreme maximum daily temperature (20-years return period) in summer for one sample grid-cell of each area were processed to derive the change in the 2050s for the 50th percentile. The increase in maximum daily temperature for the North-East region is by 0.9^{o}C and 2.3^{o}C for RCP2.6 and RCP8.5 respectively. Very similar levels of increase are reported for the South-East region (0.9^{o}C and 2.0^{o}C for RCP2.6 and RCP8.5 respectively).

3.3 Sea level and storm surges

UKCP18 marine projections of sea level anomaly (relative to the baseline of 1981-2000) for one representative coastal grid-cell in each area were processed to derive the change in the 2050s for the 50th percentile. The mean sea level is expected to increase regardless of which emission scenario is adopted, with greater increases projected for the coastal area of the South-East region. The sea level increase for the North-East region is 0.17m and 0.24m for RCP2.6 and RCP8.5 respectively, while for the South-East region it reaches 0.23m and 0.30m. Essex and Suffolk will experience greater local sea level rise than coastal areas in the North-East due to a combination of local effects including the glacial isostatic rebound which affects ground elevations.

As regards storm surges and the potential additional increase in extreme sea level due to an increased storminess, results from an ensemble of regionally downscaled climate model simulations under RCP8.5 point towards a best estimate of zero additional contribution around the UK. The largest trends across the ensemble have a magnitude of about ±1 mm/yr[4].

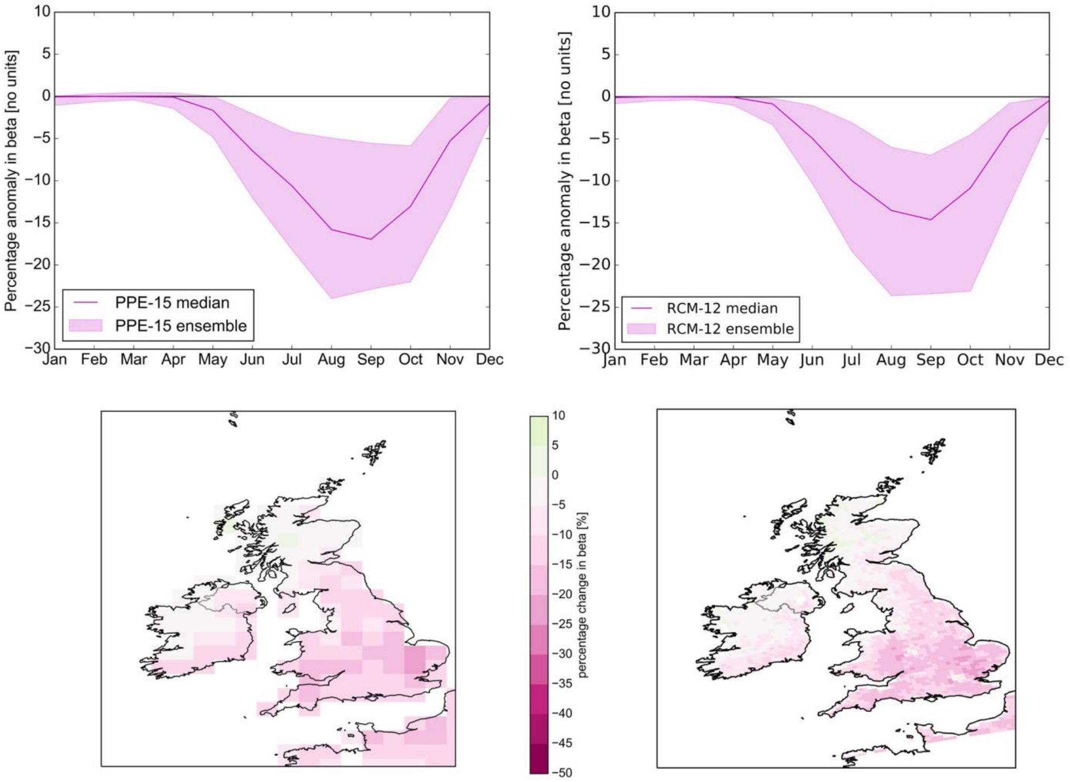
3.4 Soil moisture

Both the global and regional projections included in UKCP18 show reduced soil moisture for the period 2061- 2080 under a high emissions scenario compared to 1981-2000[5]. The projected future changes are small in winter and spring, and larger in summer and autumn. The spatial pattern of changes is similar across simulations, with the South-East showing greater summer drying than the North-East. The dry season is projected to be ‘longer and deeper’, meaning soil moisture spends a longer time below levels optimal for plant growth. This is consistent with the projected changes to precipitation, with on average drier summers causing soils to become drier for longer.

[4] ukcp18-marine-report-updated.pdf (metoffice.gov.uk)

[5] ukcp18_factsheet_soil_moisture.pdf (metoffice.gov.uk)

Figure 3.9: Projected changes in future (2061-2080) soil moisture content



Source: Met Office

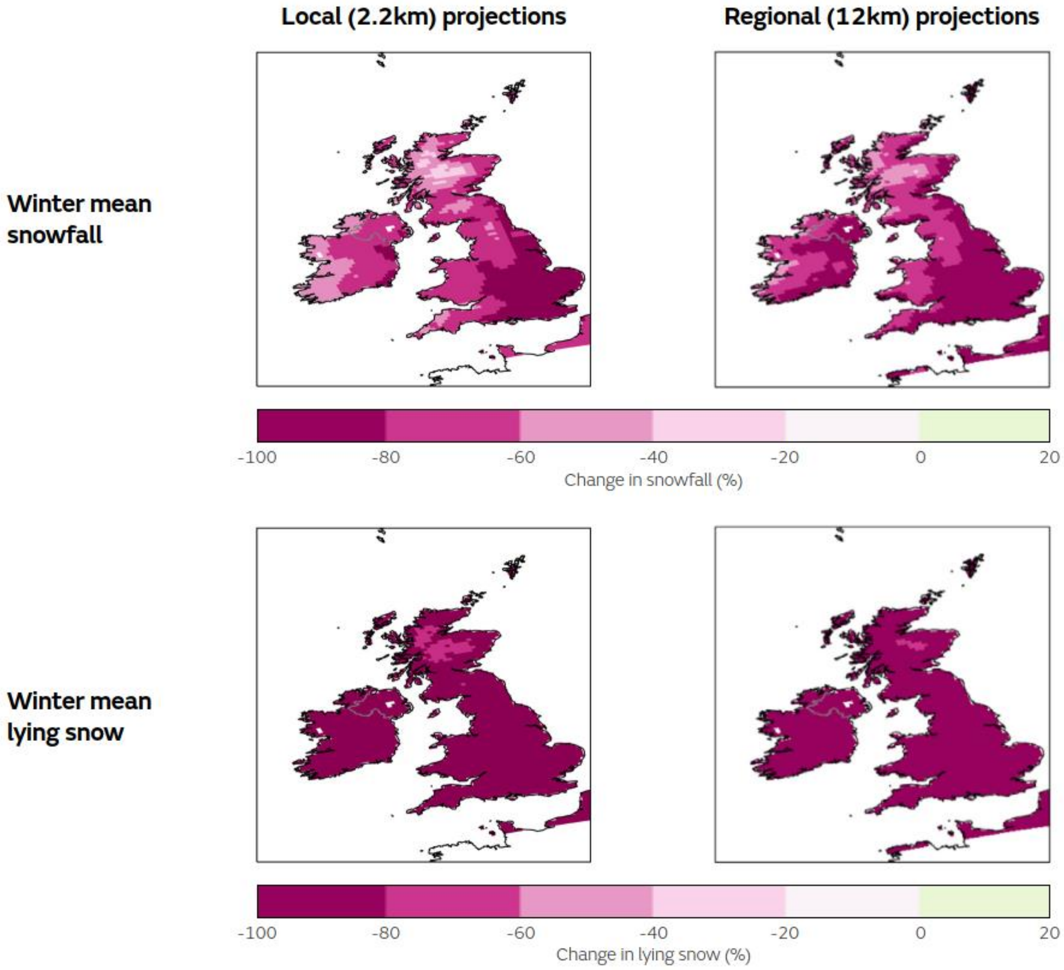
3.5 Snow

Widespread and substantial snow events have occurred in 2018, 2013, 2010 and 2009, but their number and severity have generally declined since the 1960s. The UKCP18 regional and local projections for the most extreme emission scenario show a decrease in both falling and lying snow across the UK for 2061-2080 relative to the 1981-2000 baseline[6]. In general, the decreases in percentage terms are smaller in both falling and lying snow in mountainous regions (e.g. Scottish Highlands) than in low-lying regions (e.g. southern England).

There are differences in estimates of future snow between the regional (12km) and local (2.2km) projections (see Figure 3.10). There is greater confidence in the new local projections since differences can be linked to the improved representation of wintertime convective showers and topography in the 2.2km model. Notwithstanding this, both projections are showing similar temporal trends with some more noticeable spatial differences.

[6] ukcp18_factsheet_snow_jul-2021.pdf (metoffice.gov.uk)

Figure 3.10: Projected changes in future (2061-2080) snow accumulation



Source: Met Office

3.6 Lightning

Lightning has been simulated in the Met Office convection permitting model used in the local (2.2km) projections[7]. However, a quantitative evaluation of changes in lightning rates is not possible as the mechanism used to model lightning includes both intra-cloud and cloud-to-ground lightning, whilst it is the latter component only that can cause impacts and is measured by the existing monitoring network. Given this, only a subjective qualitative projection is possible. In this sense, this convection permitting model suggests that lightning may decrease in the future in summer, although confidence in this is low. This would not be inconsistent with an increase in heavy summer rainfall, due to the role of ice fluxes in lightning generation.

[7] UKCP-Convection-permitting-model-projections-report.pdf (metoffice.gov.uk)

4 Changes in extreme weather events

Global warming is increasing the energy available in the atmosphere and there is growing scientific consensus linking this with an increasing number of extreme weather events[8]. Projecting changes in the frequency and intensity of extreme weather events is not straightforward, as climate models lack the resolution or the physics to simulate these rare events with accuracy. However, UKCP18 provide a suitable proxy in the form of weather patterns, whose assessment is presented in this section to infer the potential evolution of the extreme weather events affecting Northumbrian Water.

4.1 UKCP18 weather patterns

Weather patterns are atmospheric circulation types over a defined region and the Met Office have defined 30 of these patterns for the British Isles[9], each of them associated with specific weather conditions including the occurrence of extreme events. Any atmospheric conditions of a given day can be attributed to one of these 30 weather patterns. As per extreme events, specific events are more likely to happen under certain weather patterns in a specific season. The 30 weather patterns, relating to different patterns of mean sea level pressure anomalies, are shown in Figure 4.1.

Apart from being used in weather forecasting, weather patterns are a powerful tool in understanding how the frequency and magnitude of extreme weather events is likely to vary in the future as the UKCP18 projections include a simulation of their daily occurrence until the end of the century for the most extreme emissions scenario (RCP8.5) obtained from the Met Office Hadley Centre's global circulation model[10]. If a particular weather pattern associated with certain extreme weather conditions is projected to occur more often in the future, then the frequency of experiencing the extreme weather conditions is likely to increase. In addition, if the intensity of a particular weather variable (e.g. wind speed or daily rainfall) during the occurrence of a certain weather pattern in the future is greater than for the baseline, then the magnitude of the associated extreme weather events is likely to be greater.

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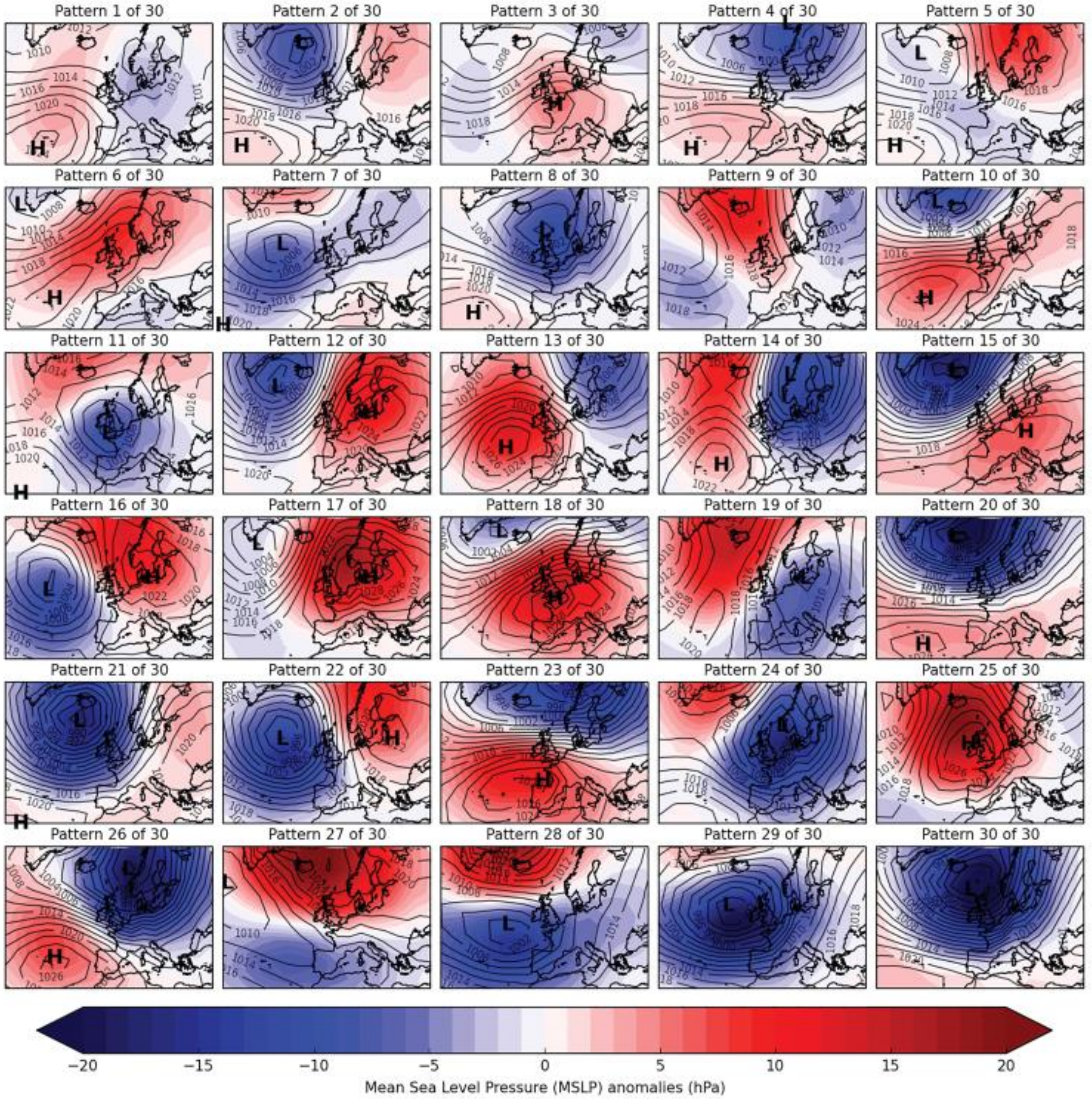
[8] How is climate linked to extreme weather? - Met Office

[9] Neal, R., Fereday, D., Crocker, R., and

Comer, R. E. (2016). A flexible approach to defining weather patterns and their application in weather forecasting over Europe. Meteorological Applications, 23(3), 389-400.

