



**21<sup>ST</sup> CENTURY DRAINAGE PROGRAMME**  
**CAPACITY ASSESSMENT FRAMEWORK**  
**PROJECT REPORT**  
**APPENDIX 6 - LITERATURE REVIEW -**  
**CLIMATE CHANGE**

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## Acronyms

CMIP	Coupled Model Intercomparison Project
DJF	December, January, February
EA	Environment Agency
FRA	Flood Risk Assessment
IPCC	International Panel on Climate Change
JJA	June, July, August
P10	Probability of occurrence of 10% for any modelled climate scenario
P50	Probability of occurrence of 50% for any modelled climate scenario
P90	Probability of occurrence of 90% for any modelled climate scenario
RCM	Regional Climate Model
TSR	Time Series Rainfall
UKCP	UK Climate Projections

## 1 Introduction

This appendix accompanies the Project Report for the Capacity Assessment Framework.

It reviews available information related to projected rainfall changes in the UK due to climate change and current methods for applying this information to urban drainage analysis. It also provides an overview of the issues that need to be considered.

The target audience for this document are expert modellers with an understanding of rainfall and drainage system analysis and therefore detailed explanation of issues is avoided where it is considered to be already understood. The references and additional information listed at the end of this document are provided should the readers wish to obtain further information.

This appendix provides an overview on the following:

- Climate change models and data sources for the UK;
- Uncertainties associated with projected rainfall climate change information;
- The limitations of climate change rainfall with respect to the requirements for urban drainage analysis;
- Other methods for determining projected change in rainfall due to climate change;
- Current guidance in the UK on climate change rainfall;
- Methods of development of urban drainage rainfall for both frequent and extreme events.

Recommendations for the development and use of climate change rainfall for the *21<sup>st</sup> Century Drainage Programme Capacity Assessment Framework* are provided in the main body of the Project Report.

## 2 UKCP09 rainfall related climate change information

The data that is currently used for climate change projections for the UK is UKCP09. The climate change model is based on three scenarios and is probabilistic. This means that the model has been run many times with perturbations made to parameters which allows an assessment to be made of the range of uncertainty for any given climate scenario and epoch (time horizon).

The UKCP09 climate change model predicts drier summers and wetter winters. Although the summers are drier, this comes about through having fewer rainfall events, but with higher rainfall intensities for the more extreme events. The model provides output for the end of the 21st century and also gives 'Control' information for the present day. Present day is assumed to be the 30 year period 1961 – 1990 for the UKCP09 runs as well as the earlier models that were produced. These two model outputs of present day and future conditions are treated as

a measure of the projected change over time rather than using the absolute values from the model outputs. This position is taken on the basis that the errors in the model should largely cancel each other out (i.e. if it over or under predicts on certain climate variables).

The climate change information is provided at a 25km scale and daily resolution. This model resolution is such that it does not capture the much smaller scale processes of convective rainfall events. Critical events for urban drainage tend to be of the order of one to four hours though both shorter and longer durations may be relevant.

Similarly the reporting of extremes is limited to the wettest day in the year. Urban drainage systems are usually designed to serve the 30 year return period event and consider the implications for conditions up to a 100 year event. UKCP09 outputs do not provide this information.

To address some of these issues a tool - the Weather Generator - was created as part of the UKCP09 outputs. This tool was trained on the UKCP09 output data. It provides rainfall information for any location at hourly intervals for a period of 30 years. It is designed to be run a number of times - usually 100 times - to obtain a probabilistic spread of results. Its main limitation is that the hourly rainfall information has the same statistical distribution of rainfall intensities as present day conditions, so in practice it is only considered to be effective at giving statistical results at the daily scale.

This means that UKCP09 climate change model information has significant limitations for urban drainage design and analysis. Outside of the considerations of accuracy described above, there are also a number of assumptions that need to be made and further processing is required to produce data for assessing climate change impact on drainage systems.

UKCP09 is the primary source of climate change information used in the UK, but there are other sources of information available for assisting in determining future rainfall characteristics, and this is addressed in the next section.

