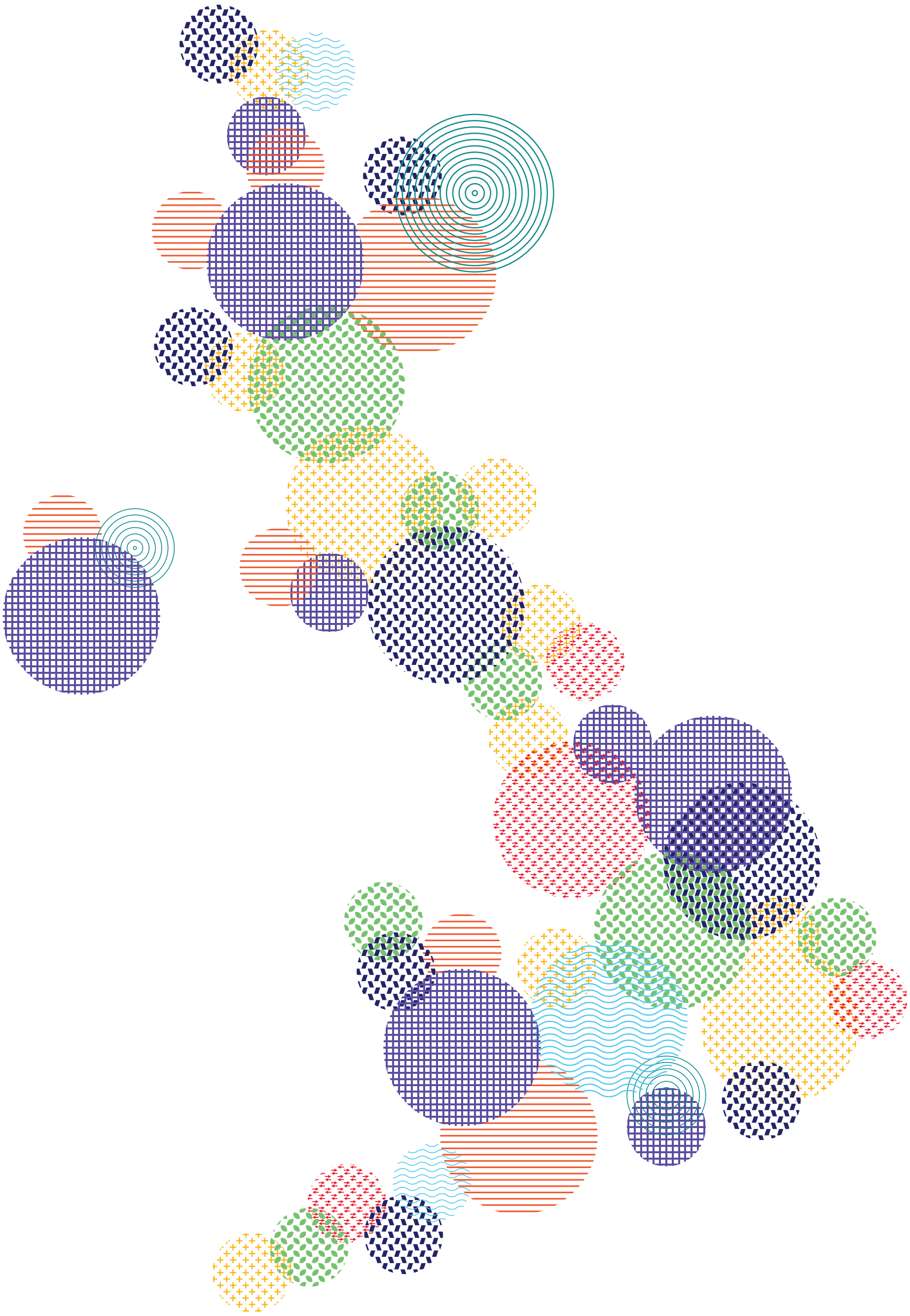
NATIONAL DIGITAL TWIN PROGRAMME

CReDo
Climate Resilience Demonstrator

CReDo Technical Report 2: Generating flood data

March 2022



The Climate Resilience Demonstrator, CReDo, is a climate change adaptation digital twin demonstrator project developed by the National Digital Twin programme to improve resilience across infrastructure networks.

CReDo is a pioneering project to develop, for the first time in the UK, a digital twin across infrastructure networks to provide a practical example of how connected-data and greater access to the right information can improve climate adaptation and resilience. CReDo is the pilot project for the National Digital Twin programme demonstrating how it is possible to connect up datasets across organisations and deliver both private and public good. Enabled by funding from UKRI, The University of Cambridge and Connected Places Catapult, CReDo looks specifically at the impact of extreme weather, in particular flooding, on energy, water and telecoms networks. CReDo brings together asset datasets, flood datasets, asset failure models and a system impact model to provide insights into infrastructure interdependencies and how they would be impacted under future climate change flooding scenarios. The vision for the CReDo digital twin is to enable asset owners, regulators and policymakers to collaborate using the CReDo digital twin to make decisions which maximise resilience across the infrastructure system rather than from a single sector point of view. CReDo's purpose is two-fold:

1. To demonstrate the benefits of using connected digital twins to increase resilience and enable climate change adaptation and mitigation.
2. To demonstrate how principled information management enables digital twins and datasets to be connected in a scalable way as part of the development of the information management framework (IMF).[1]

This first phase of CReDo running over the period April 2021 to March 2022 has focused on delivering a minimum viable product to bring the datasets together to offer insight into infrastructure interdependencies and system impact. Separate technical papers have been produced to describe each stage of the project so far:

CReDo Technical Paper 1: Building a cross sector dig-ital twin
CReDo Technical Paper 2: Generating flood data
CReDo Technical Paper 3: Assessing asset failure
CReDo Technical Paper 4: Modelling system impact
CReDo Technical Paper 5: CReDo and the Information Management Framework

The technical papers are nested under the CReDo Overview report, and all CReDo reports and related materials can be found on the Digital Twin Hub, https://digitaltwinhub.co.uk/projects/credo.

[1] IMF - DT Hub Community (digitaltwinhub.co.uk)

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Executive Summary

Climate change will bring far reaching consequences across many aspects of society, including our health, prosperity and future security. The latest climate projections from the UK Met Office indicate that we will experience warmer, wetter winters and hotter, drier summers, together with an increase in the frequency and intensity of extremes. Substantial increases in hourly precipitation extremes are expected, with the frequency of days with hourly rainfall > 30 mm/h almost doubling by the 2070s. The increase in short, intense, rainfall events may be expected to manifest in flooding which can cause serious threats to society and the economy.

This report provides details of how flood data was generated within the CReDo project. A summary of different types of flooding are considered (river, coastal, surface water) together with an outline of standard industry approaches and requirements to quantifying probabilities of occurrence. We provide a summary of the information available within the UK Climate projections 2018 (UKCP18 projections), and how this can be used for assessing changes in precipitation under climate change scenarios. This includes the UKCP18 local projections, consisting of hourly data at a 2.2km resolution for 12 simulations from a convection-permitting model, with a bias correction applied, and the prob-abilistic extremes dataset (PPCE), with discussion of what information these products can and cannot provide.

Information on the risk of river and tidal flooding in the study region is provided from Environment Agency models. UKCP18 does not provide direct information on flooding, and the flood model HiPIMS was used to convert precipitation to surface water flooding. For generating storm events, Flood Estimation Handbook (FEH) methodology was used, in combination with uplifts from different sources to represent the effects of climate change, and a discussion of how UKCP18 products may augment this approach, given appropriate consideration of the challenges in using this for decision making.

Using HiPIMS allowed the provision of multiple surface water flooding scenarios for different storm lengths, return periods (1 in 100, 1 in 1000 year events) and climate change scenarios, giving spatio-temporal maps of flood depth over time, in a form that can be used to assess the vulnerability of assets and consider how changes in the climate will affect the likelihood, and extent, of flooding in the future.

1 Introduction

Assets and networks can be impacted by several climate hazards but probably the most relevant one due to its frequency, magnitude and spatial occurrence is flooding. Floods can directly affect assets when their standards of protection are exceeded or hinder their operation if access to them is impeded. Associated damages can be significant and widespread, making recovery difficult.

From the most recent UK assessment of climate change [1]:

'Short, intense rainfall events (e.g., thunderstorms) can lead to pluvial or surface flooding as surface run-off inundates small catchments and the urban landscape. Prolonged periods of excessive precipitation saturates soil, increasing the risk of fluvial or river flooding. Above average precipitation for long periods can ultimately lead to a raised water table, which can result in groundwater flooding in areas where the geological characteristics are favourable. In the UK and Europe, flooding is one of the most economically and socially disruptive natural hazards with impacts on transport, infrastructure and energy supply.'

The climate in the UK is changing. The 21st century has so far been warmer than the past three centuries. According to the latest state of the UK climate report [2] 2020 is the first year for which all of temperature, rainfall and sunshine measurements were in the top 10 years on record. It was the fifth wettest year, the wettest February, and six of the wettest years have occurred since 1998. 2021 was the fifth warmest year on record worldwide [3] and will also be remembered as a year of extremes and global mega-disasters (with newsworthy extreme heat, wildfires and flooding). The floods that hit Germany and Belgium in July 2021 were the costliest weather disaster in Europe to date, and early results from an attribution study indicated that the likelihood of such an extreme one-day rainfall event has increased by a factor between 1.2 and nine because of human-caused global warming [4].

Climate change is expected to modify flood patterns in the UK. The latest set of climate projections for the UK, UKCP18 [5], indicate a move towards warmer, wetter winters and hotter, drier summers, with intense convective storms in summer likely to become more extreme and with a probable increase in winter rainfall when soil saturation is high, leading to more frequent large-scale floods. In addition, UK coastal flood risk is expected to increase over the 21st century under all emission scenarios considered. This means that we can expect to see an increase both in the frequency and magnitude of extreme water levels around the UK coastline. This increased future flood risk will be dominated by the effects of time-mean sea-level rise, rather than changes in atmospheric storminess associated with extreme coastal sea level events. The East of England will be particularly vulnerable due to its low-lying nature.

Given this, flooding has been the hazard of choice for the Climate Resilience Demonstrator (CReDo), with surface water and coastal flooding impacting the area of study. The present report summarises the available information and the standard industry approach to characterise the risk of flooding to any asset network, including the impact of climate change. Surface water modelling has been undertaken and is detailed as well. Finally, the report includes some recommendations for future steps. It is not intended to be exhaustive, and the reader is referred to published guidance such as 'River modelling: technical standards and assessment' [6] for a full description. Likewise, it is not intended to be prescriptive, as particular local conditions may recommend alternative approaches.

2 Understanding the sources of flooding

An asset or group of assets can be subjected to flooding from different sources, mainly from:

- **River flooding**, which occurs when a watercourse cannot cope with the water draining into it from the surrounding land, for instance due to heavy rainfall on an already waterlogged catchment.
- **Coastal flooding**, which results from a combination of high tides and stormy conditions. If low atmospheric pressure coincides with a high tide, a tidal surge may happen which can increase sea level further.
- **Surface water flooding**, which occurs when heavy rainfall overwhelms the drainage capacity of the local area.
- **Sewer flooding**, which occurs when sewers are overwhelmed by heavy rainfall or when they become blocked.
- **Groundwater flooding**, which occurs when water levels in the ground rise above surface levels. It is most likely to occur in areas underlain by permeable rocks, called aquifers.
- **Artificial waterbodies flooding**, which may occur due to the failure of an impounding structure, such as a dam or a canal embankment.

It is important that the possibility of these events happening in a certain area is well understood so that the risk of flooding is fully considered. Asset owners can consult public information to qualitatively establish the risk of flooding to their networks. For example, the Environment Agency offers under an Open Government Licence the following datasets for England:

- **Recorded flood outlines**, which contains the extent of historical flood events starting in 1946. Note that this is not a comprehensive dataset, and that the lack of past flooding does not mean that an area is not at risk, above all as regards rare flood events. It is also possible that the pattern of flooding is changing.
- **Risk of flooding from rivers and sea**, which shows the chance of flooding from rivers and/or the sea on a 50 -m grid. Each cell is allocated one of four flood risk categories (High: greater than 3.3% Annual Exceedance Probability (AEP), Medium: between 3.3% and 1% AEP, Low: between 1% and 0.1% AEP, and Very Low: less than 0.1% AEP), taking into account flood defences and their condition. Cells where the likelihood of flooding is greater than or equal to 1 in 75 (1.3%) each year are also identified. Each cell has a suitability rating to show at what scale it is generally appropriate to use the data. Note that this product presents a more realistic view of flood risk in areas benefiting from defences, unlike the Flood Map for Planning (see below), which assumes all current flood defences are removed.
- **Risk of flooding from surface water**, which offers flood extent, depth, dominant direction, velocity and hazard for three AEPs: 3.3, 1 and 0.1%, with all variables derived from a single design event at each location. Although modelling was undertaken with a 2-m spatial resolution, results are not considered accurate for scales finer than 1:10,000. Among other limitations, the mapping does not explicitly account for flood barriers or defences (fluvial,

tidal or surface water) or any flood alleviation schemes; it does not consider the effect of pumping stations in catchments with pumped drainage; there is no allowance for tide locking, high tidal or fluvial levels where sewers cannot discharge into rivers or the sea; and only three standard storm durations (1, 3 and 6 hours) were tested.

- **Risk of flooding from multiple sources**, which combines the previous two products to offer a single layer indicating risk of flooding grouped into four bands, their suitability (an indication of the scale it is appropriate to use the information), and the proportion of the combined risk resulting from the primary flood source input data.
- **Reservoir flood extents** for all large, raised reservoirs in the event that they were to fail and release the water held on a "dry" or "wet day" when local rivers are at normal levels or had already overflowed their banks respectively. The antecedent flooding condition used in the wet scenario is provided for comparison.
- **Flood map for planning (rivers and sea) - Areas benefiting from defences**, which shows those areas that benefit from the presence of defences in a 1 in 100 (1%) chance of flooding each year from rivers; or 1 in 200 (0.5%) chance of flooding each year from the sea.

Similar information can be obtained from Natural Resources Wales and the Scottish Environment Protection Agency. In addition, access to more detailed flood information can be obtained from the regulator upon request in an area of interest. Particularly useful are:

- Product 4: detailed flood risk assessment map, which, apart from the data presented above, includes details on defences and storage areas and some results from computer river models (including model extent, information on one or more specific points, flood levels, flood flows);
- Product 6: flood model output data and reports;
- Product 7: calibrated and verified model input data;
- Product 8: flood defence breach hazard map, including maximum flood depth, maximum flood velocity,and maximum flood hazard.

As regards groundwater flooding, the Environment Agency's 'Areas susceptible to groundwater flooding' map can be accessed upon request. It shows the proportion of each 1-km grid square where geological and hydrogeological conditions indicate that groundwater might emerge. It does not show the likelihood of groundwater flooding occurring and does not take account of the chance of flooding from groundwater rebound. To improve this information, the British Geological Survey Groundwater Flooding Susceptibility dataset is a commercial product showing the degree to which areas are susceptible to groundwater flooding based on geological and hydrogeological conditions.

Additional information can be obtained from local planning authorities, which should carry out a strategic flood risk assessment for their area. They are accessible to the public to help various parties consider flood risk when making planning decisions about the design and location of any development, and flood risk management features and structures. They typically contain more detailed (local) information of historical flooding, better surface water flooding maps, and information on sewer flooding.

Once all this data has been analysed to identify sources of flooding and their potential risk to assets, more in-depth assessments can be undertaken as appropriate. This ensures proportionality.

3 Defining the design events

This section summarises the standard industry approach for deriving design events of a certain probability of occurrence. Given extreme events are defined by several variables such us duration, intensity or spatio-temporal distribution, the method relies on the definition of a 'typical' rare event, with properties established from statistical analyses of climate and hydrometry data. Further details can be found in:

- Centre for Ecology and Hydrology Flood Estimation Handbook [7–9];
- FEH Supplementary Report No. 1: The revitalised FSR/FEH rainfall-runoff method [10];
- Modelling design flood hydrographs in catchments with mixed urban and rural land cover [11];
- Coastal flood boundary conditions for the UK [12];
- LIT 11832: Flood Estimation Guidelines [13].

3.1 Deterministic versus probabilistic hydrology

Flood risk is typically assessed for a certain limited number of design events associated with specific probabilities of occurrence (e.g., 1 in 100 years) and with simplifications as regards their spatio-temporal distribution. Even though these events are defined based on statistical procedures to extrapolate to, in many cases, unknown hazard magnitudes, they are only one of the possible ways flood hazard could occur. Therefore, assumptions are made as regards, for instance, the spatial and temporal distribution of the storm, the antecedent soil moisture conditions, or the tidal cycle phase. In addition, events are typically established to have the same probability across the area of study (i.e., all watercourses regardless of drainage area have the same flood intensity and at the same time) so that a single flood map representing that probability is derived. This neglects the spatial variability of flood extremity, and crucially, the joint probability of floods at river confluences or near the river mouth. All this incorporates a degree of determinism in the analysis, and hence a degree of potential bias.