[10] McSweeney, C. and Thornton, H. (2020) UKCP European Circulation Indices: Weather Patterns. UKCP Factsheet. Met Office.

Figure 4.1: Definitions for the set of 30 weather patterns



Source: Neal, R., Fereday, D., Crocker, R., and Comer, R. E. (2016). A flexible approach to defining weather patterns and their application in weather forecasting over Europe. Meteorological Applications, 23(3), 389-400.

4.2 Attribution of weather patterns to historical extreme events

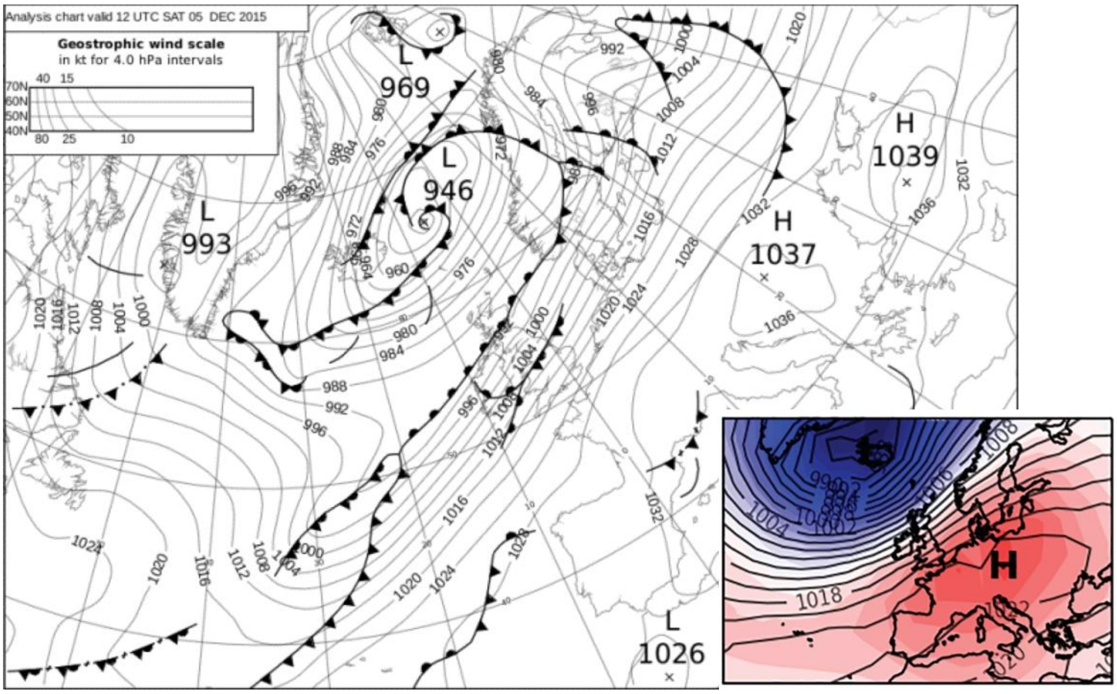
Northumbrian Water has experienced several extreme weather events in the recent past. The associated atmospheric conditions during the events are described below, together with the attribution to one of the 30 weather patterns. Synoptic maps have been retrieved from the Met Office digital archive and visually compared to the 30 weather patterns to identify the closest match.

4.2.1 Storm Desmond

Between the 4th and 6th December 2015, Storm Desmond led to exceptionally high rainfall across the north of England. Whilst extreme precipitation was widely reported across Cumbria (including a new rainfall record of 341.4mm at Honister Pass in 24-hours), heavy rainfall also affected the North-East and led to service disruptions. The resulting flooding and other storm damages led to minor incidents at many sites across the network.

The event was caused by a deep low-pressure system to the east of Iceland with fronts stretching across the north of Britain and a mild, moist south-westerly airstream forced to rise when reaching high ground, bringing prolonged and heavy rainfall across inland areas. As reported by the Met-Office, this mechanism, known as a 'warm conveyor' was very similar to the heavy rainfall and flooding that affected Cumbria in November 2009 as well as the January 2005 floods in Carlisle. The latter flood also washed away the river crossings to Hexham and surrounds leading to a no supply incident. Figure 4.2 presents the atmospheric conditions during the event, which can be attributed to weather pattern 15, described as neutral south-westerly and very windy for northwest Britain. This weather pattern has a 3% frequency of occurrence in the historical record, mostly during winter.

Figure 4.2: Storm Desmond synoptic map and weather pattern



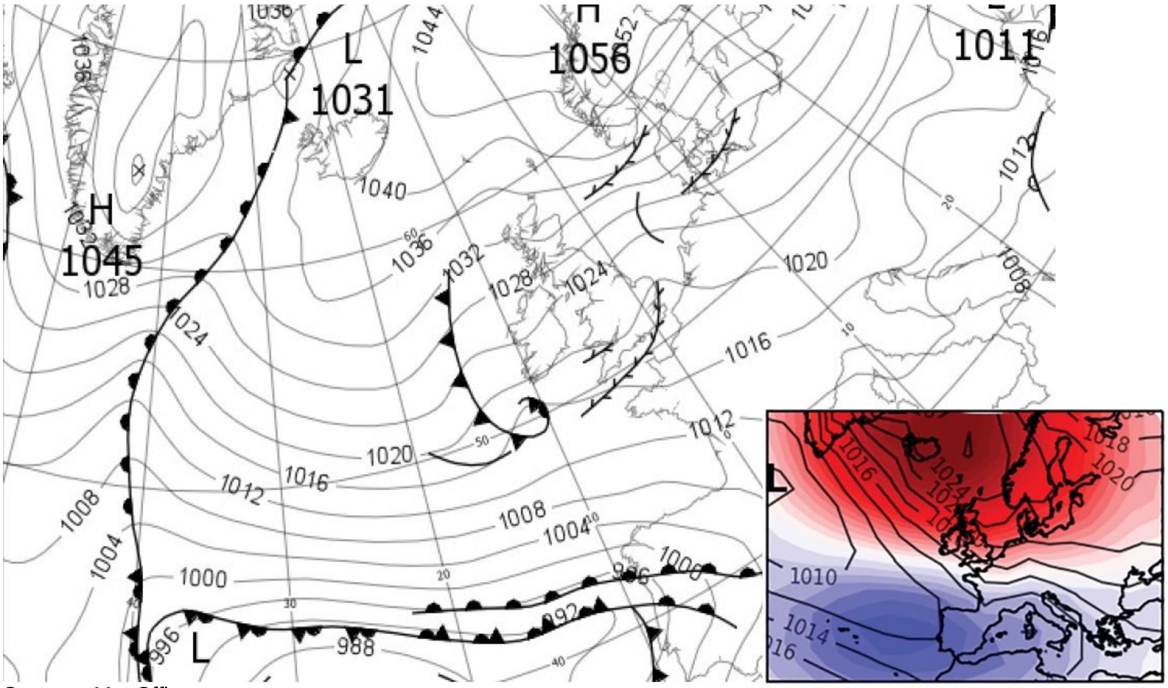
Source: Met Office

4.2.2 The Beast from the East

In late February and early March 2018, a spell of very low temperatures (below freezing levels) and significant snowfalls affected much of the country after a period of mild temperatures. Large areas of high pressure across Scandinavia and northern Europe combined with milder air within the Atlantic system led to an easterly airflow bringing cold air from Finland, north-west Russia and the Barents Sea to the UK. The freezing temperatures combined with a strong east wind, particularly on 28 February and 1 March, resulted in a wind-chill at times widely below -10 °C. A rise in temperatures during the first half of March was followed by another spell of snow and low temperatures between the 17th and 19th March with temperatures still fluctuating around freezing levels across upland areas of northern England and parts of the south-east. During the event, areas of the South-East became the most exposed to the easterly airflow.

Figure 4.3 presents the atmospheric conditions during the event, which can be attributed to weather pattern 27, described as Anticyclonic easterly with high pressure over the Norwegian Sea. This weather pattern has a 1.8% frequency of occurrence in the historical record, mostly in winter.

Figure 4.3: Beast from the East synoptic map and weather pattern



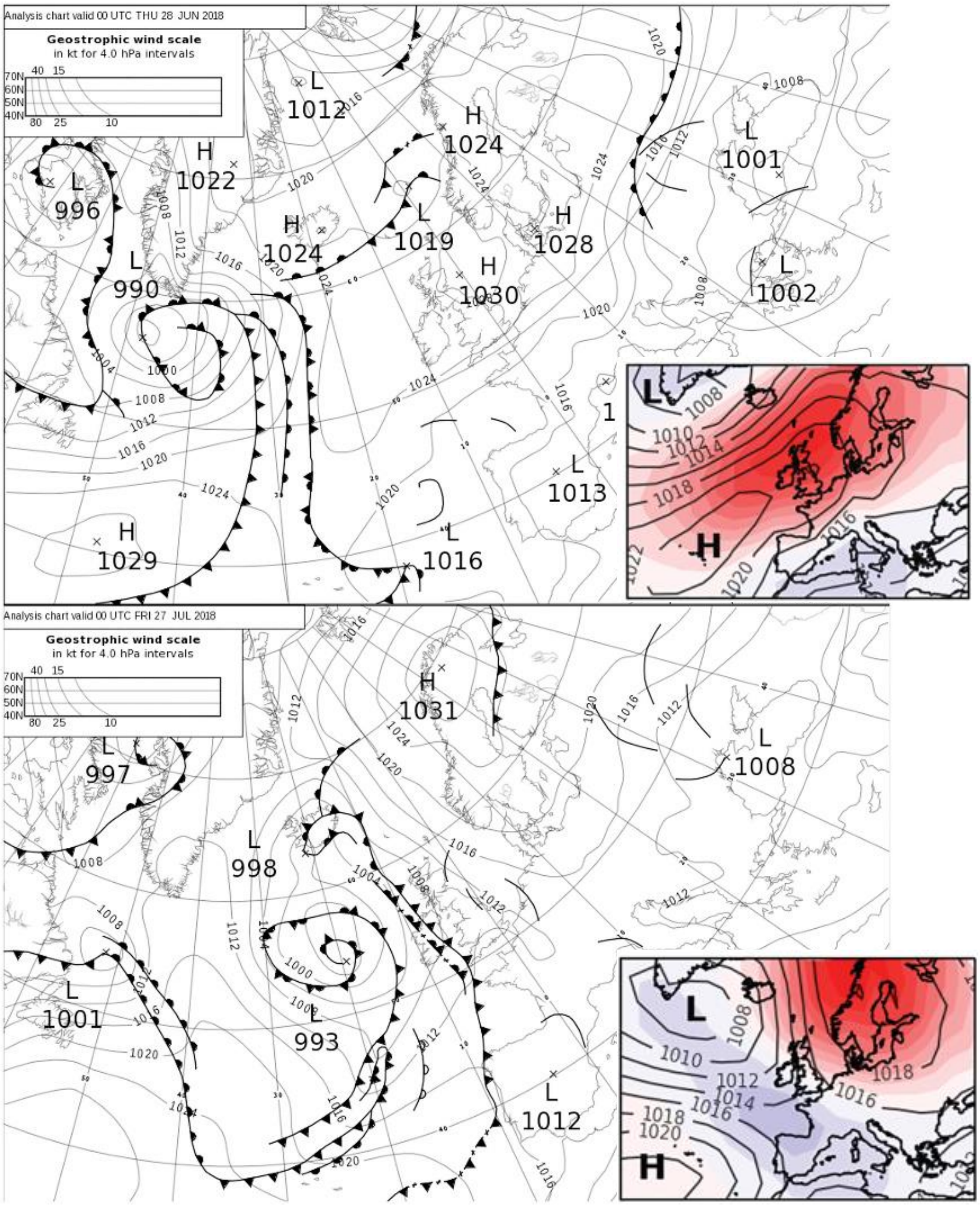
Source: Met Office

4.2.3 2018 Summer heat wave

Summer 2018 was the UK's warmest summer since 2006 and the driest since 2003, often influenced by high atmospheric pressures. The event was recorded as the fifth driest summer in a series from 1910 with the summers of 1995, 1976, 1983 and 1913 being drier. June was exceptionally dry across parts of southern England with records of over 50 dry days at some stations in the south-east lasting until late July.

Figure 4.4 presents the predominant atmospheric conditions during that period, which can be attributed to weather patterns 5 and 6. On one hand pattern 5 is described as neutral southerly with a centre of high pressure over Scandinavia. On the other hand, pattern 6 is described as anticyclonic with a high-pressure centre over the Azores. Both have a 4.9% frequency of occurrence in the historical record, more concentrated in summer.

Figure 4.4: 2018 heat wave synoptic maps and weather patterns



Source: Met Office

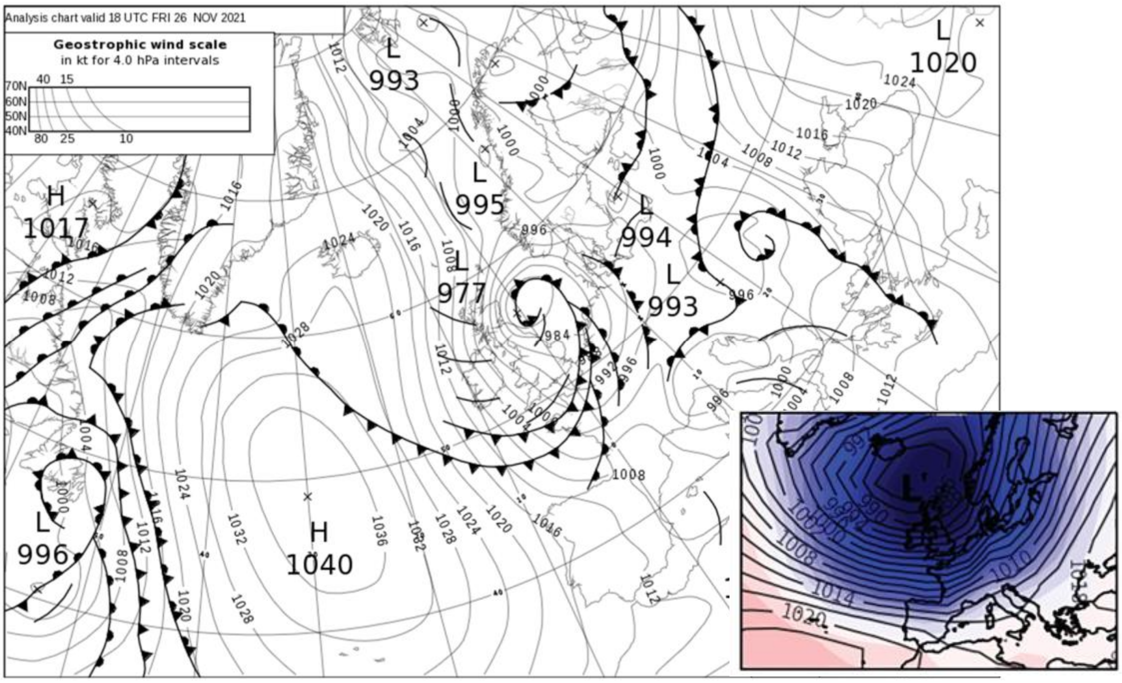
4.2.4 Storm Arwen

Between the 26th and 27th November 2021, extreme winds coming from the North Sea were recorded mainly across the north-east of England and eastern Scotland. Storm Arwen was reported by the Met Office as one of the most damaging windstorms of the latest decade with wind gusts reaching 50 to 60Kt (58 to 69mph) widely and exceeding 60Kt in many exposed coastal locations. The highest gust speed of 85Kt (98mph) was recorded at Brizlee Wood in Northumberland which remains exceptional for the north-east of England. The previous maximum record for the north-east was 89Kt (102mph) at Lynemouth, Northumberland, on 16 January 1984.

The northerly airflow associated with the storm also brought some very low temperatures and some significant snow accumulation, particularly across parts of the Pennines.

This event was classified as a civil emergency due to the nature of the disruption to power, access and amenities. Figure 4.5 presents the atmospheric conditions during the event, which can be attributed to weather pattern 30, described as cyclonic west-north-westerly with deep low pressure southeast of Iceland and very windy. This weather pattern has a 1.5% frequency of occurrence in the historical record, mostly in winter.

Figure 4.5: Storm Arwen synoptic map and weather pattern



Source: Met Office

4.2.5 Other heavy rainfall events

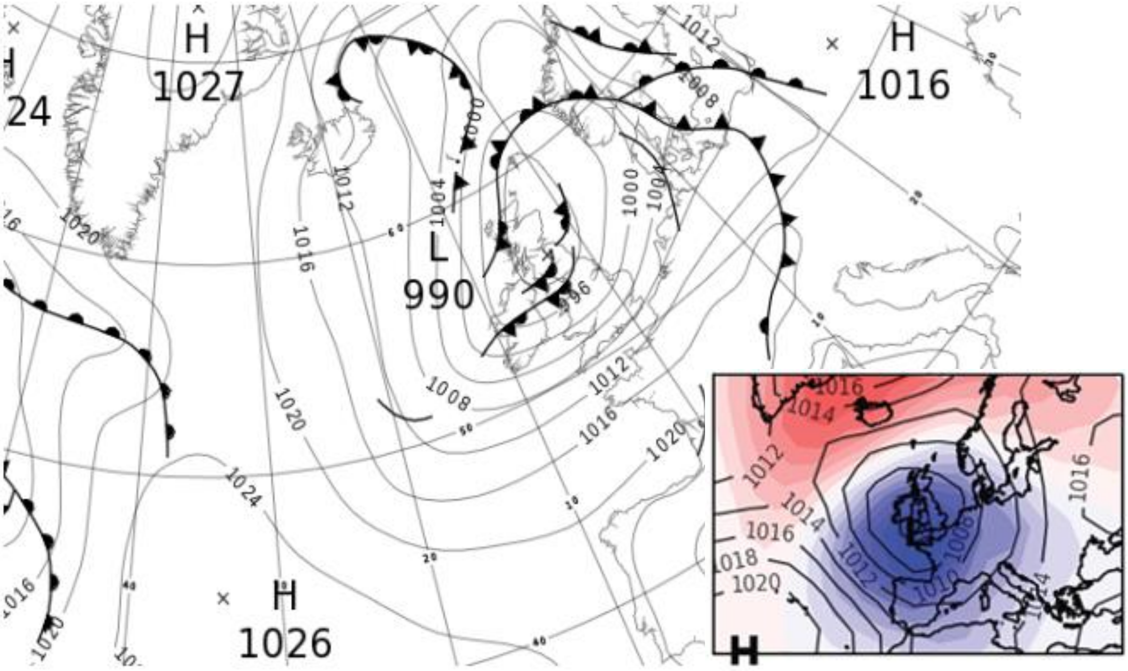
4.2.5.1 Ex-Hurricane Bertha

The remnants of Hurricane Bertha affected the North-East of Scotland as well as areas in the North-East of England between the 10th and 11th August 2014 with high wind and persistent extreme rainfall that led to flooding in various parts of the country, including in the North-East. This storm can be associated with weather pattern 24, described as cyclonic northerly with low pressure centred over the North Sea. This weather pattern has a 2% frequency of occurrence in the historical record, mostly in winter.

4.2.5.2 August 2019 storms

On the 10th of August 2019 northern England and southern Scotland were affected by heavy rain, turning thundery in places, and accompanied by strong winds. Figure 4.6 presents the atmospheric conditions during the event, which can be better related to weather pattern 11, described as cyclonic with a low-pressure centre over southern Britain. This weather pattern has a 3.7% frequency of occurrence in the historical record, mostly in summer.

Figure 4.6: August 2019 storm synoptic map and weather pattern

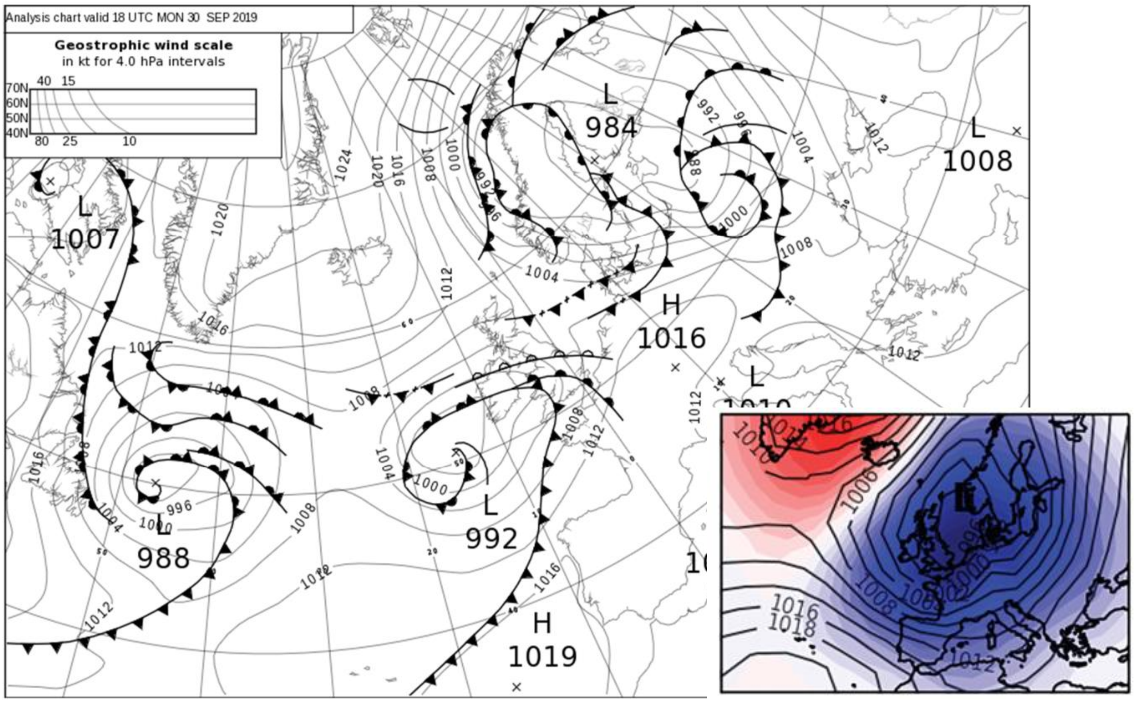


4.2.5.3 Wet weather spells and Storm Lorenzo

Storm Lorenzo, a mid-Atlantic hurricane, that passed across the UK between the 3rd and the 4th of October 2019 followed a period of wet weather conditions from late September and heavy rainfall on the 1st of October which led to flooding in parts of the country prior to the hurricane arriving. Heavy rain fell across northern England on the 30 September and thunderstorms brought torrential rain across southern England the following day.

Figure 4.7 presents the atmospheric conditions during the event, which can be better attributed to weather pattern 24.

Figure 4.7: Storm Lorenzo synoptic map and weather pattern

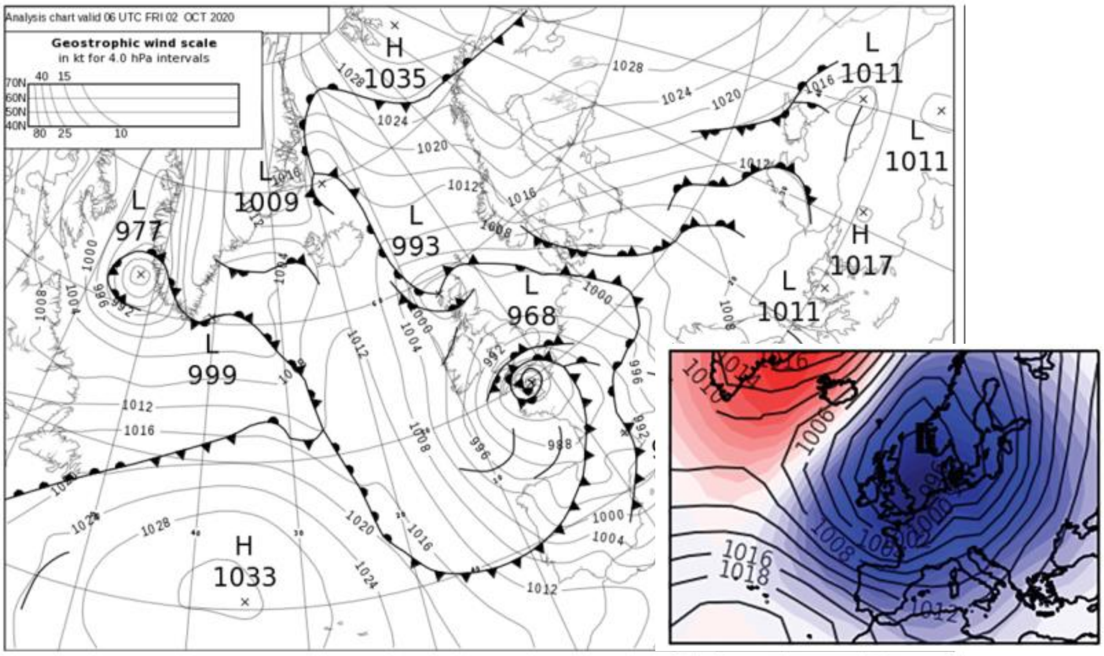


4.2.5.4 Storm Alex followed by heavy rainfall

Storm Alex brought strong winds to the southern half of the UK on the 2nd of October 2020 as well as heavy rain across southern England. A low-pressure system remained in place for a couple of days and associated fronts led to prolonged and widespread heavy rain in the following days (3rd and 4th), affecting much of the country. In the first four days of the month, 50 to 75mm or more of rain fell widely across southern England with areas recording totals of 100mm. The extensive nature of the rain resulted in the UK receiving 31.7mm as an area-average for the 3rd of October 2020, making it the wettest day on record in a daily series back to 1891.

Figure 4.8 presents the atmospheric conditions during the event, which can be better attributed to weather pattern 24.