Probabilistic flood modelling has gained attention in recent years as a way of overcoming this excessive determinism, leading to a more realistic, albeit ambiguous, representation of flood risk. It involves generating a large number of extreme events ($\sim$10,000) constructed by either a weather generator coupled with a rainfall-runoff model or by using gauge-based multivariate statistical modelling. Although conceptually appealing to quantify with accuracy the probability of flooding at a given location, this approach heavily relies on the availability of good quality and abundant meteorological and hydrometric information, which is not always the case, as well as appropriately careful statistical modelling. It is also difficult to validate. To benefit fully from its application, it requires a direct conversion into flood data by means of hydraulic modelling, which is usually unfeasible due to high computational costs or forces significant simplifications that reduce reliability.

To avoid explicitly simulating all stochastic events with hydraulic modelling, current practice involves estimating the return period of each synthetic event in a certain catchment, by comparison with the extreme value analysis performed at a representative gauging station, and determining the maximum flood depth corresponding to each event and location by interpolating between deterministic flood inundation maps derived by hydraulic modelling. This offers a way of incorporating climate change too, if the same synthetic events can be replicated for the future, or if local-scale climate model output exists offering sub-daily projections at fine spatial resolutions.

3.2 Fluvial-pluvial events: the Flood Estimation Handbook

The Flood Estimation Handbook (FEH) developed by the Centre for Ecology and Hydrology in 1999, and its related software, offers guidance on rainfall and river flood frequency estimation and development site runoff rates across the UK. It is the industry standard, and the approach accepted by the regulators.

3.2.1 Fluvial events

There are two standard calculation methods available for flood flow estimation: the 'FEH improved statistical method' and the 'Revitalised flood hydrograph' (ReFH1/ ReFH2) rainfall-runoff method.

The FEH statistical method is a lumped hydrological approach (with the spatial variability of rainfall and catchment properties aggregated) that gives peak flow estimates only. It can be applied to flow gauging stations with a recorded series or to ungauged locations. The median annual flood flow (called QMED) is estimated first, ideally based on gauged information as the median value of the annual maximum flow record if there is more than two years of data. The alternative peak over threshold method, where the number of exceedances of a certain value in a record is used, can also be adopted for good quality gauges with a record length between two and 13 years. If there is no suitable gauge at the site of interest, QMED can be derived from catchment descriptors obtained from the FEH web service. This is then adjusted using up to six donor sites (gauging stations whose flood properties can be transposed to the site of interest) selected based on proximity of catchment centroids. Once QMED is defined, growth curves showing the relationship between peak flow and flood rarity are produced to extend QMED estimates for longer return period events or lower probability AEPs. This is done using one of the following methods:

- Single site method if the flow record is of high quality and at least double the target flood return period, and climate and catchment properties can be assumed stationary. Extreme value analysis with different functions is then performed and the best fit adopted.
- Pooled method if the subject site is ungauged or the subject gauge record is less than twice that of the target return period[2]. By establishing a group of catchments with hydrological similarities to the subject site, a long record period of more than 500 years can be obtained. The catchments in a pooling group should be rural and not contain catchments with records less than eight years. Once a satisfactory pooling group is created, a statistical distribution

[2]When applying this standard recommendation, care should be taken as to the relevance of data from other sites, and the degree of statistical dependence between data from the same time at different sites.

is fitted to estimate flows for the desired event severity.

- Enhanced single site method, which combines the pooled and single site methods, with the subject site gauge included as the first entry in the pooling group. This gives it the most influence over the calculation. This method is suitable at or near gauge sites with at least eight years of good quality data.

Calculations are typically performed using WINFAP software [14], or any other software that implements the method correctly (for example, UKFE R package [15]). Growth curves may not be accurate for estimating very extreme floods (1% AEP or less). In this case, rainfall-runoff methods can be used to extend the statistical growth curve.

ReFH1/ReFH2 are rainfall-runoff models used to simulate observed floods or design events using recorded catchment-averaged rainfall data and the initial conditions as input data. This will give a flood hydrograph showing the temporal variation of flow at the outlet of the catchment as output data. They have four parameters: maximum soil moisture capacity, time to peak, baseflow lag and baseflow recharge. These should be estimated from hydrometric data if possible. Otherwise, regression equations based on catchment descriptors are available. REFH1/REFH2 can account for the level of urbanisation by dividing the catchment into rural and urban components, modelled separately, and with an impervious runoff factor of 70% applied to the urban component.

The FEH also advises on the design storm that should be adopted to generate the flood hydrograph for the target AEP. Critical storm duration is a function of the catchment geometry (with larger catchments requiring longer durations), the catchment urbanisation that could accelerate the response, and the typical antecedent moisture conditions that would influence when the catchment gets saturated. Storm depth must be affected by reduction factors due to selected seasonality and the catchment size. Finally, two design storm profiles are offered, summer and winter, with the latter preferred unless the urban extent is greater than 30% or if it greater than 15% in highly permeable catchments.

The method to use, statistical or rainfall-runoff modelling, depends on the available data and the characteristics of the catchment area. As a guidance, the FEH statistical method should be considered if there is more than two to three years of peak flow data on the watercourse from a suitable gauging station, if the catchment area exceeds 1,000km^2, or if there are lakes in the catchment. In turn, the FEH statistical method should be avoided in lowland catchments due to the lack of flow gauging sites and the importance of hydrograph volumes in these areas. REFH1/REFH2 methods would be preferable if the volume or timing of the hydrograph is relevant, if there is no continuous flow data but flow or level data is available for five or more flood events, or if the catchment area includes sub-catchments with very different flood responses. REFH2 is particularly recommended over REFH1 on permeable catchments. It also uses up-to-date rainfall statistics, hence adopting REFH1 instead should be justified.

If the FEH statistical approach is considered to give the most reliable peak flow estimates, the flood hydrograph can be derived by either scaling a REFH-derived hydrograph to the statistical peak or applying observed hydrograph shapes from a gauge averaged across multiple large events.

3.2.2 Pluvial events

Unlike in fluvial events, the FEH does not offer guidance about the critical storm duration to be applied in surface water flooding. Once the hydraulic model is available, the standard procedure is to test several storm durations and obtain the envelope of the resulting flood conditions as different locations within the urban area will have different critical storm durations. Adopting a summer storm profile is preferred as it is more likely to be critical for surface water flooding. This is due to the prevalence of intense convective storms during the summer, so the intensity is greater in the middle of the storm. Finally, using the latest FEH13 depth-duration-frequency rainfall model is recommended. Not all rain falling on the surface will generate runoff as part will be infiltrated. These infiltration losses must be considered by either reducing the storm profiles so that they represent net rainfall or by using infiltration equations dynamically within the hydraulic model.

3.3 Coastal events

Coastal flooding can occur due to a temporary increase in sea level during the passage of a large-scale storm, due to the interaction of waves with beaches and coastal defences or due to a combination of both. Therefore, flood inundation models typically require two boundary conditions:

- A still water boundary, located offshore, which allows propagation of the tide and surge representing the extreme sea level into the model domain; and
- A wave overtopping boundary along the coastal frontage, which injects wave water into the model to the rear of the flood defences to account for the water that is calculated to overtop the defences.

Statistical analysis of tidal gauges is available for UK shores, providing extreme sea levels along the coast every two km with AEPs ranging from 100% to 0.01% and relative to Ordnance Datum. Results are included in the Environment Agency's 'Coastal flood boundary conditions for the UK: update 2018'. An uncertainty bound around each extreme sea level value is also provided, which can be adopted depending on the level of protection desired. These extreme sea level values account for the effects of storm surge and astronomical tides, but do not specifically consider potential localised increases in sea level induced by onshore wave action, orientation or topography.

However, a tidal wave (or sea level time series) is needed during the flood inundation simulation given that the extreme sea level is only the maximum instantaneous level during the event. It includes a base astronomical tide and a storm surge. The base astronomical tide should be high enough to represent a larger than 'normal' event but also to reach an appropriate level, which reflects an event that occurs every year. It is generated as follows:

- An intermediate value between the Highest Astronomical Tide on record and the Mean High Water Springs level is usually recommended as peak tide level;
- Searching this value in the Admiralty Tide Tables will identify a suitable date during the year;

- For that date, the Admiralty Tide Tables also provide the harmonic constants representing the multiple contributions to an astronomical tide such as the rotation of the Earth or the positions of the Moon and the Sun relative to Earth;
- The harmonics are then used to generate the associated tidal wave.

Storm surge is then added on top. The surge shape affects the length of time total sea level is elevated by surge above a particular sea level. A wider surge shape results in prolonged high sea levels and therefore it is important to apply a representative surge shape in deriving a total storm tide curve. The 'Coastal flood boundary conditions for the UK guidance' offers standardised storm surge shapes to be applied at any given location. They are scaled to reach the target extreme sea level once combined with the base astronomical tide.

Wave action is a complex process controlled by a number of factors. Waves generate in deep water and then propagate towards land. As they do so, they enter shallower bathymetry where wave transformation processes occur, including shoaling, diffraction, refraction, depth limitation, and breaking. These waves are also subjected to additional influence from wind. It is these nearshore waves that are of most importance because they interact with beaches and defences and lead to wave overtopping.

Existing SWAN 2D wave models from other projects (e.g., Environment Agency's State of the Nation project) can be used for wave transformation modelling that can generate nearshore wave conditions. Starting from the adopted extreme sea levels, and offshore wave and wind data from Met Office WavewatchIII hindcasting study selected using a multivariate extreme value analysis, the SWAN 2D models obtain wave properties such as height, period, or direction along the coast. Given high computational costs a subset of events is usually modelled with the rest being statistically interpolated.

The overtopping method requires sea conditions at the toe of the structure. It is thus necessary to transform the sea conditions from the nearshore to the structure toe. This is normally achieved using SWAN 1D models for wave transformation through the surfzone based on the beach profile for the particular location. Overtopping rates are finally calculated using the BAYONET wave overtopping model, which relates closely to the standard Clash method, described in the EurOTop manual. A time series of wave overtopping rate is then discharged into the model cell just landward of the flood defence whenever water level is below the defence crest. If it is above the defence crest, the standard weir equation is used to calculate flow into the floodplain.

3.4 Groundwater events

Groundwater flooding can occur following prolonged above-average rainfall that allows groundwater level to build up until water emerges at point (springs) or diffuse locations. The rate of recharge and rainwater level variation are difficult to model and vary significantly across the territory following the geology. In addition, abstraction for public water supply and other uses can deplete groundwater levels notably. Although the Environment Agency has developed regional groundwater models, their use for flooding purposes would require the definition of complex rainfall design events involving up to several months, for which guidance does not exist. As an alternative, extreme value analysis can be conducted at observation boreholes with long records to estimate the expected groundwater level for different AEPs. This could be used in combination with uplifted groundwater surfaces derived from groundwater models to predict emergence locations and flows [16].

3.5 Incorporating climate change

The UK regulators, the Environment Agency, Natural Resources Wales, the Scottish Environment Protection Agency and Northern Ireland Department for Infrastructure have published guidance on climate change allowances required for peak river flow, peak rainfall intensity, sea level rise, and offshore wind speed and extreme wave height, to be adopted in flood risk assessments. They can be consulted from:

- Flood risk assessments: climate change allowances [17];
- Flood consequences assessments: climate change [18];
- Climate change allowances for flood risk assessment in land use planning [19];
- Technical flood risk guidance in relation to allowances for climate change in Northern Ireland [20].

The guidance is based on the latest Met Office UKCP18 climate projections and simplify the consideration of the impact of climate change on flood risk by uplifting baseline design events by a certain magnitude based on the location, time horizon, and desired percentile (probability that projections are equal or lower than a certain value). The latter reflects the uncertainty in climate change projections derived from the emission scenarios, the choice of model and its representation of key climate processes. Allowances are offered for central (50^{th}), higher central (70^{th}) and upper end (95^{th}) percentiles to reflect the criticality/vulnerability of the receptor. For instance, an upper end allowance (95^{th} percentile) is only exceeded by 5% of the projections (across all 4 RCPs) and can be applied to essential infrastructure where certainty is needed that the asset will not be flooded in the future.

Note that the regulator expects the application of these climate change allowances when they provide advice on flood risk assessments and strategic flood risk assessments. However, as indicated for instance by the Environment Agency in their guidance on climate change allowances [17], 'there may be circumstances where local evidence supports using other data or allowances, but these need to be approved by the regulator following presentation of the required evidence'.

4 Estimating flood hazard

This section summarises the standard industry approach for deriving flood data. It relies on the application of hydraulic models to translate design events into flood extent, depth and velocity.

4.1 Hydraulic modelling

After establishing suitable boundary conditions, these need to be applied to hydraulic models representing pathways and receptors of a fluvial, coastal or drainage system. Hydraulic models can differ in complexity depending on the problem to be simulated. For instance, simplified flood extents can be obtained by the GIS rolling-ball mapping method, which defines overland flow paths and stores water on the surface based on terrain data, or by the horizontal projection method, which projects combined tide and surge levels for coastal regions and estuaries. However, computational one dimensional (1D), two dimensional (2D) or linked 1D2D models that are able to solve the mathematical equations that govern flow by means of numerical methods are recommended for detailed studies.

A 1D model is constructed from cross-section profiles with hydraulic calculations made at each section, often called model nodes. It is suitable for representing river channels, well-defined valleys and floodplains with storage areas, but their spatial resolution is limited to the user-defined locations, floodplain flow routes and storage areas must be determined in advance, and significant post-processing is needed to generate flood maps. A 2D model solves equations across a 2D square grid or mesh for the whole modelled area, based on ground elevation. It is applicable to complex floodplains where flow routes cannot be predicted and for direct rainfall modelling representing surface water flooding. However, it is not able to simulate channel flow or hydraulic structures with accuracy. Given this, 1D2D models are typically adopted, with the 1D part simulating the channel, pipe network and structures, and the 2D part representing the floodplains. They normally use unsteady flows, or flows that vary over time during the simulation (i.e., flood hydrograph) to give a more complete picture of flood progression and to allow for attenuation. Some limitations of 1D2D modelling are large data requirements, long computing times and instabilities arisen at the 1D2D interface.

To construct a 1D2D model, the following information is usually needed:

- Boundary conditions representing the adopted design events such as flood hydrographs, storm profiles or tidal waves;
- Channel cross-sections and hydraulic structure surveys;
- Sewer network geometry;
- A Digital Terrain Model to represent the floodplain and to interpolate the bank elevation between cross sections. It should be free of vegetation but must incorporate constructed infrastructure blocking the flow;
- Hydraulic roughness estimates for both channel and floodplain. Guidance exists to define

them although professional judgement is essential here;

- Hydraulic structure parameters that influence energy losses;
- Receptors with buildings typically elevated from the ground surface 0.3m to represent individual flood defences and having a high hydraulic roughness that will effectively block flow but allow water storage.

There are different software platforms that can be used for flood inundation modelling. Flood Modeller, TUFLOW, HEC-RAS, InfoWorks ICM, MIKE FLOOD, and JFlow® are regularly applied in the UK for 1D2D simulations.

Regardless of the choice of software, it is essential to test the performance of the hydraulic model to increase the confidence in the results in at least one historical event where there is enough meteorological or hydrometric data, although verifying three events is recommended. Parameters of the rainfall-runoff and/or hydraulic model are then modified or confirmed so that a good correspondence is achieved with recorded water level or flow from gauging stations, wrack mark survey data, aerial photography showing the extent of major flood events or anecdotal information. A well-calibrated model should match reliable recorded peak data (typically to within ± 0.15 m) and provide a good representation of hydrograph timing and shape. When there is not enough data for calibration, model performance can be validated, for example, using a water level gauge, flow data or anecdotal information about frequency of overbank flow.

4.2 Dealing with uncertainty

There are multiple sources of uncertainty in estimating flood risk, including:

- The estimated flood flow for the chosen design event due to the quality of the observations, the length of the record, and the statistical or modelling methods used to extrapolate to extreme events or to ungauged locations;
- The definition of the floodplain topography, the intervals between surveyed channel cross sections and the accuracy of the measurements (e.g., LiDAR, UAV or field survey);
- The choice of effective hydraulic roughness, normally based on professional judgement from observations of bed material, vegetation, uniformity, etc. and energy coefficients associated to structures;
- The choice of hydraulic model and its representation of the physics. Depending on the problem, a 1D, 2D or 1D2D approach, or steady state or unsteady simulation with diffusive or dynamic wave could be more or less suitable for the hydraulic conditions being represented;
- The consideration of floodplain infrastructure and obstacles;
- The consideration of the performance of flood defences, which could breach during floods, changing the propagation of the flood.

These sources of uncertainty can, to some extent, be investigated and reduced by improving measurements or adopting more advanced modelling techniques. Efforts in this regard are only justified when this is likely to change a decision, and even so, there will always be some residual uncertainty. ‘Accounting for residual uncertainty: an update to the fluvial freeboard guide’ [21] presents some methods to deal with this residual uncertainty, with a freeboard allocation (additional flood depth assumed on top of modelled depth) calculated with a first order error analysis typically adopted while designing flood protection measures. This implies estimating the sensitivity of the results (e.g., flood depth at a certain location) to changes in modelling variables (e.g., flood flow or hydraulic roughness) and assuming maximum reasonable errors in these variables, with the total uncertainty in the results obtained through a simple weighted summation of independent contributions. This assumes as a simplification that each secondary variable acts independently of the others and that the uncertainty in the primary variable is at the same level of confidence as the secondary variables and is Normally distributed. The estimated total uncertainty is then added to the baseline results as a freeboard.

If the magnitude of the residual uncertainty allowance is large such that it cannot be assumed in the design without disproportionate costs or changes a key decision, a more detailed uncertainty analysis can be undertaken involving a full propagation of the effects of different sources of uncertainty through hydraulic inundation modelling. This is done randomly selecting (e.g., by Latin Hypercube Sampling) a single value of each input variable and model parameter from their associated probability distributions representing uncertainty in their values and running the hydraulic model to derive an ensemble of outputs which will give the probability a certain design value is exceeded.

4.3 Protecting your assets

Once information on flood hazard is derived, the standard of protection to be adopted for a particular asset should be a function of its criticality within the network or system and its vulnerability to flooding conditions. As indicated in Section 4.2, an uncertainty allowance should be considered. The criticality of the asset should also inform the climate change allowance to be adopted.

It is important to test the effectiveness of the protection measure within the hydraulic model developed to estimate flood risk as it can alter the flooding conditions leading to an increase in flood level. In addition, the regulator requires that flood risk to third party receptors is not increased as a result of the intervention. Any reduction of floodplain storage caused by the protection measure must also be compensated so that flood attenuation downstream is not altered.

5 Methodology/Data

Section 5.1 describes the different data sources considered from precipitation to flooding in this work. In particular, Section 5.1.1 describes data sources for climate change; Section 5.1.2 describes the precipitation component of UKCP18; Section 5.1.3 considers the use of the UKCP probabilistic projections of climate extremes (PPCE) to augment other sources of climate projections; Section 5.1.4 summarises the UKCP18 sea level rise projections; and Section 5.1.5 discusses mapping projections of precipitation to river flow.

Section 5.2 describes the modelling of surface flooding with the HiPIMS flood simulation model.

Section 5.3 outlines and compares methods for generating rainfall events for HiPIMS.

5.1 Data sources and types

5.1.1 Climate change

Climate projections can be used to understand the characteristics that natural weather-related hazards might have in the future. Climate projections are produced through various national and international, collaborative initiatives, such as CMIP6, CORDEX, EUCP and UKCP18. Each usually has a slightly different angle, such as regional or global scale, some chosen physical process to study, resolution of the resulting datasets, etc., but together constitute a wealth of data to inform the study of the future climate, both from a scientific point of view and for adaptation/mitigation strategies at the (sub)national level.

Climate projections are created with climate models that represent physical processes which govern our atmosphere and oceans. Assumed 'scenarios' (RCPs) for the concentrations of greenhouse gases, aerosols, and other atmospheric constituents that affect the planet's radiative balance (e.g., [22]). RCPS capture the economic, social, and physical changes to our environment that will influence climate change and specify concentrations of greenhouse gases that will result in total radiative forcing increasing by a target amount by 2100. For example, RCP8.5 amounts to an increase of 8.5 W/m^2 by 2100. Four RCPs span a wide range of plausible future emissions scenarios, together with five Shared Socioeconomic Pathways (SSPs) that reflect how global society, demographics and economics might change over 21st century. The higher the radiative-forcing increase, the warmer the atmosphere will be. RCPs are chosen to span a wide range of plausible future emissions scenarios which ultimately depend on socio-economic choices. SSPs show that it would be much easier to mitigate and adapt to climate change in some versions of the future than in others. It is worth noting that not all RCPs may be achieved with all SSPs.

UKCP18[3] is the latest set of climate projections for the UK and provides the most up-to-date assessment of how the climate of the UK may change in the future [5, 23]. It consists of simulations

[3] UKCP stands for UK Climate Projections; it is a climate analysis tool that forms part of the Met Office Hadley Centre Climate Programme. UKCP18 supersedes UKCP09.

of the Earth's climate in future decades (typically through 2100), performed using state-of-the-art climate models that represent physical processes governing our atmosphere and oceans, developed with users to co-design tools and capabilities, and going beyond climate trends by providing a range of climate projections, future weather, and changing seasonal weather characteristics.

There are a number of projection datasets available within UKCP18, differing by their resolution, coverage and the number of differing RCPS that are represented. Global projections are available at 60km resolution for RCP8.5 and RCP2.6 (1900-2100); regional projections (UK and Europe) are available at 12km resolution for RCP8.5 (1980-2080) and local projections are available for the UK at 2.2km resolution for RCP8.5 (1981-2000, 2021-2040, 2061-2080). [24] .

Local models better represents small-scale behaviour in the real atmosphere, such as convection; it better captures the influence of mountains, coastlines, and urban areas, due to the fine resolution. The result is that local projections enable the exploration of changes in daily and hourly extremes (e.g. storms, summer downpours, severe wind gusts), enable hydrological impacts modelling (e.g. flash floods) and assessment of the effects of climate change on cities (e.g. urban extremes).

The headline results from the latest set of local projections are a greater chance of warmer, wetter winters and hotter, drier summers, along with an increase in the frequency and intensity of extremes. By the end of the 21st century, all areas of the UK are projected to be warmer, more so in summer than in winter.

Figure 5.1.1 shows the projected changes in wet days (frequency and intensity) for 2061-2080 under RCP8.5. This suggests that both frequency of wet days and intensity of wet days will increase in winter, with increases in rainfall intensity, despite overall summer drying, in summer.

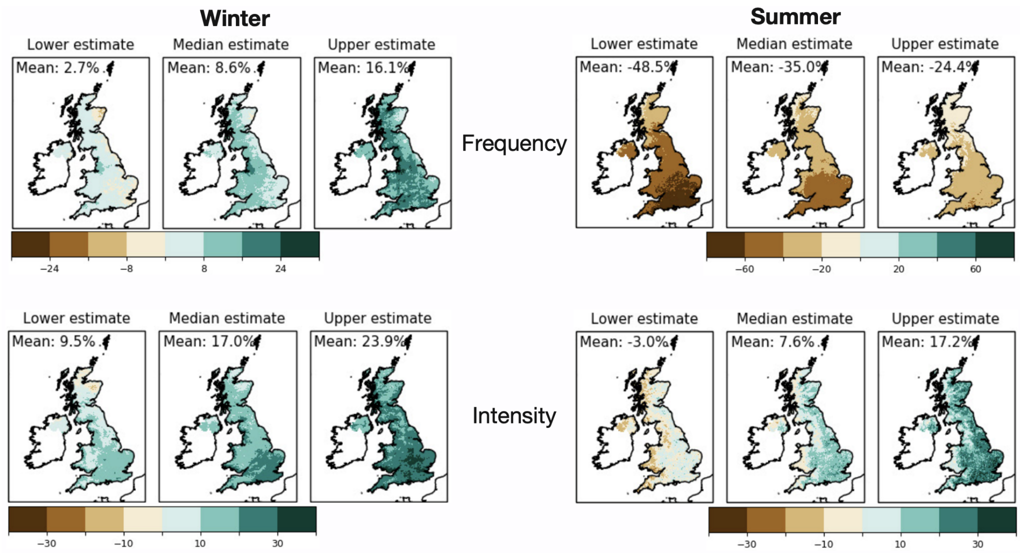


Figure 1: Projected changes (%) in wet days (frequency and intensity) for 2061-2080, RCP8.5

Future changes in hourly rainfall extremes and suggests significant increases in hourly precipitation extremes with the rainfall associated with an event that occurs typically once every 2 years increasing by 25%, by the 2070s. The frequency of days with hourly rainfall > 30 mm/h almost doubles, by the 2070s, increasing from the present UK average of once every 10 years to almost once every 5 years.

Although only available for RCP8.5, the high-resolution projections for the UK can be expressed in terms of Global Warming Levels (GWLs), the effects when projected mean global temperature reaches 1.5°C, 2°C or 4°C above pre-industrial levels. In the local projections, the approximation is often made that the near future period (2021–2040) corresponds to 2 °C of global warming and the mid-to-late century (2060–2080) to 4 °C of global warming.

The most relevant climate projection information for CReDo include:

- the **local projections** [25] (details in Section 5.1.2), a set of very high-resolution simulations[4] of the local climate under the high-emission scenario RCP8.5, allowing to examine the risk of extreme weather events in local areas in the 21st century. Precipitation projections for the study area were extracted, recalibrated and used as an input for HiPIMS;
- the **probabilistic projections of extremes** [26] (details in Section 5.1.3), derived by combining larger ensembles of lower-resolution climate model simulations with statistical methodology for estimating extreme events, and providing an indication of how much the evidence from climate models and observations taken together in the UKCP18 methodology support a particular future climate outcome (used to assess uplifts for the design storms);
- the **marine projections** [27] (details in Section 5.1.4), informing projected future changes in sea level and extreme water levels around the UK (used for comparing coastal projections from the Environment Agency based on UKCP09 with the latest UKCP18 climate projections).

[28] gives a summary of some of the caveats and limitations to consider when using any of the UKCP products. Some of these are considered in the following sections where relevant.

5.1.2 Local projections

In this study, projections of precipitation were obtained from the UKCP18 local projections. These local projections ([25]) consist of twelve very high-resolution (2.2km) simulations (members) under a high-emission scenario (RCP8.5), with data saved at an hourly resolution for precipitation and temperature. As these were produced with a convection-permitting model, they better represent atmospheric convection (including intense storm events), the influence of mountains, coastlines and urban areas. In other words, they provide credible climate information ([25], [29]) on hourly timescales and small-scale weather features which affect flooding, such as the summertime rainfall intensity and duration, short-duration rainfall extremes, and flash flooding. However, because of computational cost, unlike the other sets of UKCP18 projections, these projections cover three distinct 20-year periods instead of the whole of the 21st century: a historical period (1981–2000), the near future (2021–2040) and the mid-to-late century (2060–2080), and a single RCP (RCP8.5, a high-emission scenario).

[4] This is the first time internationally that such a high resolution is used in national climate scenarios.

Precipitation is highly variable in both space and time and the interactions between this complex field and small-scale changes in terrain are required for a complete assessment of climate impacts. Although the understanding and ability to simulate the climate is advancing all the time, climate models are not able to represent all of the features seen in the present-day real climate. They cannot capture some of the processes responsible for precipitation, especially short-duration local effects (see [1], [30] for more details). While with coarser-scale UKCP18 datasets, this is improved in the local projections, thanks to the finer spatial resolution and use of a convection-permitting model, bias-correction must be applied to the model results in order to modify the dataset for systematic difference between model results and observations (see bias-correction guidance and discussion in [31] and [32]). Bias-correction is important when the quantities of interest in the impact studies are absolute values, such as exceedances of a set rainfall amount, rather than relative changes with respect to a period of reference (or baseline). Essentially, these methods calculate the differences between the model results and observations for a particular statistic, e.g. the mean or variance, and then apply this to the future dataset.

In this work, time series of hourly precipitation were extracted over the few model grid cells corresponding to the study area and then bias-corrected using scaled-distribution mapping. The bias-correction was a two-step approach: first the daily precipitation totals were bias-corrected, then the hourly totals were rescaled to match the bias-corrected daily precipitation totals. This approach was adopted as bias-correction methods require knowledge of the 'truth' (observed precipitation). In the present case this was taken as the HadUK-Grid 1-km observation dataset ([33]), a dataset which provides daily precipitation at a 1-km spatial resolution over the study area and the historical period. While observed hourly precipitation datasets also exist and would have allowed to bias-correct directly the hourly totals, the choice was made to use the HadUK daily dataset instead as it is the reference observational dataset for UKCP18 and offers gridded observations of other atmospheric variables as well. This would ensure that, should other variables be required for the study area, some consistency would be preserved amongst them when bias-correcting. Scaled-distribution mapping ([34]) is a recent technique that has been found to outperform previous quantile-mapping approaches (see [35] for a discussion on recent bias-correction techniques). It does not assume that model biases are stationary (i.e. similar in present and future climate) and it preserves better raw projected changes to meteorological variables such as temperature and precipitation, by scaling the observed distribution by the raw model projected changes in magnitude, rain-day frequency and likelihood of events. For its mathematical formulation, see [34]; note that bias-correction should not be expected to correct any serious model deficiencies. Hourly precipitation amounts were rescaled to match the bias-corrected daily precipitation totals, ensuring that the daily minima and maxima were preserved. This approach was applied member by member. In practice, several bias-correction algorithms should be tested and possibly with several observational datasets if available, to identify that best suited to the location and application at hand. The bias corrected hourly precipitation amounts were then used to identify storm events of a future climate in the study area (see 5.3.4).

As previously mentioned, limitations of the UKCP18 local projections include that they are restricted to one RCP and available for a total of twelve simulations, which does not cover every possible future climate. An approach to mitigate partially for these is to analyse results in terms of GWL. Results are restricted to periods centred on the year the projected global (entire Earth) increase in temperature reached a given GWL, regardless of the path taken to reach that level (e.g. which RCP). The assumption is made that regardless of how rapidly the climate has warmed, the physics of the climate at a given GWL is consistent. In the case of regional precipitation changes, studies have shown that it holds for the near future but not the later part of the 21st century (see for example [36]).

5.1.3 Probabilistic projections of climate extremes

The UKCP Probabilistic Projections of Climate Extremes (PPCE) product assesses future extreme events in the UK (see [37] for an overview, [26] for a more detailed description of the methodology). The purpose of this product is to extend beyond the information given by the twelve UKCP18 local ensemble members, by incorporating uncertainties from the modelling approaches, returning probabilistic information about the occurrence of extreme events, and allowing assessments across different emission scenarios. This differs from the UKCP probabilistic projections [38], which provide distributions for mean changes, as opposed to considering explicitly extreme events, as required when assessing flood risk.

The only outputs available are daily maximum temperature, daily total precipitation, and 5-day total precipitation, but unlike the UKCP18 local dataset, the projections are probabilistic, and for multiple RCPs and years, derived by combining larger ensembles of lower-resolution climate model runs with statistical methodology for estimating extreme events. This dataset is designed to be used in combination with other UKCP18 products, and can be summarised by the following attributes:

- On a 25km grid;
- For 1 in 20, 50 and 100 year return periods;
- For all RCPs (2.6, 4.5, 6.0, 8.5);
- For individual years (up to 2100);
- Different distributions by season (DJF, MAM, JJA, SON);
- Output given as 5th, 6th, . . ., 95th percentiles (more extreme ignored as considered unreliable).

Compared to the UKCP18 local projections for precipitation, there are clear benefits and limitations. The PPCE data has a much lower spatial resolution (25 km vs 2.2 km), and has only seasonal summaries rather than sub-daily data. Only the given return periods, and daily totals can be considered, rather than the possibility of considering shorter intensity events, and their return, from UKCP18 local.

However, using the PPCE data avoids the restriction to RCP8.5 and 12 individual simulations (covering three unconnected 20-year time periods) imposed by UKCP18 local, and hence the results are not as strongly caveated on this particular set of runs and emission pathway. Instead, provided we are only interested in daily rainfall and a return level such as 1 in 100, we have a distribution for total rainfall in a 25km grid box given any combination of RCP, year, and season.