Figure 4.8: Storm Alex synoptic map and weather pattern



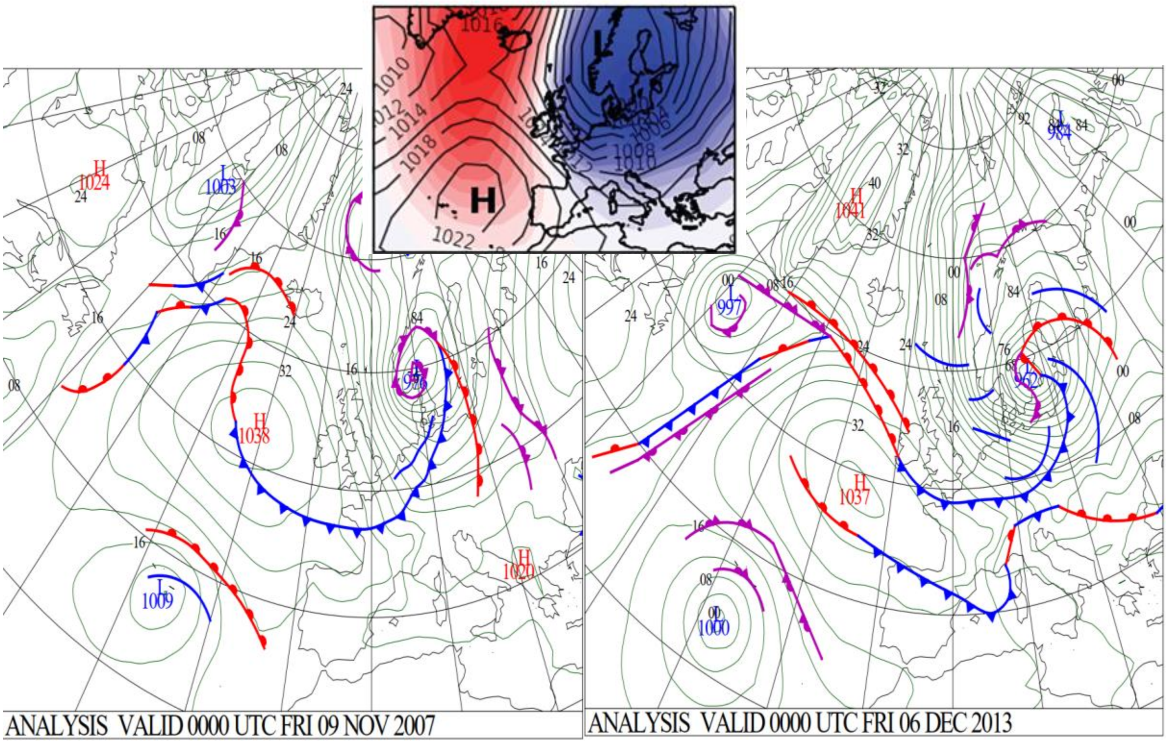
Source: Mett Office

4.2.6 North Sea storm surges

Storm surges from the North Sea occur when air pressure decreases significantly, leading to an increase in sea levels. A deep depression, with a central pressure of about 960 hPa, causes the sea level to rise half a metre above the level it would have been had pressure been about average (1013 hPa). Storm surges both lead to coastal flooding due to large waves breaking or submerging coastal/fluvial defences and infrastructures as well as saline intrusion as more sea water is pushed inland into the river system, moving the tidal interface further upstream in the watercourses. Such events of saline intrusion affected the river Waveney and affected treatment works operations during the November 2007 and December 2013 storm surges.

Figure 4.9 presents the atmospheric conditions during the events, which can be attributed to weather pattern 14, described as cyclonic north–north-westerly with low pressure centred over southern Sweden. This weather pattern has a 3% frequency of occurrence in the historical record, slightly more frequent in winter.

Figure 4.9: Storm surges synoptic maps and weather pattern



Source: Mett Office

4.3 Weather patterns assessment

4.3.1 Changes in frequency

UKCP18 projections of weather patterns for the UK have been analysed to extract occurrences/yr for each weather pattern, for the baseline period (1991-2020) and for 2050 (2036-2065). The occurrences were counted for patterns and seasons of interest, corresponding to past weather events as indicated in Section 4.2, classified into the following types of extreme events:

- Heat waves: summer 2018
- Summer storms: August 2019 and ex-hurricane Bertha
- Winter storms: Desmond, Arwen, Alex and Lorenzo
- Cold events: Beast from the East
- Storm surges: November 2007 and December 2013

These events might not capture all weather patterns leading to extreme events in the North-East and South-East regions given the short length of the record. To offer a more comprehensive assessment, UKCP18 regional projections of climatic variables (daily maximum temperature, daily minimum temperature, daily wind speed, daily maximum rainfall) for two 12km squares centred in Newcastle and Southend have been extracted and bias corrected with observations. The choice of the squares was not intended to be representative of absolute changes in climate variables across each region but to capture the relative regional trends. Time series have been filtered by season and weather pattern and relevant extreme variables have been derived as follows:

- Heat waves: Q95 maximum daily temperature in summer (value only exceeded 5% of the days in summer)
- Summer storms: Q99.9 daily rainfall (value only exceeded 0.1% of the days in summer)
- Winter storms: Q99.9 daily rainfall (value only exceeded 0.1% of the days in winter) and Q99 mean daily wind speed (value only exceeded 1% of the days in winter)
- Cold events: Q99 minimum daily temperature in summer (value only exceeded 1% of the days in winter)
- Storm surges: November 2007 and December 2013

The adopted quantiles are representative of the climate variables thresholds potentially leading to impacts, with for example heat waves needing to exceed a certain maximum temperature during a sustained period, whereas for extreme rainfall to cause flooding, its rarity should be higher.

Weather patterns have been ranked as a function of these extreme variables in the North-East and South-East. Moreover, the patterns leading to the more extreme weather for baseline conditions have been combined with those associated to past events. For example, apart from weather pattern 15 (storm Desmond), 24 (storms Alexa and Lorenzo) and 30 (storm Arwen), weather patterns 14 and 28 can lead to extreme wind in Newcastle. In the case of storm surges in the North sea, additional weather patterns have been identified from an assessment done at Lowestoft tide gauge[11].

Once weather patterns associated with certain extreme weather conditions are identified, the comparison of the occurrences between the 2050 and the baseline has been calculated as a proxy for the change in the frequency of those extreme weather conditions.

4.3.2 Changes in intensity of extreme events

To estimate the change in intensity of extreme events, the changes of the climatic variables associated with each weather pattern between the baseline (1991-2020) and future period (2036-2065) has been estimated, based on the UKCP18 regional projections of climatic variables (daily maximum temperature, daily minimum temperature, daily wind speed, daily maximum rainfall) for the representative 12km squares centred in Newcastle and Southend.

4.4 Projected changes in extreme events

4.4.1 Heat waves

The 2018 heat wave season corresponded to weather patterns 5 and 7. Weather patterns 3, 12 and 22 have also been identified as leading to similar conditions in the baseline. Changes in the frequency of these weather patterns and their reflection in maximum temperatures are presented in Table 4.1 and Table 4.2, showing that, in general, heat waves like the one experienced in 2018 are likely to occur more frequently in the future and they would intensify as regards extreme temperatures.

Other weather patterns leading to high maximum temperatures in current conditions would occur less frequently, although they would be replaced by others. Thus, for the North-East area, the total number of weather types with max temperature exceeding 25ºC (the heatwave threshold defined by the Mett Office) 5% of the time (Q95) increases from 9 in the baseline period to 26 in the 2050s, indicating that more weather types would result in heatwaves. Likewise, average increase in Q95 maximum daily temperatures would be 3.2°C.

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[11] Neal, R., Dankers, R., Saulter, A., Lane, A., Millard, J., Robbins, G., Price, D. (2018). Use of probabilistic medium- to long-range weather-patterns forecasts for identifying periods with an increased likelihood of coastal flooding around the UK. Meteorological Applications, 25, 534-547.

For the South-East area, 28 weather types result in maximum daily temperature exceeding 27°C (the heatwave threshold) for 5% of the time, which would increase to 30 in 2050, with an average increase in Q95 maximum daily temperatures of 3.4°C.

Table 4.1: Expected changes in heat waves in the North-East

Weather pattern	No. events per year			Associated Q95 max daily temperature		
	Baseline	2050s	% change	Baseline	2050s	Change (°C)
3	7.5	6.4	-15	26.0	28.7	+2.7
5 (summer 2018)	7.6	8.3	+10	25.9	29.9	+3.0
6 (summer 2018)	8.5	10.8	+28	25.6	29.0	+2.4
12	3.4	2.0	-41	26.9	29.7	+1.8
22	2.0	1.1	-46	26.2	29.3	+3.1

Table 4.2: Expected changes in heat waves in the South-East

Weather pattern	No. events per year			Associated Q95 max daily temperature		
	Baseline	2050s	% change	Baseline	2050s	Change (°C)
3	7.5	6.4	-15	30.2	33.4	+3.2
5 (summer 2018)	7.6	8.3	+10	29.8	34.1	+4.3
6 (summer 2018)	8.5	10.8	+28	29.5	33.0	+3.5
12	3.4	2.0	-41	30.0	32.7	+2.7
22	2.0	1.1	-46	30.2	32.7	+2.5

As a whole, projections indicate more frequent and more intense heat waves in both Northumbrian Water areas of operation.

4.4.2 Summer storms

The ex-Hurricane Bertha summer storm event corresponded to weather pattern 24, and the August 2019 storms to weather pattern 11. Weather patterns 1, 7 and 25 in the North-East and weather patterns 1, 7 and 26 in the South-East have also been identified as leading to similar extreme precipitation during summer. Changes in the frequency of these weather patterns and their associated precipitation are presented in Table 4.3 and Table 4.4. For the North-East results indicate that the number of events leading to extreme summer precipitation would remain the same or increase slightly, whereas for most weather patterns, the intensity of the events is expected to increase, in particular for large scale storms like ex-Hurricane Bertha. This is further evidenced by the number of weather patterns leading to a Q99.9 precipitation in summer greater than 40mm, which increases from 6 to 9 in the 2050s.

Table 4.3: Expected changes in summer storms in the North-East

Weather pattern	No. events per year			Associated Q99.9 daily precipitation		
	Baseline	2050s	% change	Baseline	2050s	% change
1	11.5	15.8	+38	49.3	49.9	+1
7	7.1	5.4	-23	48.3	53.5	+11
11 (August 2019 storms)	4.7	4.7	0	49.2	50.4	+2
24 (ex-Hurricane Bertha)	0.8	0.8	-4	38.8	54	+39

Weather pattern	No. events per year			Associated Q99.9 daily precipitation		
	Baseline	2050s	% change	Baseline	2050s	% change
25	0.9	1.2	+38	49.6	25.0	-50

For the South-East area results point to a slight decrease in the frequency of convective storm-type of events (1, 7 and 11), accompanied by significant intensification of their magnitude, where large scale storms would be less frequent but more intense.

Table 4.4: Expected changes in summer storms in the South-East

Weather pattern	No. events per year			Associated Q99.9 daily precipitation		
	Baseline	2050s	% change	Baseline	2050s	% change
1	11.5	15.8	+38	32.2	35.8	+11
7	7.1	5.4	-23	30.6	35.7	+17
11 (August 2019 storms)	4.7	4.7	0	27.4	41.3	+51
24 (ex-Hurricane Bertha)	0.8	0.8	-4	30.1	26.9	-13
26	0.7	0.6	-17	41.9	24.5	-42

As a whole, projections point towards more intense summer storms, whose frequency would not change significantly. The North-East would be more impacted by large scale storms whereas the South-East would be affected by short convective storms.

4.4.3 Winter storms

Storm Desmond (mostly characterised by exceptionally high rainfall) corresponded to weather pattern 15, storms Alex and Lorenzo to weather pattern 24, while Storm Arwen (predominantly a high wind event) to weather pattern 30. To describe winter storms both extreme rainfall and wind speed have been investigated. Weather patterns 7, 9 and 19 in the North-East and 14 and 28 in the South-East have also been identified as likely leading to similar extreme rainfall. Likewise, weather patterns 14, 23, and 26 in the North-East and 14, 20 and 26 in the South-East would be associated with extreme wind in current conditions.

Changes in the frequency of the weather patterns for the North-East area and their associated precipitation and wind speed are shown in Table 4.5 and respectively. Overall, results would indicate a decrease in the intensity of extreme rainfall events, except for storm Arwen type events, and a similar frequency of occurrence. However, looking across the whole set of weather patterns, the number of events leading to a Q99.9 rainfall greater than 30mm would increase from 9 to 16, which would imply a change in the type of winter storms impacting the area. As regards extreme winds, storms leading to these are likely to become more frequent and slightly more intense.

Table 4.5: Expected changes in winter extreme rainfall in the North-East

Weather pattern	No. events per year			Associated Q99.9 daily precipitation		
	Baseline	2050s	% change	Baseline	2050s	% change
7	1.6	1.6	+1	35.6	35.0	-2
9	1.2	1.0	-13	42.6	37.0	-13
15 (storm Desmond)	3.5	4.2	+20	23.1	21.4	-7
19	3.9	3.2	-16	45.0	32.3	-28
30 (storm Arwen)	3.9	3.9	0	25.7	30.4	+19

Table 4.6: Expected changes in winter extreme wind speed in the North-East

Weather pattern	No. events per year			Associated Q99 daily mean wind speed		
	Baseline	2050s	% change	Baseline	2050s	% change
14	2.5	2.5	+2	12.0	12.5	+3
15 (storm Desmond)	3.5	4.2	+20	9.3	10.4	+12
23	4.2	4.8	+14	12.6	13.6	+8
26	3.4	3.6	+9	13.2	13.2	0
30 (storm Arwen)	3.9	3.9	0	11.3	11.3	0

Changes in the frequency of the weather events for the South-East area and their associated precipitation and wind speed are shown in Table 4.7 and Table 4.8 respectively. In general, the area can experience more frequent storms, but their intensity would remain similar. Looking across the whole set of weather patterns, the number of events leading to a Q99.9 rainfall greater than 30mm would decrease from 8 to 6. As noted for the North-East area, both frequency and intensity of extreme wind events are expected to increase.