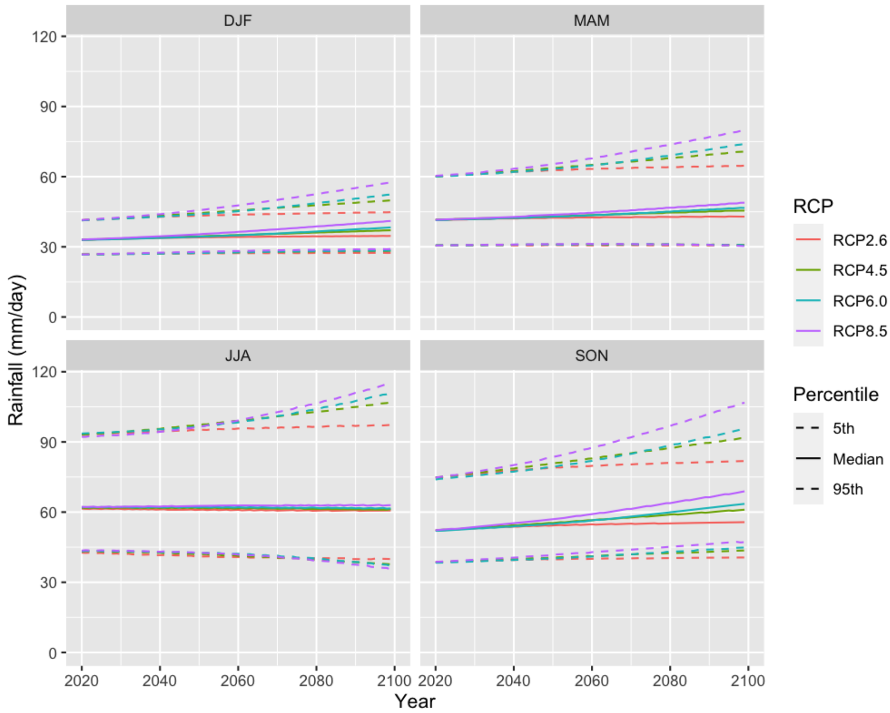


Figure 2: The 1 in 100 return level rainfall (in mm per day) at King's Lynn according to the UKCP18 PPCE, by season, RCP, and year, with the 5th, 50th, and 95th percentiles plotted.

As an example of the form of this dataset, we extract the 25km grid box containing King's Lynn. Figure 2 shows how the distribution of the daily total precipitation at the 1 in 100 return level changes over time, by RCP and season, with the median, 5th and 95th percentiles plotted in every case. In general, the median estimate for the summer (June-July-August, JJA) return level stays relatively consistent over time, for all emission pathways, although the width of the distribution increases towards the end of the 21st century, with the 95th percentile of this distribution highest for RCP8.5 in 2100. [26] also shows a limited change in the median daily precipitation total in summer, for the grid box containing London, at 1 in 20, 50 and 100 year return levels, so that this is likely not a localised, but a more general, trend in the PPCE.

For all other seasons, Figure 2 shows that the median estimates of the 100-year daily rainfall total increase relative to the present day, with the largest increases seen in the RCP8.5 scenario, and lowest for RCP2.6. This dataset highlights the fact that there is considerable uncertainty around return levels, even for the present day: for the summer event, the 5th and 95th percentiles for the 24-hour total rainfall in 2020 are 44 mm and 92 mm respectively (median = 62 mm). Again, this is consistent with the results for London in [26], with a wide distribution at and before the present day.

We consider the usage of the PPCE in terms of assessing design storms in Section 5.3.3.

	RCP2.6		RCP4.5		RCP8.5	
	5th	95th	5th	95th	5th	95th
London	0.29	0.70	0.37	0.83	0.53	1.15
Cardiff	0.27	0.69	0.35	0.81	0.51	1.13
Edinburgh	0.08	0.49	0.15	0.61	0.30	0.90
Belfast	0.11	0.52	0.18	0.64	0.33	0.94

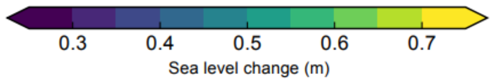


Figure 3: Range of sea level change (m) at UK capital cities in 2100 relative to 1981-2000 average for a low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emission scenario. (Source: [27].)

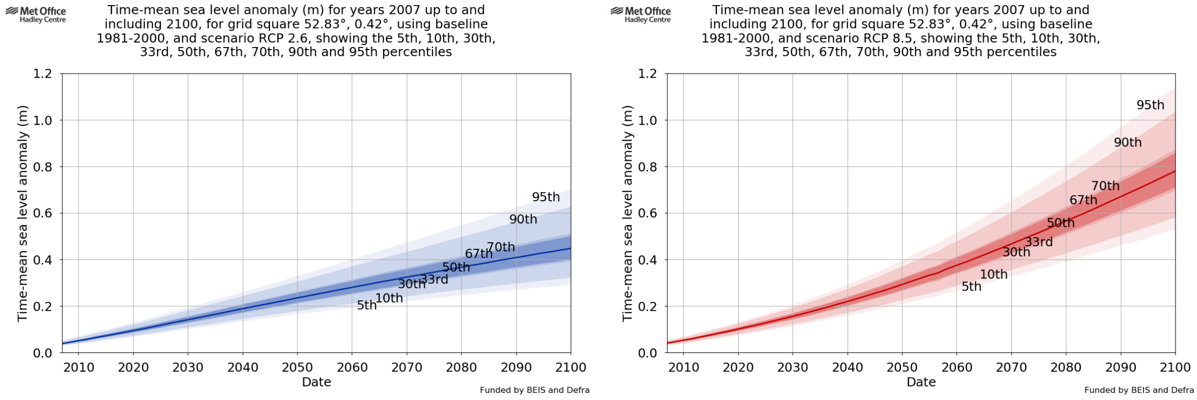
5.1.4 Sea levels

The UKCP18 marine projections [27, 39] inform projected future changes in sea level and extreme water levels around the UK across a range of RCPs, and are used in this work for comparing coastal projections from the Environment Agency based on UKCP09 with the latest UKCP18 climate projections. We used projections provided covering the 21st century, which highlight that the UK coastal flood risk is expected to increase over the 21st century. Changes in sea level occur due to a broad range of geophysical processes that operate on different spatial scales and time scales, they depend on the location around the UK and increase with higher emission scenario (e.g. see an example of this for four UK capital cities in Figure 3).

The UKCP18 projections updated most results from UKCP09 ([40]), except for the coastal water properties and the H++ scenarios for time-mean sea level and surge in particular (these scenarios are designed to explore low-probability, high-impact sea level rise around the UK). With respect to UKCP09, the UKCP18 sea level projections are consistently larger, for similar emissions scenarios, but the modelling uncertainty (per scenario) is similar. They also include a lower emissions scenario that assumes more mitigation, thereby spanning a broader range of future climate forcings which results in a larger overall spread of the projections.

Figures 4a and 4b show projections of time-mean sea level changes with respect to the baseline period 1981-2000 near King's Lynn (several grid points correspond to the area, one is used here as an example). The projected increase in the study area in 2100 ranges from about 0.3 m (RCP2.6, 5th percentile) to 1.1 m (RCP8.5, 95th percentile). See further comparison in Section 6.2.

As with climate projections, caveats apply. The best expert judgement is that the 5-95th percentile



(a) Under RCP2.6

(b) Under RCP8.5

Figure 4: Projected UKCP18 time-mean sea level anomaly (m) until 2100 near King's Lynn under low (a) or high (b) emission scenarios. The anomaly is calculated with respect to the baseline period 1981-2000.

ranges cover only the two thirds of the 'likely range'. It is advised to augment the projections of sea level rise with other strands of evidence (e.g. UKCP09 H++ scenarios). It is also not possible to rule out substantially larger rates of sea level rise over the 21st century associated with the potential for accelerated loss of ice from the West Antarctic ice sheet. Finally, for any given geographic location, there may be other vertical land motion processes at play that are important when carrying out coastal risk/impacts assessments. The extended exploratory time-mean sea level projections (those extending from 2100 to 2300) also have much lower confidence than the 21st century projections. These should be considered as sensitivity studies and not interpreted as showing the full range of post-2100 behaviour, or the most likely behaviour.

5.1.5 River flows

Future projections for precipitation can be mapped to changes in river flow. The UK Centre for Ecology and Hydrology (CEH) produce datasets of river flow under climate change, derived from UKCP data (precipitation, temperature, potential evapo-transpiration).

The UKCP09 version [41, 42] provided an 11-member ensemble of daily mean river flow for 283 catchments across the UK. This was updated based on UKCP18 [43, 44], with the outputs now given over a one km grid rather than by catchment, from 1980 to 2080. Instead of a time series of daily mean flow, the outputs are now monthly mean flow, annual daily maximum flow, and annual minimum 7-day flow. As with UKCP18 local, this dataset is linked specifically to RCP8.5.

The overall summary given by [44] suggests that across Great Britain as a whole, the median flow in the summer is projected to decrease by 45% for 2050-2080, under this high emission scenario. In some regions, for example the north and west, there is a slight increase in flow in the winter.

The 1-km CEH UKCP18 dataset does not have flow in King's Lynn directly, but we can consider changes of flow at nearby, upstream locations, in order to assess localised trends in future flow. Considering three points upstream from King's Lynn, the mean monthly flow is projected to de-

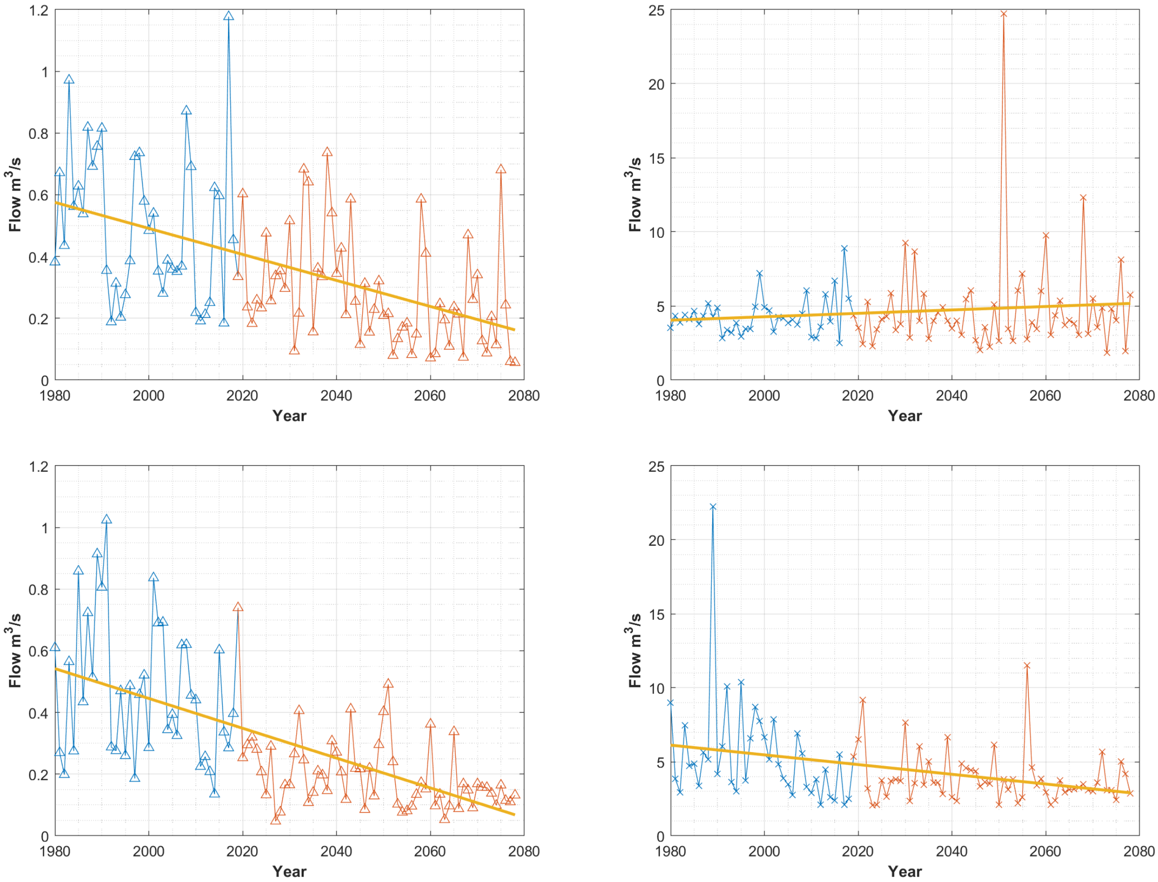


Figure 5: Example of the CEH river flow dataset, with annual minimum flow (left) and annual maximum flow (right) plotted for the Ouse upstream of King's Lynn, for ensemble members 4 (top) and 11 (bottom).

crease over time, in all 12 of the ensemble members, consistent with the overall results seen in [44]. Similar decreases are seen into the future for the annual minimum flow, and the left of Figure 5 shows the time series of annual minima for the closest point on the River Ouse to King's Lynn, for ensemble members four (top) and 11 (bottom).

However, for the annual maximum in this region the results are less consistent, with some ensemble members showing increases, and others showing decreases. The right half of Figure 5 plots the annual maximum flow for the Ouse upstream of King's Lynn for the same two ensemble members as previously, with different trends seen in the annual maximum flow.

Alternatively, [45] derives a flow series for King's Lynn itself and considers future flow at different return levels via extreme value analysis, comparing the present day with the 2040s and 2070s. This approach involved using the 12 ensemble members of the RCP8.5 regional projections coupled with daily rainfall-runoff modelling, and considering the attenution provided by the Ouse Washes, hence accounting for local characteristics. The main results are that frequent events (e.g., 1 in 2 or 5 years) are projected to decrease slightly in magnitude, whilst there is an increase in the 1 in 100 year event (4% and 6% for the 2040s and 2070s respectively). This is consistent with results above, where in general flow may decrease, but extreme rainfall may be more prevalent.

River flow by itself is not enough to consider flooding impacts, but is required for boundary conditions in hydraulic modelling, see Section 5.2. The datasets outlined here are useful for exploring possible trends in future river flows, but their resolution is not high enough in time to simulate flooding events themselves.

5.2 Surface flood modelling with HiPIMS

HiPIMS (High-Performance Integrated hydrodynamic Modelling System) is a hydrodynamic flood model [46]. The model dynamically models water flowing between different grid cells, taking an input of rainfall over time across a spatial domain, and outputting inundation extent and depth, allowing for assessment of impacts at a local level. The HiPIMS model can be run through the 'Pypims' package [47] and a tutorial is available at [48].

The study in [46] simulates 2015 flooding in Carlisle due to Storm Desmond, modelling a 2500km^2 region for a 96-hour event by exploiting a multi-GPU architecture. At a 5m resolution, this domain has 100 million grid cells, and the model takes 37.5 hours to run with 8 GPUs. The event produced by the model is compared to observed time series of water levels at several river gauges in the region. The maximum flood extent produced by the model and observed in reality in 2015 are also compared. Both comparisons provide reasonable agreement between the observations and the modelled output.

In order to run an instance of HiPIMS for a particular region, there are a number of datasets required as fixed inputs:

- A **Digital Elevation Model (DEM)** on some coordinate system. Digital Surface Models [49] and Digital Terrain Models [50] are available at different resolutions from the Environment Agency, and can be combined to form the required DEM input. The raw DEM should be adjusted to reflect the main watercourses conveyance capacity. Building footprints should also be raised 0.3 m to reflect the typical flooding threshold associated with personal flood protection measures.
- A **Land use** raster on the same coordinate system as the DEM, available from CEH [51]. Each land use class is related to a Manning coefficient to reflect its hydraulic roughness.
- Location of any inflows and outflows from the region, required as **boundary conditions** for the model.
- Surface water **catchment areas**, for defining location of rainfall.

Given this model setup for a given spatial domain, several aspects of the model can be varied to simulate different events:

- **Precipitation**: over time, by catchment area, and with a certain time interval, derived from FEH or similar (see discussion of different approaches for this in Section 5.3)).
- **Event duration**: we consider standard storm lengths (one, three, six, eight, and 23 hours).
- **Boundary conditions**: river inflows and downstream levels. These are linked to the storm durations and can be derived via FEH.

Resolution	Storm length	Model time	Run time
2m	1 hour	26 hours	1h01m
2m	3 hours	27 hours	1h06m
2m	6 hours	30 hours	1h15m
2m	23 hours	41 hours	1h47m
1m	1 hour	26 hours	8h37m

Table 1: Time taken to run various configurations of HiPIMS for the study region, using DAFNI and 2 GPUs. Model time is the length of the particular model event (6 hour spin-up + event + time until inflow peak + 6 hours thereafter), run time is how long it takes to execute this event.

- **Model resolution**: we consider 1 m and 2 m resolution, with the focus on 2 m (faster run-time), with comparisons to selected 1 m runs to assess the model sensitivity to this choice.

The area of study here is restricted to a relatively small region (around 12.7km^2), and hence HiPIMS can be run at a relatively high resolution. Even so, going from 2 m to 1m resolution results in an increase from 3.2 million to 12.7 million grid cells, and hereafter we focus on a 2m model resolution.

In general, to avoid the need to initialise non-zero depth values across the spatial domain, and the assumption that precipitation events begin over a completely dry domain, prior to simulating any rainfall event, the model is run for a six hour 'spin-up' phase, with baseline values for the boundary conditions, so that there is flow through rivers in the study region. The model is also in general run for six hours after the peak in input flows, so that any effects due to increased flow from upstream catchments are accounted for.

Table 1 gives the time required to run various configurations of the model (changing resolution and length of the model run) on the DAFNI platform with two GPUs. In general, higher resolution requires substantially more computational time, with around an eight-fold increase (from around an hour to over eight and a half hours) to run an identical event at 1m resolution instead of at 2 m. For larger regions, lower resolutions (5 m, 10 m) may be necessary to keep computational time reasonable. In these situations, a 1D-2D approach would likely be needed to represent the watercourses conveyance capacity properly.

5.2.1 Uncertainty

Computer models are not perfect representations of reality, and a number of uncertainties exist. For example, the model may not be being run at settings of the input parameters that would lead to output most consistent with the real world, and even if we could run the model at such input settings, there may be a difference between the output of the model and the real world. There are a number of reasons why these inconsistencies may be present, for example missing or simplified physical processes in the model, or differences occurring due to the resolution at which the model is run, so that finer-scale processes are not represented.

In this particular modelling exercise some limitations are:

- The critical storm duration in each area of the model domain does not need to be one of the adopted;
- Infiltration and drainage within the area have not been explicitly modelled, in particular the sewer network and its capacity;
- Surface catchment areas and their catchment descriptors have not been adjusted to reflect the drainage network;
- The conveyance capacity of main watercourses has not considered the effect of structures and has not been based on surveyed cross sections;
- Water levels in the River Ouse are likely to be higher than tidal levels offshore.

Understanding the uncertainties in a computer model, and calibrating it based on observations in the real world, are important steps in order to be able to trust a model for decision making. Unlike in [46], where a recent flooding event was being explicitly considered, the region we are considering has not suffered recent flooding, and so there is no reliable data for calibrating modelled events against reality in terms of flood extent or depth. We are also focusing on relatively extreme events and how these may get more extreme in the future, so a lack of data may be somewhat inevitable (we are extrapolating beyond what may be observed at the present day). Hence, such events should not be treated as a prediction of exactly what will happen (e.g., this particular property will have a certain depth of flooding in a particular event), but rather as representative of what may happen in a certain scenario, conditional on assumptions such as emission pathways. Comparing the range of possible events under plausible storm designs and under different climate change pathways may still be informative.

The only type of calibration step we have carried out is ensuring that when there is no rainfall, no flooding occurs. We also compared our results with the EA Risk of Surface Water Flooding maps as a sense check, in particular to validate the lack of significant overbank flow in main watercourses. For a certain choice of boundary definition, and when the tide level is high, there was occasionally overspill over defences that would not be expected in these conditions in reality. Hence the definition of this boundary was adjusted in order to avoid this unrealistic flooding, and so that when run without precipitation, the model output is plausible.

5.3 Precipitation events for HiPIMS

5.3.1 FEH

To run HiPIMS requires a time series of precipitation that can be spatially indexed, here by catchment area, and time series for any boundaries (inflows, tidal levels). The standard methodology for deriving design events for a particular location and return period is described in Section 3.2. For our region of study, [52] describes how to derive the required storm profiles, inflow flood hydrographs, and tidal boundary conditions using this standard approach, considering the 1 in 100 and 1 in 1000 year events.

For our region, there are four surface water catchment areas, each of which has its own design

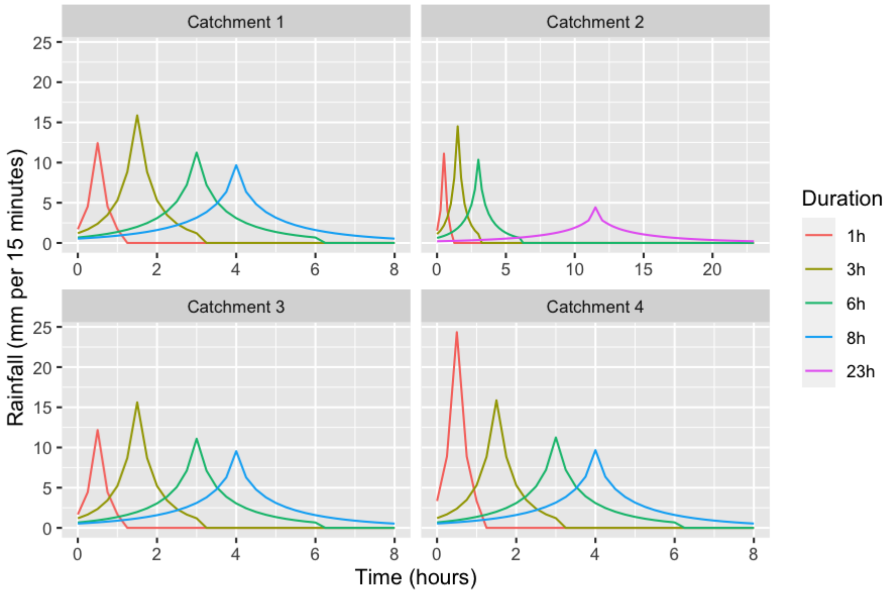


Figure 6: The standard design storms for the 1 in 100 year event, for the 4 catchments in the study area.

event, and two river inflows. The derived standard storm lengths are one, three and six hours in all catchments, and either eight (three catchments) or 23 hours. In what follows, we consider the eight and 23 hour events to start at the same time, as there are no interferences across catchments during flood events, and refer to this as the 8/23 hour event. The design storms for the 100 year return period for the four catchments are broadly similar, and are shown in Figure 6. The temporal resolution of all the standard designs is 15 minutes, with the amount of rainfall per 15 minutes (in millimetres) plotted on the y axis. The flood hydrographs (100 year return) that are consistent with the design rainfall for the two inflow locations are shown in Figure 7.

Note that in general the peak rainfall intensity is higher for shorter storms, but this is not the case for the 1 hour event for catchments one through three. Per [52], the 1 hour storm for these three catchments has the ten-year event subtracted to represent the capacity of the sewer network, whilst the fourth catchment is rural, hence this adjustment is not required.

Given these designs for the present day, 'uplifts' (changes compared to the present-day) can be applied to the precipitation and hydrographs in the design event to assess potential effects under climate change. To find the uplifted storm, the rainfall and inflow for these events is increased by $x\%$, where the value of x could be derived from different sources (see Sections 5.3.2, 5.3.3). The only deviation from a uniform increase by $x\%$ is in the case of the one hour events for catchments one through three: to find the uplifted event here, the ten year event is added in, the uplift applied to this total, and then the baseline ten year event subtracted again, reflecting the sewer capacity.

5.3.2 Climate change uplifts

A potential source of storm uplifts under climate change scenarios is available from the FUTURE-DRAINAGE project [53] (data available from the CEDA archive [54]), where these uplifts were

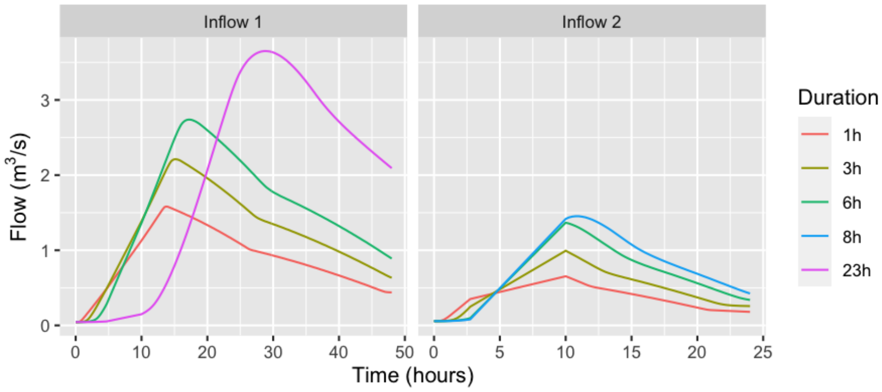


Figure 7: Inflow flood hydrographs for the 2 model inflows, for the 1 in 100 year event.

derived from precipitation in the twelve UKCP18 local runs.

The available data can be summarised as follows:

- For return levels of 1 in 2, 30 and 100 years;
- For RCP8.5 only: the uplifts are derived from the twelve UKCP18 local runs, hence we are restricted to this pathway;
- For 2050 and 2070 only: the 2070 estimate aligns with the centre of the third, 2060-2080 timeslice from the UKCP18 local projections. The 2050 estimate is an interpolation between the 2020-2040 and 2060-2080 timeslices, and is chosen as this was considered a key date by the FUTURE-DRAINAGE project;
- The spatial resolution is 5km;
- Storm lengths considered are one, three, six, 12 and 24 hours.

For a given year, return level, storm length and grid box, the output is a 'central' and an 'upper' estimate of the uplifts. All uplifts are given to the nearest 5% ([53]: 'providing uplift values to higher precision than 5% is not scientifically justifiable').

These central and upper estimates are not directly associated with a probability of occurrence, and are not intended to be percentiles of a full distribution across future climates [53]. Instead, they are the 50th and 95th percentiles of the distribution given by a statistical model used to predict the uplifts at different locations, fitted using the 12 UKCP18 local runs. It is therefore restricted to RCP8.5, but cannot be treated as probabilistic estimates for the RCP8.5 scenario as a whole, as 12 runs are not sufficient to describe the full distribution of possible climate trajectories under this emission pathway. The upper estimate is described by [53] as representative of a 'reasonable worst case' (under RCP8.5).

This dataset, therefore, can be used for assessing the effects of relatively extreme climate change scenarios: the 12 UKCP18 local RCP8.5 runs in 2050 have an average of 2.9°C warming above pre-industrial levels (range: 2.3-3.5°C); for 2070 the average is 4.2°C (range: 3.8-4.8°C). Table 2 summarises the central and upper estimates for King's Lynn for 2050 and 2070, with variability across different storm lengths: in general, shorter storms increase in intensity by a higher

Year	Estimate	1h	3h	6h	12h	24h
2050	Central	20%	20%	20%	15%	10%
2050	Upper	40%	40%	37.5%	35%	35%
2070	Central	20%	25%	25%	15%	10%
2070	Upper	40%	40%	45%	45%	45%

Table 2: Uplifts at King's Lynn for different storm lengths and years for the 1 in 100 return period, from the FUTURE-DRAINAGE dataset.

percentage than 12+ hour events.

The Environment Agency also provide standard values for peak rainfall uplifts under climate change [17] as 10% (2050s) and 20% (2080s). These differ from those seen in Table 2, with the central estimates for 2050 higher than 10% for all storm lengths except the 24-hour event. However, the FUTURE-DRAINAGE uplifts are derived only for RCP8.5, the most extreme climate change scenario, whereas the Environment Agency figures of 10% and 20% are a more general 'total potential change anticipated' in peak rainfall. For flood risk assessments, it is recommended to consider also the Environment Agency's upper estimates of 20% (2050s) and 40% (2080s). This upper estimate for the 2080s is relatively consistent with the FUTURE-DRAINAGE upper estimates for both 2050 and 2070, despite the different interpretation (extreme emissions versus climate change in general).

There is overlap between some of these events. For example, the standard Environment Agency climate change increase for the 2080s is 20%. Similarly, for one, three and six hour events at King's Lynn, the FUTURE-DRAINAGE central estimate for 2050 is also 20%, and so these different storm uplifts and hence flooding scenarios are in fact the same. However, the interpretation is slightly different: the former is intended as a blanket estimate of climate change, whereas the latter is specific to RCP8.5 and a particular location.

5.3.3 Probabilistic uplifts

The UKCP18 PPCE data (described in Section 5.1.3) offers an alternative source of increases in precipitation due to climate change. Due to the construction of this product, there is no restriction to RCP8.5 and two particular time horizons as in the previous section. Instead, there are percentiles of return level rainfall for different years and emission scenarios, with this probabilistic information available to be converted into uplifts. This potentially allows statements to be made about the likelihood of storm events under different climate change scenarios.

This benefit is traded-off with the ability to only consider 24-hour rain totals, rather than applying distinct uplifts for different storm lengths [53] shows that uplifts are different by duration. Although this is conditional on RCP8.5, it is reasonable that this would be true for other RCPs.

To calculate uplifts in rainfall versus the present day requires a baseline level for present day storms. For consistency with the FUTURE-DRAINAGE dataset, we assume a baseline period of 1981-2000. Restricting the PPCE dataset to King's Lynn, the 1 in 100 return level, and 1981-2000, gives distributions of daily total rainfall for each year, season and RCP (although as this is a past period, the levels across RCPs are the same, up to $\sim$0.1 mm). Setting the baseline as the seasonal medians across the 1981-2000 period gives baseline daily total rainfall for the 1 in 100 year event equal to 32 mm (DJF; December-January-February), 40 mm (MAM; March-April-May), 62 mm (JJA; June-July-August), and 49mm (SON; September-October-November).

Using these seasonal baselines, we can calculate the future uplifts under each RCP according to the PPCE, and Figure 8 converts Figure 2 from raw rainfall totals to percentage uplifts relative to the baselines. The standard Environment Agency uplifts, and the central and upper FUTURE-DRAINAGE uplifts for King's Lynn from the previous section are overlaid. These different sources of information are relatively consistent (in terms of median uplift) with the spread given by the different RCPs for winter, spring, and autumn, although the summer changes are much flatter according to the PPCE. In all cases apart from DJF RCP2.6, the 95th percentile uplift from the PPCE is higher than the FUTURE-DRAINAGE upper estimates, and in some of the RCP8.5 cases, the 95th percentile is close to, or above, 100%, by 2100, substantially beyond the maximum uplift in Table 2.

Some aspects of this plot are not perfectly comparable: the standard Environment Agency uplifts apply to all storm durations, rather than only the daily total available from the PPCE, and the FUTURE-DRAINAGE values are only derived for RCP8.5. Clearly there is temporal correlation in the projected return levels, so that a world where the median estimate is the truth at the present day, and then the 95th percentile is in 2050, is perhaps unlikely, so that the uplifts of the 95th percentile should not be completely taken at face-value as storms getting worse by, say, 100%. As mentioned in Section 5.1.3, there is considerable uncertainty in the rainfall at the 1 in 100 return level at the present day, and so following this derivation of uplifts, for the summer event, an uplift relative to the 'median' event may already be 50% at the present day. Therefore, the 95th percentile uplift in Figure 8 accounts for uncertainty in the mis-specification of the baseline event, as well as future changes.

Comparing the daily rainfall totals given by the PPCE to the standard design storms in Figure 6 highlights a potential issue with purely deriving uplifts from the PPCE baseline period. The longest events modelled (8 hours for three catchments, 23 hours for the fourth) have total precipitation of 77 mm, 77 mm, 76 mm, and 88 mm (23 hour event) for the 1 in 100 return level. This is in contrast to the 1 in 100 event calculated from the baseline period 1981-2000 in the PPCE in Section 5.3.3, where the median of the 1 in 100 daily total rainfall distribution was 62 mm for summer. (The 95th percentile across the baseline period is 92 mm, so that the standard events do fall within the uncertainty in the PPCE.) This may be a resolution issue (small catchment areas vs a 25km^2 grid box), but suggests a different, higher median baseline may be required (which would then avoid some of the most extreme increases in Figure 8).

As well as the variability between the total rainfall in the longest storm events from different sources, there is the issue that in general shorter storms require larger uplifts (as in Table 2 for RCP8.5 specifically). In general, if higher intensity is the expectation under climate change, rather than higher rainfall overall, then the information within the PPCE does not give a represen-

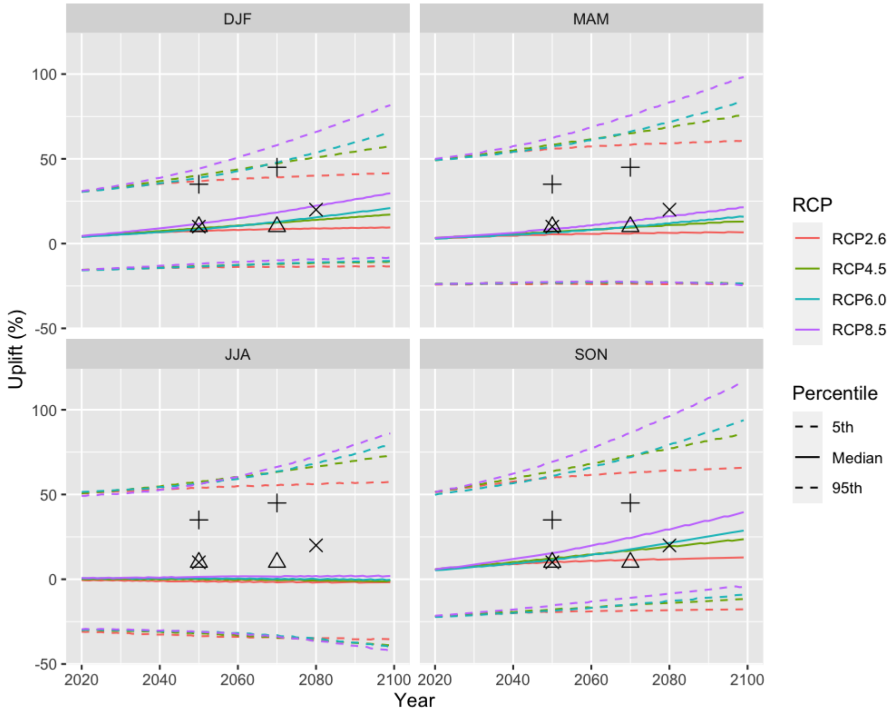


Figure 8: The 1 in 100 return level rainfall (in mm per day) at King's Lynn according to the UKCP18 PPCE, by season, RCP, and year, in terms of percentage uplift relative to the 1981-2000 baseline estimate. The Xs on the plot indicate the standard Environment Agency climate change uplifts (10% for 2050, 20% for 2080); the triangles (+s) show the central (upper) estimates for 2050 and 2070 from the FUTURE-DRAINAGE data.

tation of this.