Table 4.7: Expected changes in winter extreme rainfall in the South-East

Weather pattern	No. events per year			Associated Q99.9 daily precipitation		
	Baseline	2050s	% change	Baseline	2050s	% change
14	2.5	2.5	+2	32.6	34.0	+4
15 (storm Desmond)	3.5	4.2	+20	25.3	17.9	-29
24 (storms Alex and Lorenzo)	2.6	2.8	+5	39.5	28.3	-28
28	3.0	2.5	-17	31.2	34.5	+11
30 (storm Arwen)	3.9	3.9	0	29.1	31.4	+8

Table 4.8: Expected changes in winter extreme wind speed in the South-East

Weather pattern	No. events per year			Associated Q99 daily mean wind speed		
	Baseline	2050s	% change	Baseline	2050s	% change
14	2.5	2.5	+2	12	12.7	+6
15 (storm Desmond)	3.5	4.2	+20	8.8	9.8	+11
20	3.5	3.9	+12	11.7	11.8	+1
26	3.4	3.6	+9	13.1	13.3	+2
30 (storm Arwen)	3.9	3.9	0	12.7	13.0	+2

As a whole, winter storms leading to extreme rainfall will intensify less than summer ones, and would be slightly more extreme in the North-East. Their frequency is likely to remain the same or increase slightly. However, extreme windstorms will become more frequent in winter and more intense. This is consistent with the regional analysis presented in Section 2.3.

4.4.4 Cold events

The Beast from the East 2018 cold event corresponded to weather pattern 27. Other weather patterns associated with extreme minimum temperatures during winter in current conditions would be 11, 17, 19 and 28 in the North-East and 16, 19, 25 and 28 in the South-East. Changes in the frequency of these weather patterns and their corresponding minimum temperatures for the North-East and South-East regions are presented in Table 4.9 and Table 4.10 respectively.

Results indicate that for both regions, weather patterns relevant to cold events are expected to decrease in frequency and intensity, with significant increases in Q99 minimum daily temperature (from +2.1 to +5.8ºC).

Table 4.9: Expected changes in cold events in the North-East

Weather pattern	No. events per year			Associated Q99 min daily temperature		
	Baseline	2050s	% change	Baseline	2050s	Change (ºC)
11	1.2	1.3	+10	-9.9	-5.1	+4.8
17	2.9	3.1	+6	-10.2	-4.7	+5.5
19	3.9	3.2	-16	-10.2	-5.9	+4.3
27 (Beast from the East)	2.7	2.3	-16	-9.7	-6.5	+3.2
28	3.0	2.5	-17	-11.8	-6.8	+5.0

Table 4.10: Expected changes in cold events in the South-East

Weather pattern	No. events per year			Associated Q99 min daily temperature		
	Baseline	2050s	% change	Baseline	2050s	Change (ºC)
16	1.9	1.7	-11	-7.6	-4.2	+3.4
19	3.9	3.2	-16	-7.4	-4.3	+3.1
25	3.8	3.7	-3	-5.2	-3.3	+2.1
27 (Beast from the East)	2.7	2.3	-16	-9.8	-5.0	+4.8
28	3.0	2.5	-17	-9.5	-3.7	+5.8

4.4.5 Storm surges

The November 2007 and December 2013 storm surges corresponded to weather pattern 14. From literature, weather patterns 13, 23 and 26 would also be associated with the occurrence of these events. Frequencies of these patterns are presented in Table 4.11, showing that overall winter storm surges are likely to occur more often in the future. Their intensity is not expected to increase as indicated in Section 3.3, but they will be associated with higher sea levels, and therefore, their impacts would be greater.

Table 4.11: Expected changes in winter storm surges

Weather pattern	No. events per year		
	Baseline	2050s	% change
14 (Nov 2007 and Dec 2013 storm surges)	2.5	2.5	+2
13	3.2	2.6	-17
23	4.2	4.8	+14
26	3.4	3.6	+9

5 Preliminary climate change risk assessment

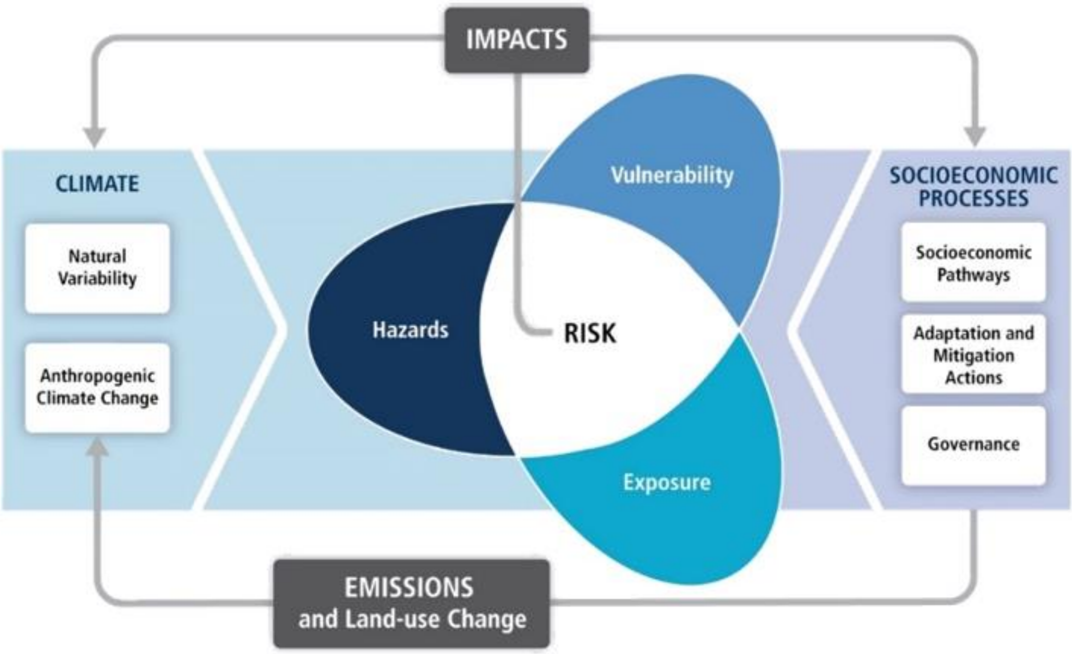
A preliminary climate risk assessment has been undertaken to identify the greatest risks to Northumbrian Water operations that will be explored in more detail in the subsequent phase. The analysis combines changes in the likelihood of climate hazards as presented in sections 3 and 4 with the magnitude of the related consequences, building on records of impacts during past events complemented with expert judgement where possible.

5.1 Approach and method

Climate risk is defined as the combination of the climate hazard likelihood of occurrence, the exposure of the system, as well as its vulnerability to the hazard. Climate risk is influenced by both natural and anthropogenic factors as presented in Figure 5.1, where:

- Adaptation actions (or a lack of) affect the level of vulnerability of the system;
- Location of assets influence their exposure; and
- Natural as well as human driven climate changes affect the magnitude and frequency of hazards the system becomes exposed to.

Figure 5.1: Definition of climate risk



Source: IPCC, 2013

The preliminary risk assessment presented here investigates risks at a system level, both for the water and wastewater systems. Risks are assessed for a range of climate hazards to identify those that pose the greatest threats to Northumbrian Water operations. The analysis considers changes in the likelihood of climate hazards together with the magnitude of consequences. As the latter has been based on the impacts recorded during past extreme weather events, it already combines the system exposure and vulnerability to specific hazards. The known consequences have been supplemented with expert judgement where necessary. The classification presented in Table 5.1 has been adopted for all risks investigated in this preliminary assessment.

Table 5.1: Climate risk definition

		Magnitude of the consequences		
		Low	**Moderate**	**High**
Likelihood of hazard	**Lower**	Low	Low	Medium
	Stable	Low	Medium	High
	Greater	Medium	High	Very High

5.2 Extreme heat

A heat wave is defined by the Met Office as a period of 3 consecutive days exceeding 25°C in the north and 27°C in the south-east[12]. As reported in Section 4.4.1, the likelihood of experiencing heat waves will increase in the future and they will become more extreme, in particular in the South-East. The typical consequences of heatwaves across the systems are:

- Increase in water demand beyond or at network capacity leading to pipe bursts or failure to supply;
- Algal blooms due to increased evaporation from reservoirs, reduced flows and increased water temperatures, impacting on pumping and treatment operations;
- Odour and septicity;
- Pumps operating inefficiently, leading to increased operating costs;
- Failure of ICT and communications equipment if they are not sufficiently cooled; and,
- Lower efficiencies in the processes of water and wastewater treatment works during extreme temperature changes.

Recorded costs for the 2018 hot summer clearly exceeded those of other recorded events. Whilst they are mainly associated with pipe bursts linked to drier ground conditions (discussed in Section 5.4), it is likely that some of these incidents resulted from a combination of ground subsidence with an added pressure of increased customer demand on the networks. Overall, the magnitude of the consequences can be classified as low for the North-East and as moderate for the South-East, which faces higher increases in temperature. Together with a greater likelihood of the hazard for both regions, this risk is estimated as **medium** for the North-East area and as **high** for the South-East area.

5.3 Drought and water scarcity

A drought is most commonly referred to as a lack of water within an area. However, drought events have been classified by the Intergovernmental Panel on Climate Change into four types:

- Meteorological drought that occurs when rainfall is below the local, regional, national average;
- Hydrological drought that occurs when availability of water for supply from streams, reservoirs and aquifers is low. This can be caused by low rainfall as well as a lack of snowmelt or other natural or anthropogenic reasons;

[12] McCarthy, M., Armstrong, L., and Armstrong, N. (2019) A new heat wave definition for the UK. Weather, 74(11), pp 382-387.

- Agricultural drought that occurs when a lack of rainfall and/or dry ground affect farming and crop growth; and,
- Ecological drought that occurs when the lack of water affects the ecology of aquatic and terrestrial ecosystems.

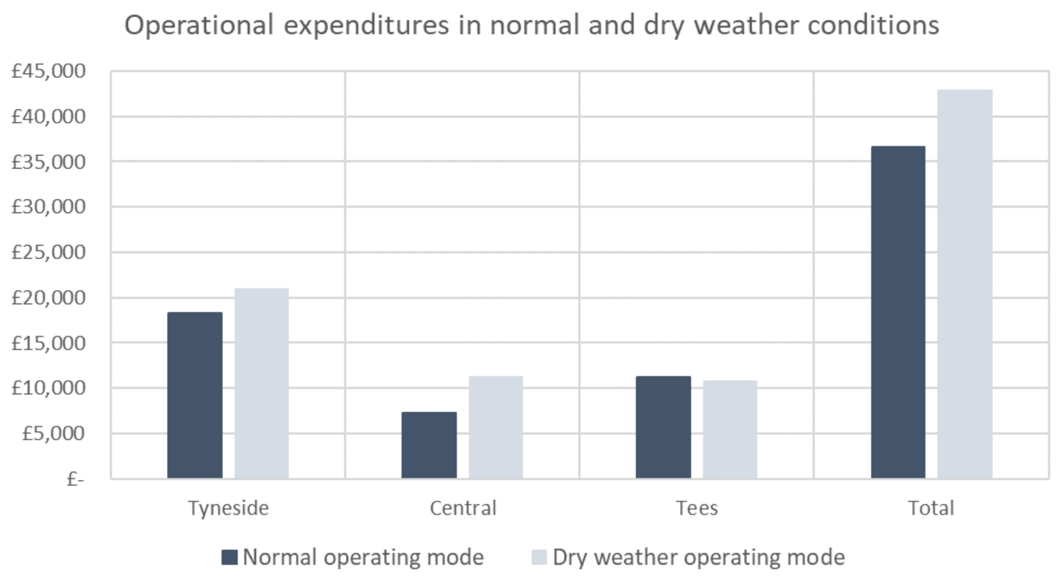
Moreover, groundwater drought, relating to low groundwater levels, originates from reduced recharges over a prolonged period, and is mostly caused by dry winters rather than dry summers. Aquifer-dependent areas like East Anglia are susceptible to groundwater drought conditions. Although winter precipitation is expected to increase, the same applies to the frequency of droughts, indicating that there could be more dry winters causing stress in aquifers in the future.

Whilst lower and unevenly distributed rainfall is an important cause of drought conditions, warmer temperatures also lead to increased evaporation from water bodies and higher evapotranspiration from the land that can result in soil moisture deficits and drier ground conditions overall. The resulting consequences of drought across water and wastewater systems are:

- Decrease in river water levels and flows with impact on intake operations and source yields (i.e. drought triggers). Temporary shut-downs can affect treatment operations with reduced inflows to the works and overall reduced deployable output with impacts on supply to customers. In addition, poorer raw water quality can increase water treatment costs;
- Reservoir depletion from increased evaporation and/or reduced inflows if fed by restricted and/or temporarily unavailable fluvial abstractions, leading to the need for activating other more expensive resources;
- Pumps working under capacity from reduced flow rates;
- Sedimentation and blockages in sewers due to low flows;
- Impact on wastewater treatment operations from less water available for dilution of effluents leading to increased concentration of pollutants in receiving waterbodies. Possible interruptions or additional costs for chemicals and energy could occur if discharge compliance is compromised; and,
- Shift to other sources and treatment works with increased operational costs.

Costs associated with the operations of sources and works during dry weather conditions, such as those of the summer 2018, can become relatively high if the scale of the event leads to regional water deficits. In order to meet demand needs, a shift to pumped sources was required during that period (e.g. transfer from Kielder reservoir), implying greater energy consumption, as well as a shift to treatment works with higher power and chemical unit costs. This means that in that dry year, daily operating costs were significantly higher than in an average year. As shown in Figure 5.2, the annual average difference was £6,163 per day or £2.25m per annum.

Figure 5.2: Differences in north-east operational costs under dry weather conditions



Source: Northumbrian Water

In addition, historical outages at Barsham water treatment works have been experienced due to low water levels. In February 1996, the river level dropped below the minimum operating level for the intake structure, reducing the output from the works during the following month. The River Waveney Augmentation scheme owned and operated by the Environment Agency is designed to prevent this occurring. However, this mitigation might be threatened by the impact of climate and the increased likelihood of droughts.

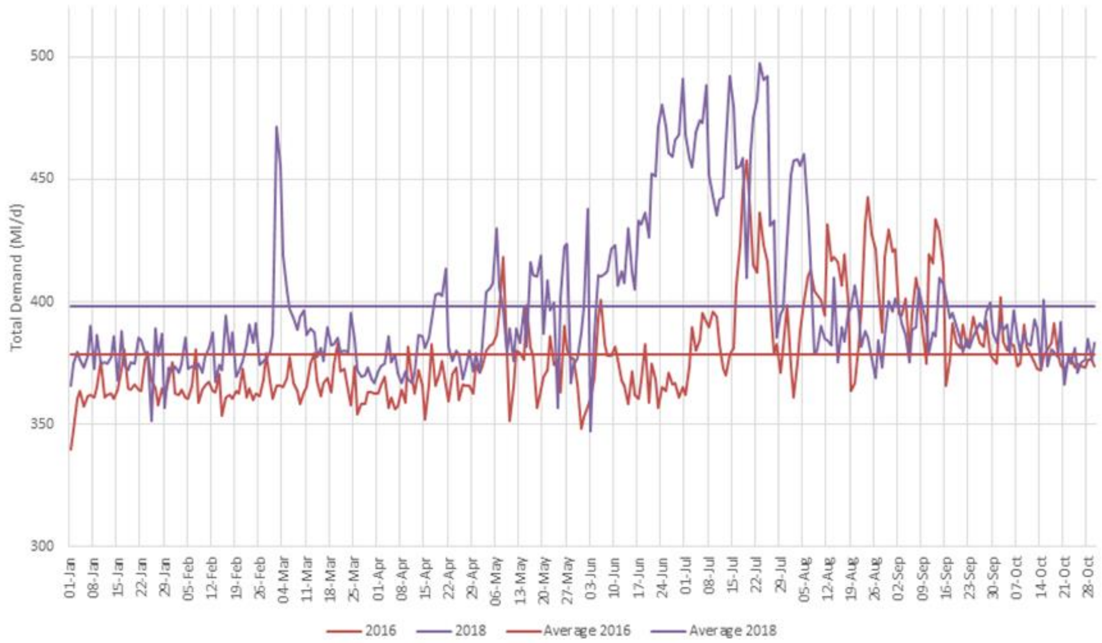
Large scale and prolonged drought conditions can further affect supply in the situation when the system has to work at capacity. The magnitude of consequences for this hazard is assessed as moderate for the North-East region and as high for the South-East region. Although the North-East region has historically had a surplus in Northumbrian Water WRMPs, and the Kielder reservoir and Berwick water resource zones have sufficient water according to WRMP19, the past assessments do not account for the 1 in 500-year drought and the impact of the latest climate change projections. Lacking a full supply demand balance assessment incorporating these aspects, there is still a possibility the North-East region could incur in some deficit. A likely decrease in annual rainfall, concentrated in summer and autumn, as well as an increase in temperatures as reported in Section 2.1, result in a greater likelihood of occurrence for this hazard. The risk of drought is thus estimated as **high** for the North-East region and as **very high** for the South-East region.

5.4 Soil moisture deficits

Soil moisture deficits are closely linked to drought conditions, when increased evapotranspiration due to high temperatures combined with low rainfall lead to drier ground conditions. The main consequences across the networks are swelling and shrinking of soils as well as erosion, causing subsidence on engineered slopes and foundations, damaging infrastructure and increasing the levels of leakages and bursts in water pipes, further exacerbated by a higher water demand.

Most of the costs relevant to the 2018 hot summer were associated with attending and fixing increased rates of pipe bursts and leakages on the networks. The magnitude of those impacts was slightly higher in the South-East, but overall the costs remained high across both service areas. The increase in total demand (including leakages) as a result of this extreme weather event in Essex is presented in Figure 5.3 in comparison to a more normal year of 2016, with an increase in average production of 14Ml/d (4% over planned). The North-East and Suffolk also experienced increases in annual demand of 17 and 2Ml/d respectively, which implied additional power and chemical costs over budgeted. An increase in bursts on larger pipe diameters was reported throughout the period and the deployment of operatives required longer intervention time to limit leakages in both the North-East and South-East supply areas. This disruption extended beyond the event, with recovery efforts for bursts and leakages on-going until November.

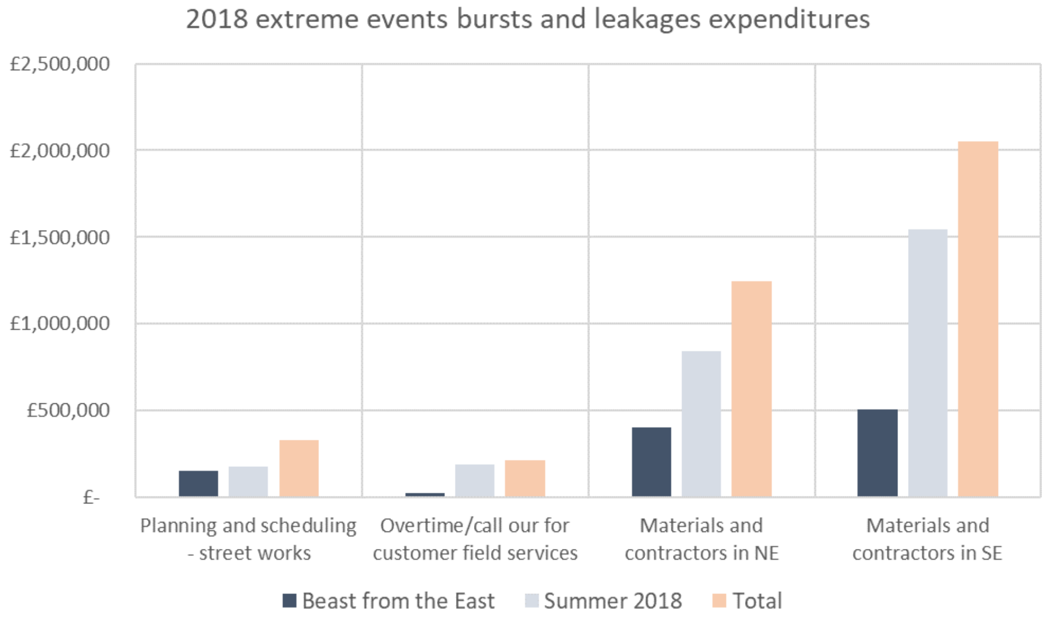
Figure 5.3: Variations in annual total demand from 2018 extreme weather events in Essex



Source: Northumbrian Water

Repair costs, including those associated with surrounding impact mitigation/reinstatement (i.e. damage to road surface, traffic management/diversion) were significant at £2.75m, with the majority of them (£2.39m) required to repair the associated leaks and bursts (see Figure 5.4) The recovery time for interventions on larger mains also increased and further resulted in an increase in overtime and out-of-hours activities.

Figure 5.4: Operational costs for 2018 leakages and pipe bursts



Source: Northumbrian Water

Costs also clearly exceed those of other recorded events and thus the magnitude of consequences is assessed as moderate for the North-East and as high for the South-East. A likely decrease in rainfall during the summer, more pronounced in the South-East, as well as an increase in temperatures would result in a large decrease in soil moisture during the summer. Soils are expected to be drier for longer during the summer period and greater drying is anticipated in the South-East. This hazard will then have a higher likelihood of occurrence in the future, and overall, the risk is estimated as **high** for the North-East and as **very high** for the South-East.

5.5 Wildfire

Wildfires are uncontrollable fires that spark from the combination of very hot weather and very dry conditions and spread across a large area sometimes for days, weeks or months such as those that devastated the Australian states of Queensland and New South Wales between September 2019 and early 2020. No instances of wildfires with impacts on Northumbrian Water assets and operations have been reported to date. Even though maximum temperatures and air temperatures overall are likely to increase alongside a reduction of rainfall in summertime, leading to drier conditions, the likelihood of occurrence of widespread wildfires remains relatively low given the range of temperatures experienced across the UK. In case they do occur, the impact on the water and wastewater system is considered to be low, and the overall risk is assessed as **low** for both North-East and South-East regions.

5.6 Cold and freeze thaw

A freeze thaw event occurs when temperatures fluctuate around zero, leading to an alternating pattern of freeze – defreeze of the ground which can affect the integrity of buried pipelines. Extreme cold weather conditions can sometimes occur during freeze-thaw events, although this is not always case, and extreme cold should be treated independently as well as in combination. Overall, the consequences of these events are:

- Failure of filtering processes from frozen water or water below optimal temperature;

- Pipe bursts and increased leakages from the alternating freeze-defreeze;
- Decrease in groundwater recharge from frozen ground and lower infiltration rates;
- Cracking of concrete structure with fluctuating temperature;
- Freezing of equipment (i.e. valves) and subsequent operational impacts; and,
- Slowed biological activity from cold temperatures, affecting treatment and sludge processes.

The impacts of previous freeze-thaw events like the Beast from the East followed by periods of mild and cold weather are relatively high, with significant costs associated with the increased rates of pipe bursts and leakages across the network as well as an increase in customer-side leaks in both the North-East and South-East service areas. Teams in Essex reported a threefold increase in mains bursts compared to the previous March 2017. During the event, failures were unusually reported on larger diameter pipes and network repair and maintenance teams from direct labour and supply chain partners worked around the clock 7-days a week to maintain service delivery to customers and manage losses in the system.

The increase in total demand due to leakages can be seen in Figure 5.3 alongside that of summer. Although the peak had a magnitude similar to the summer period, it lasted only for a week due to the rapid interventions. In any case, the recovery efforts from the Beast from the East and the subsequent freeze thaw events that followed continued over a period of three months, particularly to attend and repair main bursts and other leakages in the network.

As can be seen in Figure 5.4, costs associated with this event were significant although lower than during the heatwave in the same year, totalling £1.09m. Therefore, the magnitude of consequences is assessed as high for both regions. As a result of increased temperatures, cold events like the Beast from the East are likely to decrease in frequency and intensity (see Section 4.4.4) and the associated risk of cold events is only assessed as **medium** for both North-East and South-East regions.

5.7 Snow

Consequences of past snow fall and snow accumulation across Northumbrian Water service areas are relatively minor in comparison to other hazards discussed in this section. Snow falls that occurred during the Beast from the East and storm Arwen have not been reported with significant cost impacts compared to other sources of incidents that affected the networks at that time, but there were some business impacts nonetheless associated with operations, for example by blocking access for operatives to attend to other hazards such as frozen assets. However, there is likely to be a decrease in both falling and lying snow across the UK in future climate conditions and the likelihood of the hazard will be lower for both regions. As a whole, the risk of snow is assessed as **low** for Northumbrian Water operations across both North-East and South-East regions.

5.8 Flooding

Flooding can result from a variety of sources and affect different parts of the network depending on location:

- Fluvial flooding occurs when water levels in the fluvial system are too high and exceed bankfull capacity, spilling over the river banks and across the floodplain;
- Surface water flooding occurs when heavy and/or prolonged rainfall falling on saturated or impervious ground leads to increased runoff rates across catchments and increases volumes of water into the drainage networks beyond their capacity;
- Coastal flooding occurs as a result of storm surges and wave action, increasing sea levels and causing overtopping of costal defences and inundating protected or non-protected areas; and,

- Sewer flooding can occur as a consequence of other types of flooding that impact the wastewater system (i.e. flooding of wastewater site, pumping stations) or as a result of external power outage (i.e. shutdown of pumping stations). Disruptions lead to backing-up in the network.

Fluvial and surface water flooding often result from heavy and prolonged rainfall whilst high sea levels and extreme waves have a bearing on coastal flooding. The main consequences of flood events are:

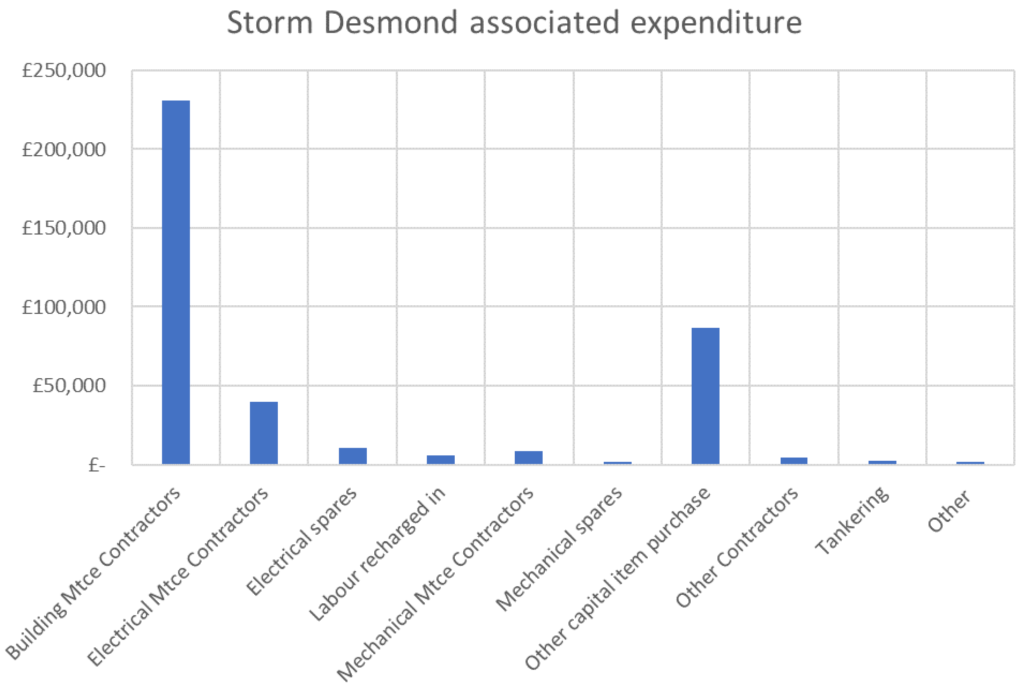
- Inundation of water and/or wastewater sites;
- Damage to infrastructure from flow-carrying debris;
- Floatation risks of buried infrastructure and increased risks of pipe bursts from increased ground saturation and surface water flooding;
- Exceedance of drainage network capacity (i.e. overloading of pipes and stormwater storage beyond capacity) with effect on the magnitude of surface water flooding;
- Tide-locking or high fluvial level locking conditions affecting ability of network to discharge in waterbodies and triggering back-up inundation along networks. This can affect treatment operations;
- Increased volumes in combined sewer systems beyond capacity which can trigger unscreened discharges into the environment and/or sewer flooding;
- Increased turbidity and/or pollutant levels in river systems with effect on raw water quality impacting intake and treatment operations;
- Upstream migration of saline interface in tidal waterbodies with impact on river abstractions (i.e. intake closure);
- Increased use of wastewater asset beyond throughput; and,
- Restricted access to site from flooded access routes.