Given an appropriate baseline level, we have access to a distribution of uplifts for a given year and RCP, and this distribution of uplifts (or particular percentiles) could be applied to the standard events, and run through HiPIMS, returning a distribution of flood depths and extents for any given year or RCP. However, this may only be applicable for longer events and, given the current choice of baseline, negative uplifts are within the distributions and running such events is not necessarily useful from a decision making or planning perspective.

The lack of changes seen in summer daily totals over time motivates the need for considering the UKCP18 local dataset, with its ability to capture shorter, higher intensity convective storms.

5.3.4 Using UKCP18 storm profiles

As an alternative to the standard design storms, it is possible to extract hourly precipitation values from UKCP18 local projections (after bias correction, as in Section 5.1.2), and run this as the precipitation input for HiPIMS. This would not necessarily be suitable as a risk assessment tool, as the same drawbacks discussed earlier apply here (RCP8.5 only, twelve runs only, so we cannot make statements about probability, whereas the standard design storms are derived to be median estimates of a given event/return period) but such events may be used to add some sensitivity around the standard design events, and may become a more suitable approach in future given

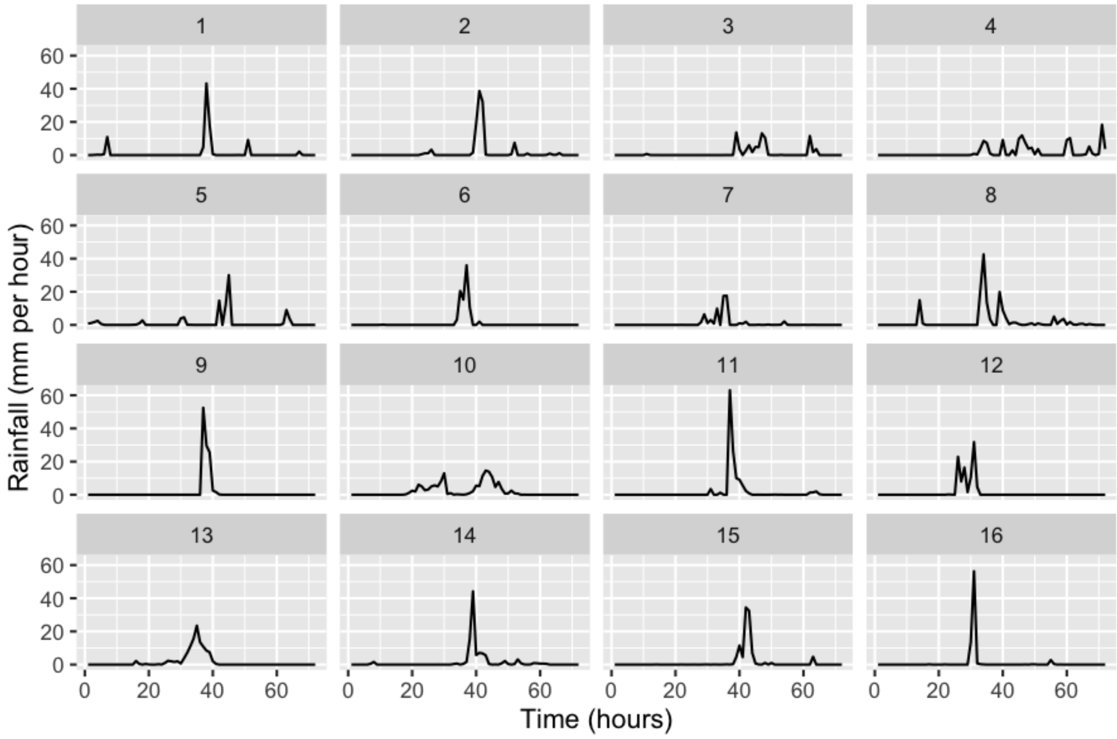


Figure 9: Profiles of 16 events extracted from UKCP18 local, for the grid cell containing King's Lynn.

a larger set of high-resolution climate projections.

The rainfall events from FEH have an arbitrary, symmetric profile enforced, with a sharp peak, and are calibrated based on observed data, so are representative of events under a stationary climate [55] discusses issues with this, and applies non-stationary techniques instead. Conversely, UKCP18 local projections come from a convection-permitting model, designed to simulate better intense storm events, with future emission pathways to simulate climate change, and so we might expect that storms from UKCP18 local projections could give an improved understanding of future, climate change-induced storms, compared to applying a percentage increase to the standard, present-day profiles. Due to its high spatial resolution (2.2 km) and the use of a convection-permitting model, UKCP18 local projections are able to represent local variability, and to advect convective storms across the landscape which the coarser-resolution models cannot do, and so events could be derived for particular sites/catchments, as with FEH. However, precipitation data from the UKCP18 local projections are archived at a time interval of one hour (the model timestep itself is one minute), so cannot provide information on shorter-timescale extreme events.

Figure 9 shows 16 precipitation events from UKCP18 local for the 2.2 km grid cell containing King's Lynn, selected based on searching the twelve ensemble members for relatively extreme storms occurring in this region. The maximum hourly total rainfall across these 16 events is 63 mm (event 11). Some of these events have much lower peaks, indicative of either a more prolonged storm, or of the centre of the storm not being located in this particular grid cell. Some of the events (e.g., 13, 16) do have sharp peaks in intensity and a relatively symmetric profile around this, but the profiles are often skewed in one direction (e.g., six, nine, 15) rather than being forced into perfect symmetry. Some events (e.g., 12) have multiple peaks of differing intensity across the space of a few hours, and such a storm may have a different impact in terms of flooding.

Simply extracting a storm event from UKCP18 local projections and running this through HiPIMS does not allow for this event to be placed in context (e.g. what is the return period?), but if it is selected in combination with uplifted totals or UKCP PPCE information, then it could be. We can aim to align roughly total precipitation from an event in Figure 9 with standard design storms, and use this to test out alternative, non-symmetric storm profiles, and assess whether this makes a difference in terms of impacts. Given enough data, we could better estimate the return levels in a certain year (given RCP8.5) or at a certain global warming level, extract multiple events with these characteristics, and then run all of these through HiPIMS. A hybrid approach, given the lack of UKCP18 local runs (twelve ensemble members), would be to:

1. Use the UKCP PPCE dataset to find the distribution of total rainfall for a given year, RCP, return period;
2. Extract set of events from UKCP18 local that have precipitation that falls within this range within a day;
3. Run this set of events through HiPIMS.

This bypasses the need for selecting a storm length, applying a scaling for seasonality, or proscribing a symmetric storm profile. This however restricts to daily events, and alternatives (e.g., the earlier described uplifts) would be required for shorter storms, but could work similarly e.g., the uplifted storm has X mm rainfall in Y hours, and search UKCP18 local projections for storms that align with this total and timeframe.

This approach is not perfect: there is the issue that the inflows are derived from and linked to the standard storms, which is not possible via this framework.However, as the UKCP18 local runs are actual climate change projections (given emissions assumptions), using this to augment the standard approach in some way may be beneficial. Overall, this can allow alternative, non-symmetric and different length events to be tested, whilst staying close to the standard risk framework where possible.

Figure 10 shows an example profile of an event selected from UKCP18 local projections (event six from Figure 9), chosen as a relatively extreme storm that occurs over King's Lynn in the available dataset. Note that this event has a temporal resolution of 60 minutes, compared to 15 minutes for the standard design events, but for consistency, the 60-minute total rainfall is split equally between each 15-minute interval when displayed in Figure 10.

The selected storm has 85 mm of rainfall in five hours, peaking at 36 mm in the fourth hour, followed by 2 hours with nearly zero rainfall, before 2mm further rainfall in hour eight. There are a couple of possible interpretations of this single event: a five (or six) hour event with 85 mm of rainfall, and an eight hour event with 87 mm. In this example, the extra 2 mm may not make a large difference in impacts, however this may not be generally true. The peak intensity of the event is 36 mm/hour, and as the data is given on an hourly timescale, when input to HiPIMS this

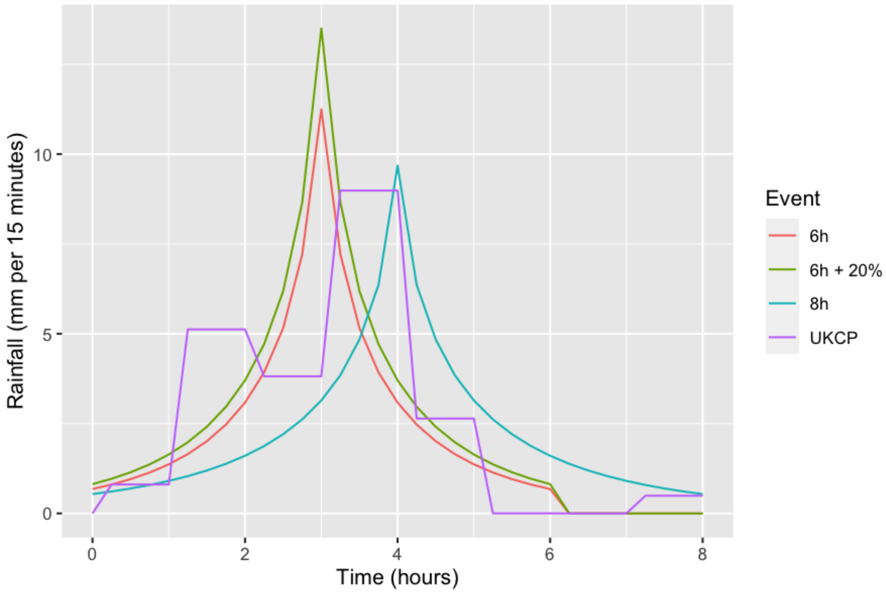


Figure 10: Profile of an event from UKCP18 local projections compared to the 6 hour and 8 hour standard design storms, and the 6 hour event with a 20% uplift.

rate is maintained for an hour.

Comparing this to both the six and eight hour design storms, the 6 hour design event has a total of 72 mm rainfall, with a peak intensity of 45 mm/hour for a 15 minute period in the middle. The eight hour design event totals 77 mm rainfall, peaking at 39 mm/hour (again, for a 15-minute spell). Hence, the UKCP18 event has more rainfall in total, but a lower peak intensity, traded off with the fact that its peak is 60 minutes long, rather than 15.

Applying a 20% uplift to the six hour event, per the Environment Agency 2080s allowance, and the central FUTURE-DRAINAGE uplift for 2050, gives the green line in Figure 10, and a total of 86.57mm of rainfall. Hence, the UKCP18 storm could be considered as representing a similar scenario, with a different storm profile featuring a lower peak intensity. Other events (from UKCP18 local projections) with a similar total across the same timeframe could be considered, and between them, give an ensemble of possible flood events under a certain scenario.

5.3.5 Summary

In all, several aspects of rainfall events can be varied (return period, storm length, seasonality, climate change scenario), and the resulting flood events are discussed in Section 6.3.

6 Results

In this section, we consider the different sources of flooding in King's Lynn. Section 6.1 summarises fluvial flood risk based on Environment Agency (EA) reports for different catchments; Section 6.2 summarises the EA report on coastal flooding in the region, with a link to sea level rise under latest UKCP18 projections; and Section 6.3 explores various surface water flooding scenarios derived from running HiPIMS.

The Environment Agency reports and datasets referred to in this section were obtained following a request for Products 4, 6, 7 and 8 for the region of interest (as described in Section 2). For general information about how the modelling was done, Section 4.1 provides an overview of hydraulic modelling. The below referenced EA reports provide more details about the modelling in each individual region.

6.1 Fluvial

There are 3 relevant catchments in the study area, and each is modelled separately:

1. Fenland (Section 6.1.1);
2. Cut-off Channel/Lower Rivers (Section 6.1.2);
3. Lower Nar (Section 6.1.3).

Overall there is limited fluvial risk in this region, even in the most extreme scenarios, due to the high level of defences. Any flooding is restricted to areas away from King's Lynn and is mostly flooding of upstream storage areas.

6.1.1 Fenland

For full details, see 'Fenland Flood Risk Mapping' [56].

The Fenland region is a 1435 km^2 low-lying catchment lying to the west of the Ouse. 17 and 60 hour storm durations are considered, with return periods of five, 10, 20, 25, 50, 75, 100, 200 and 1000 years. 100 and 1000 year events under climate change (100+CC, 1000+CC) were also modelled. All scenarios assumed defence levels consistent with the present day, as it is unlikely these would be removed or not maintained.

Even in the 1 in 1000 year scenario, the only fluvial flooding risk is to the south of Downham Market, on the edge of the study area.

6.1.2 Cut-off Channel/Lower Rivers

For full details, see 'Eastern Rivers Modelling Report: Lower Rivers' [57].

This region lies to the south of Downham Market. Return periods are 1 in two, five, 10, 20, 30, 50, 75, 100, 200 and 1000 years. For assessing climate change, flows and rainfall for the 100 year event were increased by 20%, to create scenario 100+CC.

The overall conclusion of the modelling report is that 'fluvial flood risk from the Lower Rivers is very limited' due to substantial storage capacity. There is some flooding in the 10 and 25 year events (generally outside the area of interest), and more widespread flooding for 100+ year events, however there is overall very limited risk to property.

6.1.3 Lower Nar

For full details, see 'Eastern Rivers Modelling Report: River Nar' [58].

The River Nar is a tributary of the Ouse at King's Lynn. Return periods modelled are 1 in two, five, 10, 20, 30, 50, 75, 100, 200 and 1000 years, with 100 and 1000 year events under climate change assessed via a 20% increase in flows.

Similarly to the other catchment areas, there is limited flood risk to property or at King's Lynn, even for the most extreme events, due to flood defences and upstream storage areas.

6.2 Tidal

For further details on the results, see summary report 'East Anglian Coastal Modelling: Final Summary Report' [59]. For details on the methodology, see the accompanying model development report [60].

The Wash model considers flood risk due to coastal flooding/wave overtopping using a flood inundation model. Return periods are 1 in 10, 20, 30, 75, 100, 200, 500 and 1000 years. Under climate change, 1 in 20, 200 and 1000 year events are modelled. For the climate change scenarios, two sea level rise datasets are considered:

- UKCP09, medium emission scenario 95th percentile for 2115 [61];
- National Planning Policy Framework (NPPF), 2115 estimate [62].

These scenarios correspond to a sea level rise (relative to the present day) of 0.75 m and 1.11 m respectively. Additionally, offshore wind and wave height is increased by 10%. All scenarios assume present-day levels of flood defences. The outputs provided by the Environment Agency consist of maximum inundation depths for each of the modelled events (i.e., there is no temporal element).

The modelling in [59] was performed prior to the release of UKCP18, hence the use of now outdated sea level projections. From Figure 4, the median sea level rise by the end of the century under RCP8.5 is just below 0.8 m, with 1.11 m falling around the 95th percentile of this distribution. For comparison, a rise of 0.75 m lies beyond the upper end of the distribution for RCP2.6 at 2100.