Previous extreme summer and winter storms have led to a variety of flood incidents across the system with significant associated expenditure (i.e. building costs for infrastructure damage). For example, during storm Desmond heavy rainfall falling across the north-east combined with high winds led to:

- Inundation at some of the sites with high water levels reaching electrical components, damaging equipment (i.e. control panels) and leading to shutdowns;
- Storm tanks reaching capacity due to higher volumes of water conveyed through the system;
- Pumps working at high capacity for prolonged periods leading to damage of parts and/or failure;
- Damage to access road and infrastructures (e.g. entrance gates, building roofs) from high winds, falling trees and high velocity flood waters carrying debris. This type of impacts also occurred during storm Arwen; and,
- Damage to a river intake from increased siltation levels resulting from increased runoff across the land.

Whilst storm Desmond lasted over two-days, the recovery efforts extended for a period of a month after the event. The event response required attendance of sites by operatives and other contractors and the deployment of tankering/pumping facilities to pump water out of storm tanks. Recovery efforts focussed on the replacement of building parts, electrical components and in some cases, pumps and control panels damaged during the event. Other post-event interventions included cleaning up debris left by the storm. The total cost related to responding and recovering from storm Desmond was evaluated at £392,338 with 59% of the expenditure related to building costs (see Figure 5.5)

Figure 5.5: Impact costs from Storm Desmond



Source: Northumbrian Water

Overall, the magnitude of consequences for flood hazards is assessed as high for the North-East region and as moderate for the South-East region, the latter due to the smaller number of assets at risk and the lack of flooding reports.

As indicated in Section 4.4.2, whilst the frequency of weather patterns leading to current summer storms is likely to remain unchanged or slightly increase, an intensification of extreme precipitation is likely across both regions, suggesting that other weather patterns will lead to extreme rainfall and summer storms in the future. Similarly, a trend towards more pronounced extreme precipitation is highlighted in winter, in particular in the North-East, and events like storm Desmond are also likely to be more frequent though less intense (see Section 4.4.3). However, given the particular properties of the North-East valleys, the magnitude of floods is expected to increase significantly as evidenced in the EA climate change allowances for peak flows. Furthermore, the rise in mean sea level (generally higher in the South-East) is likely to lead to an increase in the frequency and magnitude of costal flood events. Overall, the likelihood of occurrence is expected to be higher for all types of flood hazards and the risk is assessed as **very high** for the North-East region and as **high** for the South-East region.

5.9 Coastal erosion

Coastal erosion is linked to sea level rise, where high water levels and extreme coastal events can affect the integrity of infrastructures located on the coastline, with risks of subsidence and or loss of access routes. No past records of incidents are available, indicating a lower vulnerability of Northumbrian Water system to costal erosion. Furthermore, the impact of coastal erosion is likely to be limited to localised areas and thus the magnitude of consequences is estimated to be low for both regions. Whilst sea level rise increases the likelihood of occurrence of this hazard, in the medium term (2050) and in relation to Northumbrian Water operations, coastal erosion is likely to remain stable. The overall risk is then assessed as **low** for both North-East and South-East regions.

5.10 Wind

Extreme wind such as that which occurred during storm Arwen (which granted red warnings) and other winter storms can lead to both direct damages on water and wastewater infrastructures as well as indirect impacts from failure of other infrastructures (i.e. power network). The main consequences of extreme winds are:

- Damage to water/wastewater infrastructure from high winds and/or falling structures;
- Falling of trees knocking down power lines causing power outage;
- Falling of trees causing pipe bursts;
- Reduced access to site from high winds, fallen trees, power lines and others;
- Knocked-down power lines leading to power outage.

Most of the impacts on the water and wastewater networks that occurred during storm Arwen in 2021 resulted from major disruptions to the power grid due to extreme winds sweeping across the region. Northern Power Grid estimated that at any one time 240,000 people were without power given the devastation the storm had on the power network.

The loss of external power across large parts of the water and wastewater networks required deployment and maintenance of resilience and recovery measures, particularly calling on power generators to prevent loss of power at key assets and subsequent loss of supply to customers. However, due to the widespread nature of the external power outages, a number of assets were affected and went without power, resulting in large areas with no water as well as areas of low pressures across the network. Overall, 1127 no water incidents, 127 low pressures, 83 appearance, 1 complaint of illness and 4 taste and odour contacts were reported in relation to this event. The event affected water supply across 15 water quality zones with a combined population of 295,255. However, only a proportion of these water quality zones were affected by these issues.

Power supply issues impacted a number of pumping stations (including borehole pumps) and booster pumping stations and triggered temporary shutdowns. In most cases, this caused service reservoirs depletion and a subsequent loss of supply to customers. In some instances, this affected supply to water treatment works which cascaded down the network and led to further service reservoirs depletion and loss of customer supply. The stoppage of booster pumps also led to areas of no water or of reduced pressure. In other cases, the loss of power was combined with telemetry and communication issues which impacted the recovery efforts. Recovery interventions including the deployment of mobile generators, refill of fixed generators and tankering were hampered by the severity of the event with access to sites prevented by flooding, fallen down trees or overhead power lines. In one instance, the manual operation required at a strategic valve during peak demand times was prevented by extreme weather conditions.

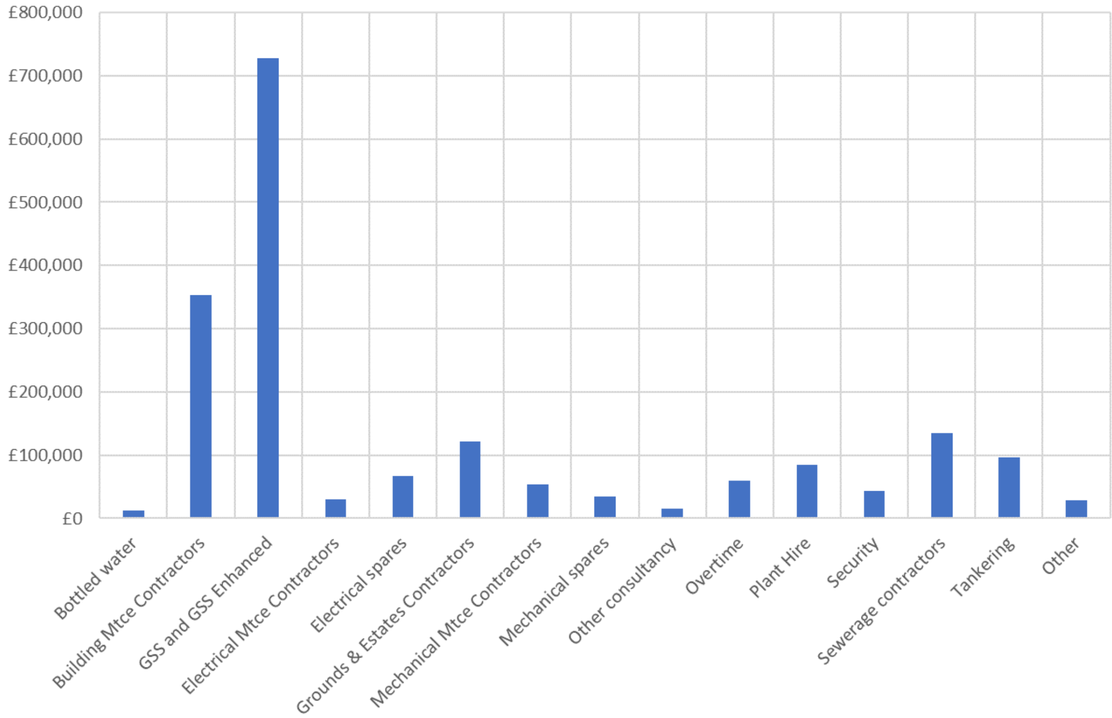
Storm Arwen began to affect the North-East on the evening of Friday 26 November and impacts continued throughout the next day. Recovery efforts were required for another couple of days and it was only on the 4th of December that supply was brought back to all customers within the impacted areas.

On the wastewater side, 55 instances of discharge incidents were recorded, most of them as a result of control system failure due to the loss of external power triggered by high winds. Emergency discharge of sewage materials led to water environmental impacts recorded as Category 3 and 4. In some instances, this was mitigated by the presence of a storm water tank on site and other tankering measures deployed locally.

Instances of pipe bursts also occurred during this storm as a result of a falling tree bursting a water main at a reservoir outlet. The tree further brought down overhead power lines causing power issues in the area, leading to reservoir depletion and a loss of visibility of telemetry and ultimately causing an area of no water until the burst was isolated. The recovery and repair time was extended by extreme weather conditions affecting the area.

The impacts of storm Arwen from external power outages and directly on the water and wastewater systems resulted in an estimated cost of £1.86m (see Figure 5.6). Beyond GSS and GSS Enhanced expenditure (associated with compensatory payments related to failure to comply with standards of service), the second item that resulted in the highest impact costs (19%) was related to building expenditures, similar to those that occurred during storm Desmond, including remedial tree works, infrastructure (e.g. roof, fencing, pumps) repairs and replacements, cleaning and clearance works (i.e. debris, silt).

Figure 5.6: Impact costs from Storm Arwen



Source: Northumbrian Water

Given the above, the magnitude of the consequences is assessed as high for both regions. The increase in the frequency of winter windstorms, together with an increase in wind speed, makes this type of hazard more likely (see Section 4.4.3) The risk is the assessed as **very high** across both regions.

5.11 Lightning

Lightning occurrence is often concurrent with extreme storm events, particularly summer convective storms that can lead to other hazards such as flooding. There are no previous records of incidents directly resulting from lightning on water and wastewater assets though strikes have the potential to damage electrical components and control panels. Similarly, impacts of lightning on power assets could cause cascading disruption across water and wastewater systems. This is largely mitigated by lightning detection equipment, diverters and other mitigation measures, though power cuts still remain possible. Whilst lightning strikes are localised, if the impact is on a key asset, this could result in significant disruption to the network.

With consideration of the mitigation measures in place, the consequences are estimated to be low for both regions.

There remains significant uncertainty behind the future likelihood of lightning occurrence and without substantial evidence, the likelihood of this hazard is assumed to remain stable. Overall, the risk of lightning on the network is estimated to be **low** across both regions.

5.12 Water quality deterioration

Raw water quality deteriorations can occur as a result of a variety of weather events and consequences are multiple across the water and wastewater systems, such as:

- Increased turbidity and/or pollutant levels in river systems during extreme rainfall/flood events, impacting water treatment operations;
- Increased freshwater salinity levels during storm surges combined with increased sea levels, affecting river abstractions;
- Saline intrusion into groundwater sources from sea level rise/storm surges, affecting groundwater abstractions;
- Reduction in effluent dilution during drought/low flow periods, impacting wastewater treatment operations; and,
- Increased pollutant levels during drought conditions affecting treatment operations; and,
- Algal blooms in rivers and/or reservoirs, impacting filters and requiring additional treatment.

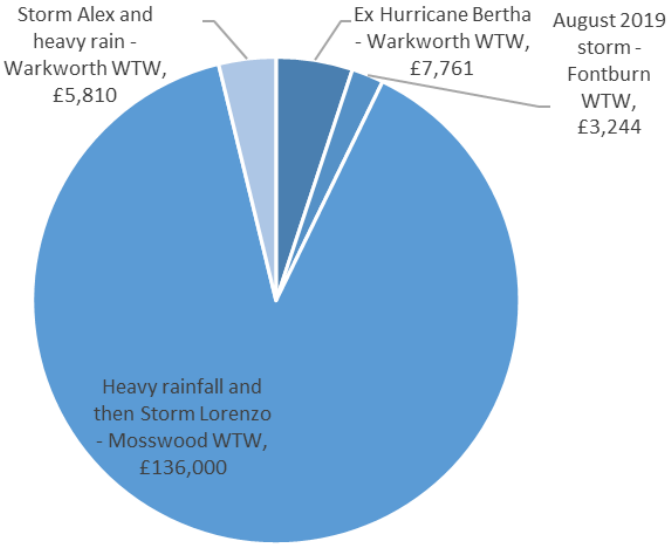
The consequences of reductions in water quality have historically been localised and have not affected large parts of the networks. Whilst other parts of the system can cope with minor incidents and supply water to mitigate for the loss of one asset, the headroom of the system drops as a result. For instance, another consequence of storm Arwen was a reduction in raw water quality from heavy rainfall falling on the catchments and an increase in turbidity in rivers. High turbidity levels resulted in a water treatment works shutdown, causing service reservoir depletion further down the system and a subsequent loss of supply. Depleted service reservoir levels also had an impact on other supply areas as water rates pumped in normal conditions from the depleted reservoir to other reservoirs were hampered, leading to further loss of supply.