For the present day scenarios, there is no risk at King's Lynn (although there is flooding up the coast in Hunstanton starting from the 10% AEP event, and in Heacham starting with the 5% AEP event). For the climate change scenarios (i.e., with 0.75m and 1.11m sea level rise) there is flooding in King's Lynn itself for all return periods modelled (1 in 20, 200 and 1000 years), with

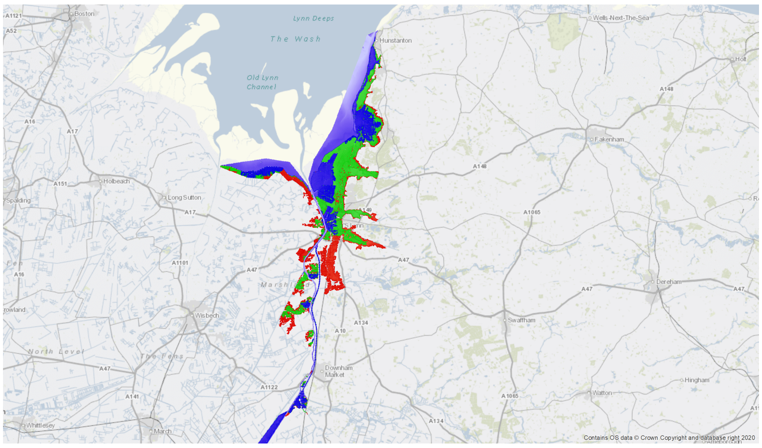


Figure 11: Maximum extent of coastal flooding in the climate change (NPPF) events. Blue = 5% AEP, green = 0.5%, red = 0.1%.

the maximum extents of flooding in the 3 NPPF scenarios shown in Figure 11.

6.3 Surface water flooding

6.3.1 Storm events

We initially focused on 1-in-100 year events, as plotted in Figures 6 and 7. This return period is the one at which there is most common ground across different datasets and approaches (there are available uplifts), as well as in guidelines, and is extreme enough that there may be impacts to assets. Standard designs for 1 in 1000 years were also run, but uplifts of an event this rare were not considered, as they are not available in either the FUTURE-DRAINAGE data (too few runs to derive this from) or PPCE (although EA uplifts could be used here).

A number of ensembles of HiPIMS were run that can be broadly characterised by the following summaries (similarly described in Table 3):

1. Standard design storms;
2. With climate change via standard Environment Agency uplifts (10% for 2050s, 20% for 2080s);
3. With climate change via FUTURE-DRAINAGE uplifts, per Section 5.3.2;
4. With UKCP18 2.2km-derived storms, per Section 5.3.4.

Within each of these ensembles, the storm length is varied across the standard design lengths (one hour, three hours, six hours, and eight of 23 hours, catchment dependent). As described in Section 5.2, each event is initialised with zero rainfall and baseline inflows for six hours, prior to the start of the input precipitation event, of chosen duration and uplift.

Note that eight and 23 hour events are not explicitly covered by the FUTURE-DRAINAGE dataset (six, 12 and 23 hours are the closest). The 12 hour and 24 hour uplifts are generally consistent for this location, so we apply the 24 hour uplift for eight and 23 hour events (the six hour uplift is

Description	Return period	Resolution	Storm length
Standard design	1 in 100	2m	1, 3, 6, 8/23 hours
Standard design	1 in 100	1m	1 hour
Standard EA uplifts, 2050s	1 in 100	2m	1, 3, 6, 8/23 hours
Standard EA uplifts, 2080s	1 in 100	2m	1, 3, 6, 8/23 hours
FUTURE-DRAINAGE uplifts, 2050	1 in 100	2m	1, 3, 6, 8/23 hours
FUTURE-DRAINAGE uplifts, 2070	1 in 100	2m	1, 3, 6, 8/23 hours
Standard design	1 in 1000	2m	1, 3, 6, 8/23 hours

Table 3: Overall summary of events run on HiPIMS

often larger, but the 24 hour uplifts have the same range across scenarios, e.g., the maximum uplift is 45%, so that this assumption provides similar events to if we were to instead apply the 6 hour uplifts).

Overlaps between different uplifts, and there being different possible interpretations of the same event, were discussed in Section 5.3.2. An exhaustive list of the HiPIMS model runs performed to date is given in Table 4, with a description of each individual run's interpretation. For example, the one hour event, with 100-year return period and 40% uplift, can be interpreted both as the upper (reasonable worst case) scenario for 2050 and 2070 from the FUTURE-DRAINAGE uplifts (as in Table 2).

In all that follows, we ignore the first six hours of a simulation (i.e., when no rainfall occurs), and so time zero is in fact after six hours of model time.

6.3.2 Flood events

For any given flooding event, the depth at a particular time can be plotted. For example, the left of Figure 12 shows the depth after 2 hours for the standard 1 hour, 1 in 100 event, and the right shows the percentage increase in flood depth at this time, when the design storm has a 40% uplift applied (the reasonable worst case 1 hour event for 2050 and 2070 from FUTURE-DRAINAGE). The highest depths are seen in river channels, with the north generally having more surface water. This is unsurprising, as for the 1 hour event, the northern-most catchment has the most extreme rainfall (the others have a reduction to represent sewer capacity). When uplifted by 40%, more areas are liable to flood.

Taken alone, such maps aren't that informative (higher rainfall = more flooding), however they are useful when combined with asset locations and assessments of when failures may occur, and hence the actual impacts of an event, these flooding scenarios, and their evolution in time. The differences between present-day and uplifted events are much more informative when considering impacts: at what level of uplift (climate change) do certain assets or locations become vulnerable?

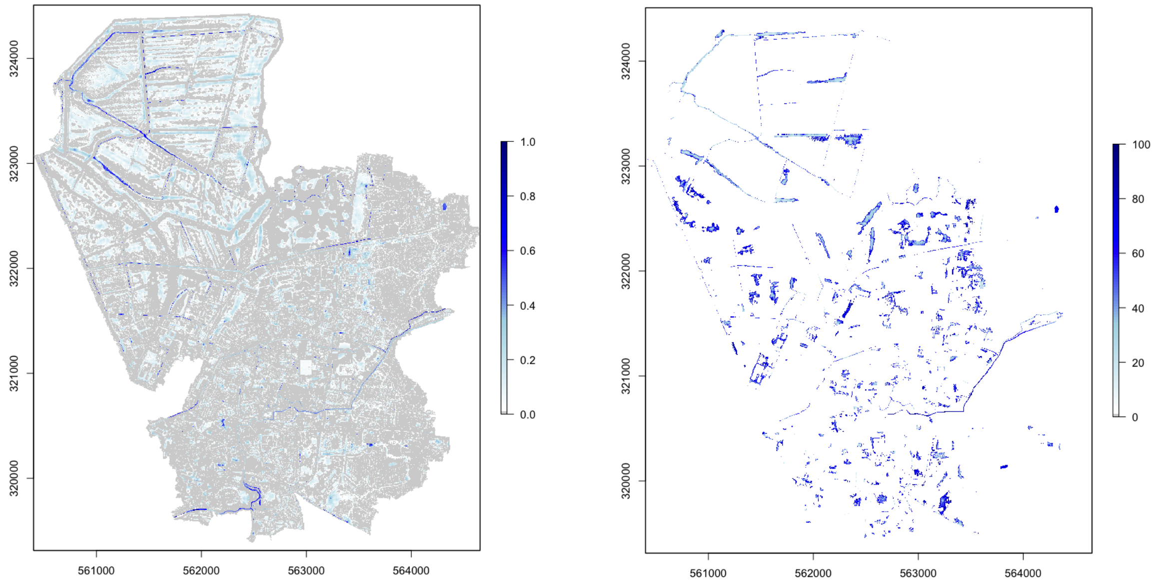


Figure 12: Left: depths after 2 hours for the standard 1 in 100 1 hour event. Right: the percentage increase in depth (with changes and depths of $<$5cm filtered out) at the same time, for the equivalent event with 40% uplift.

Figure 13 compares several of the flood events, across four different locations and the four different design storm lengths. The four sites chosen here are not representative of any particular land use type and were chosen semi-randomly in order to show locations where flooding does occur, and where different behaviours were observed across scenarios. Each panel contains the baseline event, the two standard EA uplifts, and the FUTURE-DRAINAGE central and upper uplifts (some of these overlap and so not all lines are present on all plots, see Table 4 for a list of distinct runs). Each location is a 10 m^2 box across the output domain, with the maximum depth within this box plotted over time, and so may be considered representative of an asset location. Unsurprisingly, as rainfall increases in intensity under the climate change scenarios, flood depth may increase, although the extent of changes is sensitive to location.

For some of the sites and storm lengths (e.g., site one), the flood profile is relatively consistent across events, with increases in depth as the uplift increases. In terms of impacts, there may be less difference, e.g., if we take a threshold of one metre, above which there is some negative effect seen at this location, then this is reached in the standard 1 in 100 year event, and the addition of climate change uplifts adds flood depth, but doesn't necessarily change impacts at this site.

However, instead considering site two, for the six hour and longer events there is much greater variability in the flood depth, and in the temporal progression of the flooding, with a 3-4x increase in depth for the most extreme climate change scenarios considered, relative to the standard present-day event. This site is more representative of a location where there may not be adverse effects expected at the present day, but where climate change may change this, and so e.g., better protection would be needed if this site is important.

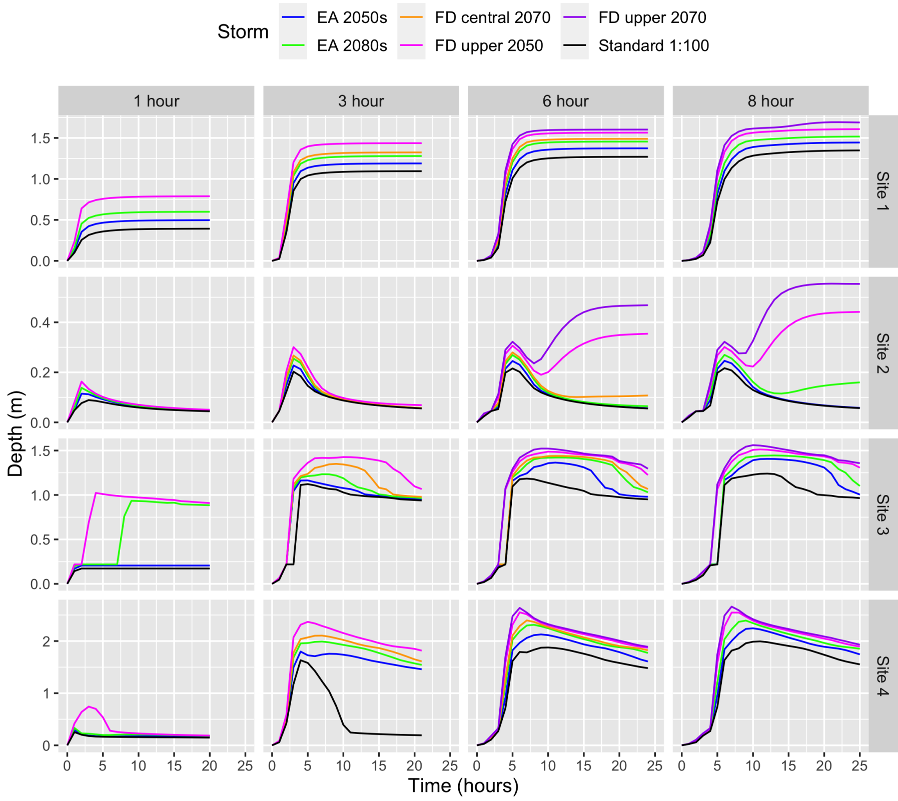


Figure 13: Flood events for 4 different locations, by storm length and event.

6.3.3 UKCP18 events

We run the precipitation event selected from UKCP18 local, as described in Section 5.3.4, on HiPIMS. This event is treated as six hours long (although almost all of the rainfall occurs in five hours), and the total rainfall is roughly consistent with the total for the six hour design storm with 20% uplift, hence the standard 1 in 100 year inflows with 20% uplift are used as the boundary condition.

The left of Figure 14 compares the two events at the four sites that were plotted in Figure 13, and shows that there is little difference in terms of the depth profile over time, or in the maximum depth achieved, at these particular locations. The green line (uplifted event) increases slightly faster than the UKCP18 event, consistent with the former storm peaking earlier, as seen in Figure 10. The right of Figure 14 plots the locations where the flood depth is higher for the two events (ignoring any locations where the flood depth is below 5cm, or where the difference between the two events is less than this threshold), and we see that the UKCP18-derived flooding event generally has higher flood depths.

There are a few reasons for this difference. Firstly, the widespread presence of blue regions at the southern end of the region is expected as this catchment area has a six hour design storm with only 66 mm of total rainfall, compared to 71-72 mm for the other three catchments, and hence the UKCP18 storm has 29% higher rainfall rather than the 20% compared here. This doesn't however explain the presence of only blue and white pixels elsewhere. A possibility here is that the UKCP18 storm, whilst being compared to a standard six hour event, actually has all its rainfall in the space of five hours, and hence in general the precipitation rates are higher (although not in short-term peak intensity) leading to slightly higher flooding.

This is not necessarily a problem with using UKCP18, as the restriction to a six hour event need not be strict, and non-standard storm lengths are certainly possible, with the UKCP18 local dataset giving the ability to consider alternative lengths. For considering the likelihood of the event or for use in assessing risk, however, a comparison to the standard storms is currently required, given by the choice of the six hour 20% uplift event here. These two events therefore represent reasonably similar events, with slightly changed profiles (rainfall occurring in a five or six hour window), roughly representative of a 1 in 100 year event with a 20% uplift - or consistent with the EA climate change allowance for the 2080s.

There are other possible interpretations of this: restricting to rainfall within a five hour period instead of six creates a more extreme, and hence less likely event, under the present day climate; e.g., rather than 1 in 100 years, it is more representative of a 1 in 120 year event, and so comparisons should be made with the latter rather than the former. As the PPCE shows, there is considerable uncertainty around the present day rainfall levels at the 1 in 100 year return level, so that the median 1 in 120 year event may still fall within the distribution of possible 1 in 100 events.

Running further events that are considered similar enough (e.g., alternative profiles, slightly changed lengths, etc.) would add sensitivity around the future flooding impacts under such scenarios, however a proper assessment of the likelihood of storms from UKCP18 is required in order to produce a true distribution of events and hence impacts at a given return level under climate change.

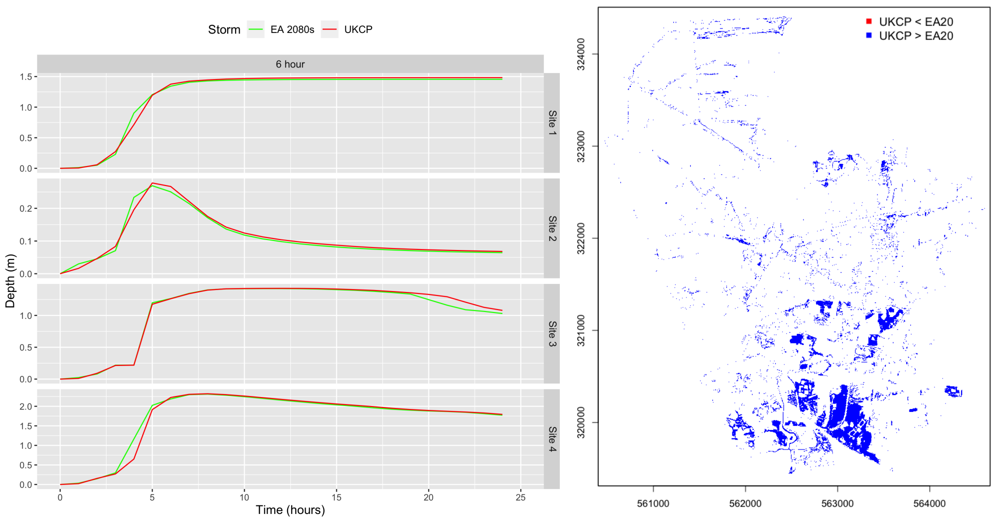


Figure 14: Comparing the UKCP18 event and the comparable uplifted storm (6 hours, 20% uplift). Left: depth over time for the 2 events, at the 4 sites where depth was considered earlier. Right: plotting locations where the UKCP18 event (blue) or uplifted EA event (red) has a higher flood depth, with depths and differences of less than 5cm filtered out.