This failure mechanism also occurred following various storm events when heavy rainfall falling on the catchments led to shutdowns of water treatment works:

- Warkworth works went offline for 4 days as a result of ex-hurricane Bertha and for 3 days following storm Alex due to heavy rainfall leading to poor quality of raw water, beyond the works' treatment capability;
- Mosswood works experienced treatment difficulties for 30 days following storm Lorenzo and as a result of a sudden refill of Derwent Reservoir with deteriorated water quality; and,
- Following August 2019 storm, Fontburn works went offline for 22.5 hours due to water quality reaching beyond the works' treatment capability.

The temporary shutdowns and treatment difficulties experienced during and following those events required extra water to be supplied from other works to cover for the loss in output and ensure supply to customers. A comparative analysis between those three events (Figure 5.7) shows that the prolonged treatment disruptions that occurred at Mosswood following storm Lorenzo resulted in much higher costs despite the works being able to work at 75% capacity. The extended period of disruption together with a much higher difference in the costs of water between Mosswood and the recovery works (Carr Hill and Lumley) explains the overall cost impact of that event. In comparison, shutdowns at Warkworth only lasted a couple of days and the cost of water from Horsley, which operated at a higher capacity, remained around 25% higher than Warkworth.

Figure 5.7: Impact costs from changes in raw water quality



Source: Northumbrian Water Limited

In November 2007, storm surges from the North Sea led to tidal-locking conditions that caused flooding along the upper Waveney and resulted in a temporary shutdown of the Barsham river line due to high turbidity beyond operating levels. Other historical surge events are also known to have caused a movement of the saline interface further upstream in the river Waveney to the point where water is abstracted to feed Barsham works, which led to temporary shutdown of the intake. The closure of the abstraction resulted in a reduction in overall output from the works, partly compensated by emergency bore streams that limited the output reduction from 40.5Ml/d to 27Ml/d instead of to 14Ml/d.

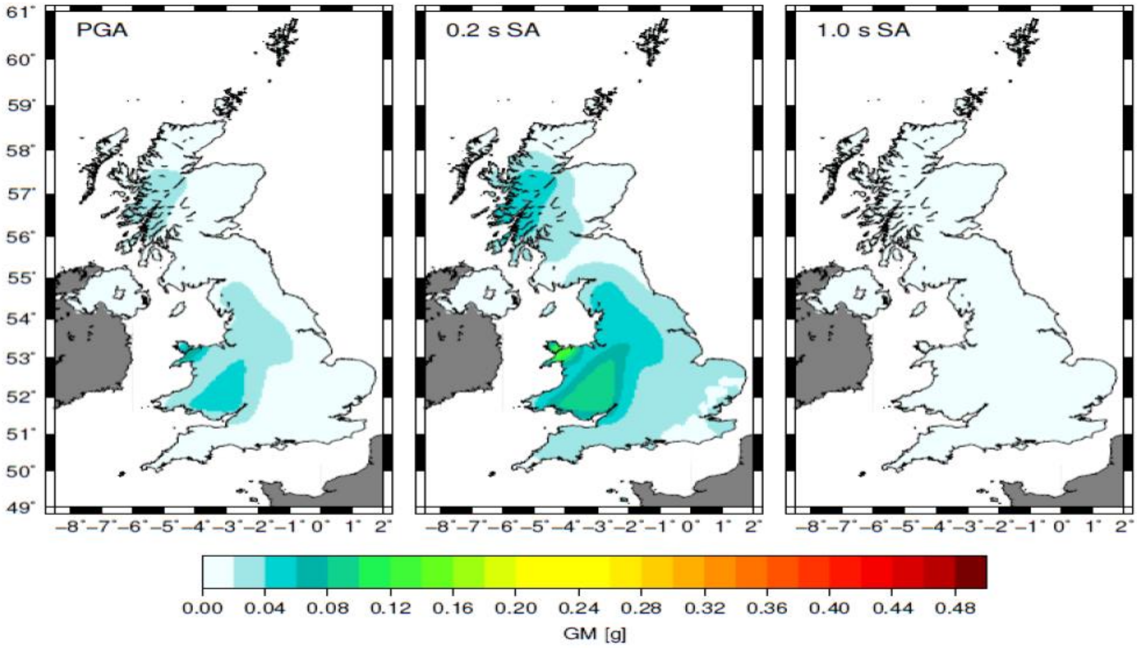
Notwithstanding the localised nature of recorded impacts, there is potential for larger magnitude and wider spread future events affecting multiple assets within the network. Overall, the magnitude of consequences is assessed as moderate for the North-East region until more evidence is gathered, and as low for the South-East region, which lacks wastewater systems. Together with the increased likelihood of flood and drought hazards as well as sea level rise, the risk of raw water quality deterioration is assessed as **high** for the North-East region and as **medium** for the South-East region.

5.13 Earthquake

As a result of its geographic position, the UK is characterised by low levels of earthquake activity[13]. Evidence for this comes from observations of earthquake activity dating back several hundred years, which suggest that although there are many accounts of earthquakes felt by people, damaging earthquakes are rare. Figure 5.8 presents the results of the latest seismic hazard study for the UK conducted by the BGS (GeoIndex - British Geological Survey (bgs.ac.uk)) which show that the hazard level is generally low across the country particularly in the Northumbrian region. For 475 years, PGA (Peak Ground Acceleration) is less than 0.04 g for most of the UK, with the exception of North Wales and the English-Wales border region where the hazard reaches around 0.09 g and 0.05 g, respectively.

[13] Musson, R.M., 2012. The effect of magnitude uncertainty on earthquake activity rates. Bulletin of the Seismological Society of America, 102(6), pp.2771-2775.

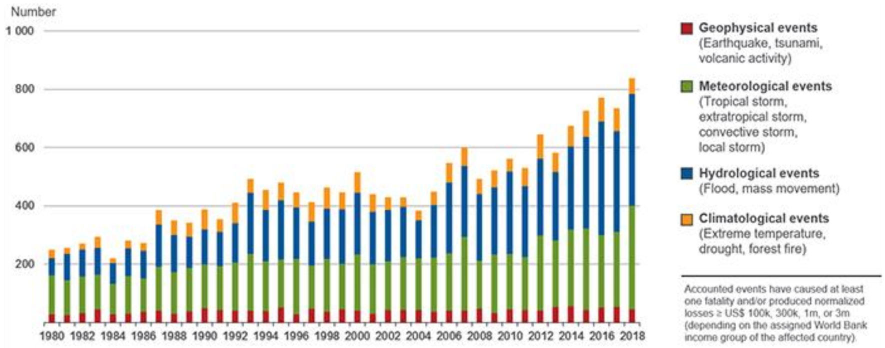
Figure 5.8: Hazard Map for UK based on 475-year return period



Northumbrian North-East and South-East areas of service are located out of the higher seismic area, and therefore, in case of occurrence, consequences of an earthquake are likely to be low.

Figure 5.9 presents the catalogue of the number of catastrophes from 1980 -2018 from the global database. It can be seen that the number of geophysical events has remained relatively constant over the years and there is an increase in climatological events. In earthquake probability assessment, looking at historical events is common practice to assess future probabilities, and therefore, the likelihood of this hazard is considered to remain stable, meaning that the risk can be classified as **low** for both regions**.**

Figure 5.9: Number of World Natural Catastrophes, 1980-2018, 2019 Munich Re, Geo Risks Research, NatCatSERVICE.



6 Conclusion

Weather events that have affected Northumbrian Water systems during the recent past have led to significant extra-costs to respond, limit impacts during the event and undertake post-event repair and maintenance works to restore the performance of the system to pre-event levels. In the future, some of them are likely to increase in frequency and/or intensity (i.e. storms Desmond and Arwen, 2018 heat wave) whilst others will be less likely to occur (i.e. Beast from the East, ex-Hurricane Bertha). In addition to the weather patterns currently affecting the networks, it is likely that, in the future, other patterns could lead to more summer heatwaves, winter extreme rainfall in the north and summer extreme rainfall in the south, thus increasing the subsequent risks these types of events pose to the integrity of the assets and the company operations, particularly to its ability to supply water to its customers. These findings tie in with the predicted future changes in temperature and precipitation, pointing towards drier and hotter summers (though an increase in extreme summer rainfall is likely) as well as wetter winters, across both the North-East and South-East.

The consequences of these events on the networks are not only dependent on their magnitude but also on pre-event and post-event conditions. Significant rainfall falling prior to a large winter storm would lead to soil saturation and affect the network headroom prior to the main event occurring. Similarly, whilst an isolated storm event could result in minor damages, subsequent episodes of heavy rain can be more impactful. These cumulative impacts were seen during storm Desmond, and in the future, the trend towards wetter winters is likely to result in similar mechanisms occurring more often.

Furthermore, consequences should not be considered as impacts on specific assets in isolation. Instead, cascading impacts across the water and wastewater systems must be analysed to understand the systemic risks as well as the asset-specific risks, both within the boundary of the company and beyond, such as the impacts of failures in the power network experienced during storm Arwen.

The trend towards more frequent extreme rainfall events, together with more frequent and longer droughts is also likely to reduce the resilience of the system in areas where it can currently cope with its current capacities. Water quality deterioration in particular is a risk whose magnitude is likely to be amplified in the future. At present, impacts have been localised and limited to specific works whose outage could be mitigated by other works taking over in time of need. Future weather conditions affecting multiple works at once could stretch the ability of the system to shift demand to other works with direct impacts on customer supply.

Overall, the review of recent incidents and changes in weather conditions within Northumbrian service areas have highlighted two very high, three high and two moderate risks in the North-East (Table 6.1), and three very high, two high and two moderate risks in the South-East (Table 6.2) that should be investigated in more detail in the next stage. In particular, the risk of freeze-thaw should be verified, given that the general trend to warmer winters cannot rule out an intensification in the number of fluctuations around freezing conditions.

Table 6.1: Summary of key climate risks to Northumbrian Water- North-East

Hazard	Magnitude of consequences	Future likelihood of the hazard	Future risk level	Comment
Flooding	High	Greater	Very high	The risk is assessed as very high for Northumbrian given expected changes in peak flood flows and summer rainfall.
Wind	High	Greater	Very high	The North-East will see an intensification of winter windstorms like storm Arwen and Desmond
Drought and water scarcity	Moderate	Greater	High	The risk is assessed as high as decreases in summer rainfall and increases in temperatures are likely to be smaller than in Essex and Suffolk, leading to lower impacts, and because the system has considerable resilience.
Soil moisture deficits	Moderate	Greater	High	The risk is assessed as high as decreases in summer rainfall and increases in temperatures are likely to be smaller than in Essex and Suffolk, leading to lower impacts.
Water quality deteriorations	Moderate	Greater	High	The risk is expected to increase in the future and be more widespread.
Heat	Low	Greater	Medium	The risk is assessed as moderate given that the increase in temperatures is likely to be lower than in Essex and Suffolk.
Cold and freeze thaw	High	Lower	Medium	This risk will decrease progressively during the century with global warming.
Lightning	Low	Stable	Low	
Earthquake	Low	Stable	Low	
Coastal erosion	Low	Stable	Low	
Wildfire	Low	Stable	Low	
Snow	Low	Lower	Low	

Table 6.2: Summary of key climate risks to Northumbrian Water- South-East

Hazard	Magnitude of consequences	Future likelihood of the hazard	Future risk level	Comment
Drought and water scarcity	High	Greater	Very high	The risk is assessed as very high given that decreases in summer rainfall and increases in temperatures are likely to be greater than that in the North-East.
Wind	High	Greater	Very high	The risk is assessed as very high due to the projected intensification of windstorms and the possibility of cascading failures.
Soil moisture deficits	High	Greater	Very high	The risk is assessed as very high given that decreases in summer rainfall and increases in temperatures are likely to be greater than that in the North-East.
Flooding	Moderate	Greater	High	The risk is assessed as high given the absence of wastewater assets. To note that the risk of coastal flooding is likely to be greater in the South-East due to higher increases in sea-level and the low-lying nature of the area.

Hazard	Magnitude of consequences	Future likelihood of the hazard	Future risk level	Comment
Heat	Moderate	Greater	High	The risk is assessed as high given that the increases in temperatures are likely to be greater than that in the North-East.
Water quality deteriorations	Low	Greater	Medium	The risk is assessed as medium in absence of wastewater systems that are more likely to be impacted by lower river dilution.
Cold and freeze thaw	High	Lower	Medium	This risk will decrease progressively during the century with global warming.
Lightning	Low	Stable	Low	
Earthquake	Low	Stable	Low	
Coastal erosion	Low	Stable	Low	
Wildfire	Low	Stable	Low	
Snow	Low	Lower	Low	

These risks have been ranked in relative terms within Northumbrian Water operations and cannot be compared with similar risk categorisations done by other water companies and included in their Adaptation Reports. As the category of the risk is a function of not only the magnitude of the hazard but also of how exposed assets are to it and how vulnerable they are, a cross company comparison is not possible without understanding the level of resilience currently built in each water company's systems. However, assuming the same level of resilience, Northumbrian Water would experience a greater change in the magnitude of several hazards compared with the UK average. In particular:

- The North-East would be particularly susceptible to climate change impacts on winter windstorms and extreme summer rainfall. Extreme winter rainfall would increase as well, and the EA has derived higher allowances for peak flood flows than in other areas of England. Finally, annual rainfall is expected to decrease significantly, above all in autumn compared with the rest of the country.
- The South-East would be significantly impacted by extreme summer rainfall associated with convective storms and sea level rise is likely to affect this region more than others. Droughts and heatwaves are a particular concern in an area already under water stress.