Return period	Event length	Res (space, time)	Uplift	Interpretation
1 in 100	1 hour	2m, 1 hour 1m, 1 hour 2m, 15 mins	n/a	Standard design storm
1 in 100	1 hour	2m, 1 hour	10%	EA climate change, 2050s
1 in 100	1 hour	2m, 1 hour	20%	EA climate change, 2080s FUTURE-DRAINAGE central, 2050 FUTURE-DRAINAGE central, 2070
1 in 100	1 hour	2m, 1 hour	40%	FUTURE-DRAINAGE upper, 2050 FUTURE-DRAINAGE upper, 2070
1 in 100	3 hours	2m, 1 hour	n/a	Standard design storm
1 in 100	3 hours	2m, 1 hour	10%	EA climate change, 2050s
1 in 100	3 hours	2m, 1 hour	20%	EA climate change, 2080s FUTURE-DRAINAGE central, 2050
1 in 100	3 hours	2m, 1 hour	25%	FUTURE-DRAINAGE central, 2070
1 in 100	3 hours	2m, 1 hour	40%	FUTURE-DRAINAGE upper, 2050 FUTURE-DRAINAGE upper, 2070
1 in 100	6 hours	2m, 1 hour	n/a	Standard design storm
1 in 100	6 hours	2m, 1 hour	10%	EA climate change, 2050s
1 in 100	6 hours	2m, 1 hour	20%	EA climate change, 2080s FUTURE-DRAINAGE central, 2050
1 in 100	6 hours	2m, 1 hour	25%	FUTURE-DRAINAGE central, 2070
1 in 100	6 hours	2m, 1 hour	37.5%	FUTURE-DRAINAGE upper, 2050
1 in 100	6 hours	2m, 1 hour	45%	FUTURE-DRAINAGE upper, 2070
1 in 100	8/23 hours	2m, 1 hour	n/a	Standard design storm
1 in 100	8/23 hours	2m, 1 hour	10%	EA climate change, 2050s FUTURE-DRAINAGE central, 2050 FUTURE-DRAINAGE central, 2070
1 in 100	8/23 hours	2m, 1 hour	20%	EA climate change, 2080s
1 in 100	8/23 hours	2m, 1 hour	35%	FUTURE-DRAINAGE upper, 2050
1 in 100	8/23 hours	2m, 1 hour	45%	FUTURE-DRAINAGE upper, 2070
1 in 1000	1 hour	2m, 1 hour	n/a	Standard design storm
1 in 1000	3 hours	2m, 1 hour	n/a	Standard design storm
1 in 1000	6 hours	2m, 1 hour	n/a	Standard design storm
1 in 1000	8/23 hours	2m, 1 hour	n/a	Standard design storm
n/a	5 hours	2m, 1 hour	n/a	UKCP18 local example

Table 4: Index of all events run on HiPIMS.

7 Recommendations

The Intergovernmental Panel for Climate Change (IPCC) defines the risks associated with climate change as the combination of three components: hazard; exposure; and vulnerability ([63, 64]). A schematic of the IPCC risk framework can be seen in Figure 15. The framework for defining risk in this manner originated in disaster risk in which risk is defined as the likelihood over a specified time of alterations in the normal functioning of a community or society due to hazardous physical conditions ([65]). This risk is a consequence of physical hazards and the vulnerabilities of exposed elements and signifies the potential for severe interruptions in the normal functioning of the affected society when the risk materialises in the form of an impact.

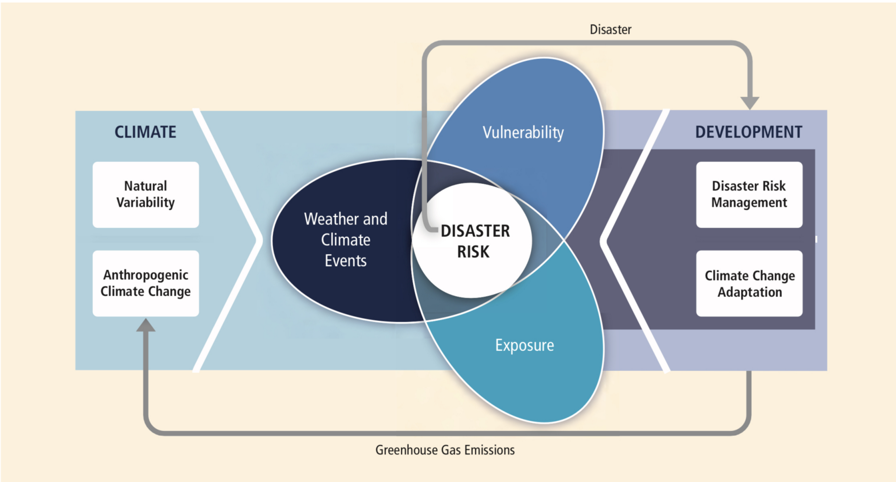


Figure 15: Schematic showing the key concepts in the IPCC framework for quantifying climate related risks

Hazard : The possible, future occurrence of natural of human-induced physical events that may have adverse effects on vulnerable and exposed elements.

Exposure : The inventory of elements in an area in which hazard events may occur.

Vulnerability : The propensity of exposed elements and assets to suffer adverse effects when impacted by hazard events.

Expressing the risk of climate related impacts in terms of the triad of hazard-exposure-vulnerability has been developed in the area of disaster risk over many decades ([66–68]), but the concept applies equally to examining the impacts of climate change in non-disaster situations and can be applied to the effects of changes in environmental conditions for a range of different paradigms. Here we consider the use of the IPCC framework in terms of the potential effects of climate change on individual assets. Hazards are changes in environment conditions predicted under climate change, i.e. increased precipitation, long-term changes in temperatures and other factors that may affect populations and infrastructure. In the example presented in this report, CReDo focuses on the potential for increased precipitation and sea level rise leading to flooding and effects this will have on infrastructure-related assets; other examples might include increases in temperatures in urban areas affecting people's health and wellbeing, and how changes in wind patterns might affect energy supply. Climate related impacts on such systems cannot exist based solely on environmental hazards; to quantify the risk of climate related impacts it is important to consider the vulnerability of assets when they are exposed to different hazards.

Providing a logically complete risk assessment given complexity of the systems involved and the consequent complexity of models is a challenge. The full chain of datasets and models contain various uncertainties and assumptions, all of which are important to understand and attempt to quantify properly. There are a range of possible future climates, even under a single emission scenario, and so when such climate information filters through to events such as flooding, any impacts should have some distribution. This is often treated via the provision of central and upper/reasonable worst-case assumptions, which aim to capture some of this uncertainty under climate change.

In the case of flooding, other uncertainties arise from the models used to simulate flooding where, due to the rareness of extreme flood events, reliable calibration data often may not be available. This is the case here, and as such depths should not be treated as predictions but as instructive of possible relative changes under climate change versus present-day extreme events.

Publicly available data, such as flood risk maps, assess the long-term risk of flooding in a location with some link to flood depth, but there is no temporal aspect or ability to view individual possible events, which may not have the same extent. The Environment Agency modelling data described in this report generally only provides maximum depths, although hydraulic models can also be accessed for a more detailed assessment.

UKCP products can give more information about potential future precipitation, and given some processing can be combined with HiPIMS to produce flooding events - either through directly running bias corrected spatio-temporal storms from UKCP18 local, or through deriving a percentage uplift to be applied to the present-day design events. Each UKCP dataset comes with a set of assumptions, with trade-offs between resolution and limitations in the available emission scenario.

It is possible to run spatio-temporal events from UKCP18 local over regions, offering alternative storm profiles spatially (grid-based rather than catchment-based) and in time (not constrained to be exactly symmetric). Storms may not have the exact same profiles in the future as at the present-day, and so allowing alternative profiles, not from directly uplifting a profile derived from the present-day climate, may offer useful information on risk under climate change, given a careful formulation of what such an event is conditioned upon, Hence this is slightly more challenging than a simple 1 in N year description. Analysing how storm profiles change between the present-day and future scenarios according to UKCP18 may also offer useful information, and allow standard profiles to not only be uplifted, but modified.

Incorporating high resolution (in space and time) UKCP18 local projections and probabilistic projections with the standard methods for designing storm events may augment existing practices, but a careful quantification of risk, and clarity of what events do and don't show, is important. It is also important to consider all sources of flooding for particular area. For our region of study, river flooding is not much of a concern due to the presence of defences. Tidal flooding becomes an issue under climate change given current levels of protection, due to the combination of sea level rise and an increase in event extremity (for example, with wind speed leading to higher waves).

Offering a clear comparison between Environment Agency guidance, and the changes implied by UKCP18 projections, would be beneficial for asset owners, to understand the assumed risk by following the standard allowances. The uplift dataset offers something like this, but is restricted to RCP8.5, and the chosen timeframes of 2050 and 2070 relate to 2.9°C and 4.2°C of warming, so does not allow the assessment of the full possible distribution of warming. The PPCE offers all emission pathways, but has lower resolution in both space and time, and hence does not capture intense short storms, critical for flash flooding. Bridging the gap between these two products, providing probabilistic uplifts for different emission scenarios or global warming levels for different storm lengths, would allow a much clearer quantification of risk under climate change and the likelihood of EA guidance being exceeded.

In addition to the information on precipitation used in CReDo, the local UKCP18 climate projections offer a wealth of information on other hazards. An example of implementation of the IPCC approach to quantifying the risks associated using information on other hazards based on UKCP18 is the Joint Centre for Excellence in Environmental Intelligence (JCEEI)'s CLimate Impacts, Mitigation, Adaption and Resilience (CLIMAR) framework (see [69] for details)). Within CLIMAR, data science methods are used to integrate multiple sources of data, across multiple temporal and spatial scales and acknowledging the potential for different biases and uncertainties in different data sources, to align information on hazards exposures and vulnerabilities. Climate related *impacts* are defined as an event occurring, e.g. an adverse health event outcome associated with increased temperature or a building flooding, and the *risk* of that event being the probability that that event happens in a defined time period and location.

In addition to participating in CReDo, the JCEEI have recently developed CLIMAR to quantify the effects of increased summer temperatures in urban areas on human health. The aim is to assess how the impacts on health, which will be determined by the magnitude of the hazard (heat) and the vulnerabilities of local populations (determined by demographic and health information) could be reduced by changing building stock in order to reduce exposures (e.g. improved ventilation, double glazing) to keep people cool and safe at home and work.

In the future, there are great opportunities for extending CReDo and other digital twin approaches to incorporate other hazards and in building digital twins that consider the effects of multiple hazards. Note that research will be required to characterise coincident events, i.e. when more than one extreme happens at the same time.

UKCP18 local projections offer information on a wide variety of variables including:

- Mean temperature, minimum/maximum temperature;
- Relative humidity, specific humidity, precipitation, snowfall amount, lying-snow amount;
- Wind gusts, wind speed, wind speed east/northwards components;
- Sea-level pressure, cloud cover, lightning (flash rate), radiation (net long/short waves).

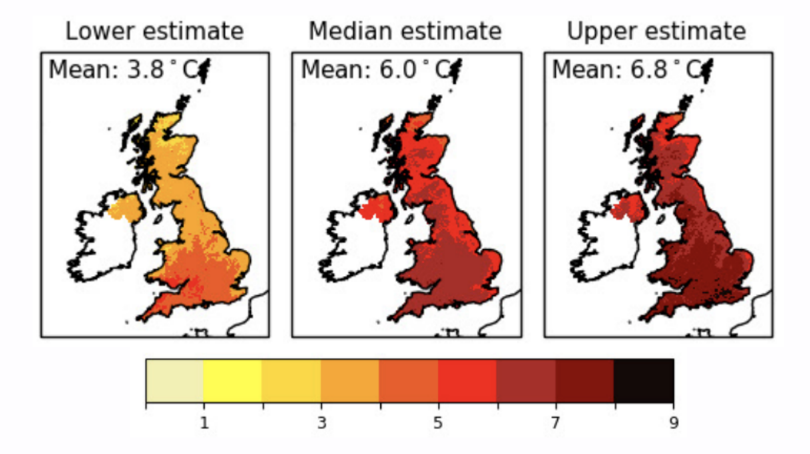


Figure 16: Projected changes (°C) in hot summer days for 2061-2080, RCP8.5

These are available a range of different temporal resolution (hourly, daily, monthly, seasonal, annual, 20- or 30-year means).

In terms of projected increases in temperatures, Figure 16 shows the projected changes in hot summer days for 2061-2080 under RCP8.5. For this highest emission scenario, warming is very likely to be in the range of 1.5 to 5.9°C and hot summers are expected to become more common. Hot summer days warm more than cold winter days and it is projected that hot summer days will warm more than the summer average with range of 3.8 to 6.8°C. Changes at a regional level can be seen in Figure 17, which shows the distributions of daily maximum temperatures for the King's Lynn area in the 1980s and the 2070s. Clear increases in maximum temperatures can be seen, notably in the summer months.

A crucial aspect in realising the full potential of the CReDo digital twin, allowing the approach to incorporate wider geographical regions, and the possibility of real-time digital twinning, is the need to speed up the transformation from the hazards (e.g., precipitation) to the specific outcome of interest. As seen in the case of flooding, the description of the hazard itself requires considering multiple strands of environmental information, from the detailed topography of the region of interest, through its fluvial, tidal and coastal characteristics, to profiles of storm events, as well as two physical models (climate model, flood model) one of which had to be run (HiPIMS). Assessing the effect of other hazards will require several steps before information from UKCP18, or other climate projections, can be incorporated within a decision-support system. Firstly, data from the climate projections will commonly need calibration, and the precise approach will be determined by the availability of measurements and the atmospheric variable under condition. Secondly, there will often be a step required to transform the UKCP18 output into a form that represents the hazard that is of interest, at the resolution that is required. Lastly, there might be a need to consider other environmental data to reach a complete definition of the hazard.

In the example developed within CReDo, it is the flood model and this transformation of the outputs of UKCP18 to flooding that provide the biggest challenge in scaling up to achieve comprehensive coverage. In the example presented in this report, surface flood modelling was only

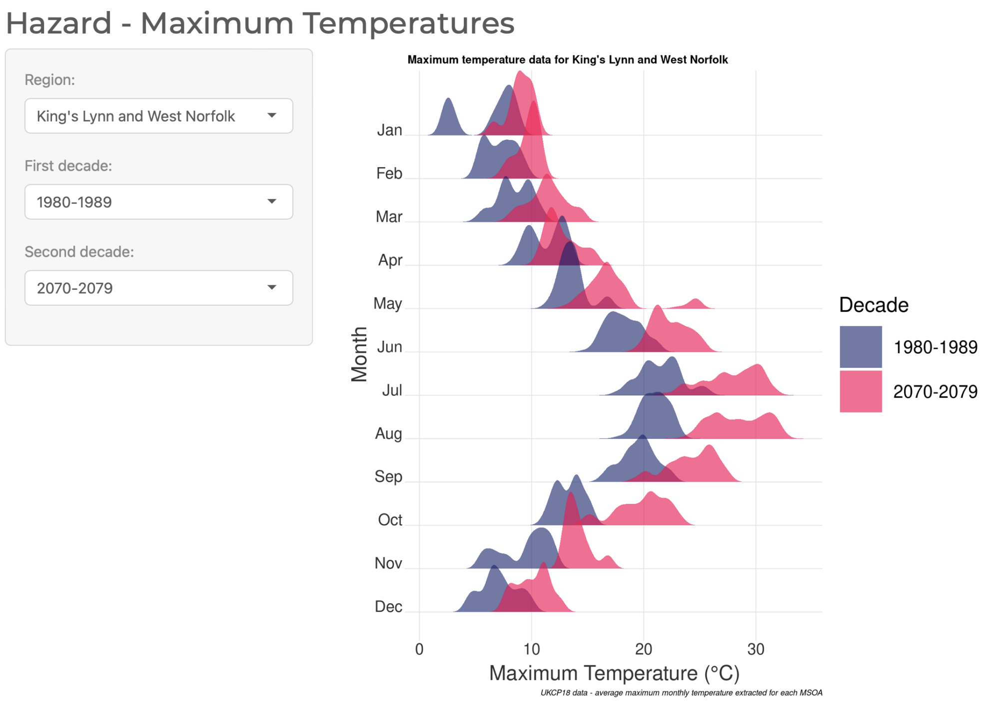


Figure 17: Projected changes in maximum temperature, by month: 1980-89 vs. 2070-2079, RCP8.5, for Norfolk.

achievable due to the small region selected. To avoid substantially increasing the computational time, or forcing a restriction to a smaller subset of runs, will require several advances to allow scaling up to larger regions.

Statistical emulators provide an attractive approach to addressing this challenge. Emulators can be used to approximate the outputs of complex physical models, trained on an ensemble of model simulations where the input parameters are varied (here, this could be the precipitation and inflows, but also other internal model parameters representing physical processes). Based on this set of runs, the emulator approximates the true model (either the full model output fields, or aspects of them), with an assessment of uncertainty on predictions, with the benefit that they are much faster to evaluate than the underlying model itself, allowing alternative configurations of the inputs to be considered (e.g., different storm events). Emulators could also be used to model the relationship between flood depth and return period at particular locations of interest (e.g., where assets are), allowing a fuller assessment of impacts and uncertainty in these critical locations.

This type of approach would offer a number of benefits, including: (i) allowing a larger set of scenarios to be produced without the computational expense of repeatedly needing to run computational expensive models, in this case HiPIMS; (ii) allowing an easier assessment of the uncertainty in the various model parameters and/or boundary conditions, capturing uncertainty in the model itself, as well as across different climate scenarios; (iii) allow users to input their own scenarios, without needing to wait a significant amount of time for the expensive model to run. As such, embedding emulators within digital twins to bypass the most computationally challenging parts of linked systems could be key in unlocking the true potential of digital twins and moving us closer to being able to use them to support real-time decision making.

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