### **3 Other climate change rainfall information**

In recognition of the limitations of the rainfall resolution information in UKCP09 there has been interest in improving on this information. This section briefly details other climate change rainfall information.

#### **3.1 The CONVEX project and UKWIR guidance**

A project called CONVEX<sup>1</sup> was carried out by the Met Office with Exeter, Reading and Newcastle universities, which started in 2011. The resolution of this model is 1.5km and temporal information was provided at hourly time steps. This is effectively the same model as

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<sup>1</sup> CONVEX is a three and a half year project involving Newcastle, Exeter and Reading Universities and the UK Met Office. It brings together UK climate modelling, statistical modelling, Numerical Weather Prediction (NWP) scientists and the impacts community to work together to improve understanding of the characteristics extreme rainfall and its underlying causative processes. It aims to provide a better understanding, essential for improved model projections of extreme rainfall change under global warming. See <http://research.ncl.ac.uk/convex/>

used to give the daily and weekly forecasts. Due to the computational effort needed, only one run was carried out and this was limited to a 13 year period for the 2080s epoch. It assumed the High Emissions Scenario future state. It was also limited to England and Wales, with the English northern borders, Scotland and Northern Ireland excluded.

The CONVEX project looked at evaluating a high resolution (1.5 km) Regional Climate Model (RCM) in comparison with the coarser resolution 50km and 12km RCMs of UKCP09, with the aim of improving climate projections, particularly for extreme rainfall. The advantage of the high resolution 1.5km RCM is that convection processes can be explicitly modelled. These events are critical for urban drainage analysis.

The 25km resolution RCM which underpins the UKCP09 Weather Generator projections of future climate time series uses rainfall approximations which do not explicitly represent convective processes, and relies on 'parameterisation' to represent convective events. This means summer convective storms are poorly represented in the UKCP09 RCM. Although convection processes are modelled in CONVEX, these are complex processes and therefore just because the model includes them, it does not mean that the model is accurate in what it is predicting. It is known that there is an element of over-prediction of both extreme events and annual rainfall depths.

The high resolution model is computationally very expensive to run and the first run was made for just England and Wales. However, due to the need to have information for the whole of the UK Scotland was also run in 2016. Unfortunately, due to the time needed to make this additional run the area of Northern Ireland could not be included. The single run of the 13 year period for the 2080s is a limited output which has implications for assessment of extreme events and also prevents any assessment of the variability of future conditions in the same way that UKCP09 allows.

This highlights the need for caution in using this information even though it provides very useful information that is not available in UKCP09. Ensemble modelling and analysis of the degree of wetness of the model and the implications this has on using the output is required to increase confidence in this model before it can be trusted as the basis for assessing future rainfall uplifts for short duration rainfall.

The CONVEX output has been used by the UK Water Industry Research (UKWIR, 2015) to develop guidance on climate change design event uplift factors for rainfall for the purposes of drainage modelling. Recognising the lack of consistency in some of the results, further work is currently being carried out to provide improved guidance. This is expected to be produced in summer 2017.

In the current UKWIR project the CONVEX model results have been extracted for several locations across the UK and analysed. As the UKWIR work is on-going, actual design event uplift values are still unknown. These uplift values are expected to be higher than current guidance. In addition there is the intention to produce a time series rainfall tool.

## **3.2 IPCC 5th Assessment report and CMIP5**

In April 2016 Defra published a report (Defra, 2016) comparing the UKCP09 projections with the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate projections which are used in the International Panel on Climate Change (IPCC) 5<sup>th</sup> Assessment report. CMIP5 projections are more recent than the UKCP09 projections which use CMIP3. However, the CMIP5 projections are a global dataset and are not focussed on representing climate change in the UK specifically.

The report concludes that the UKCP09 is still fit for use for adaptation planning purposes for the UK. A key finding for drainage is that CMIP5 would appear to give slightly wetter average summer rainfall than UKCP09, although a decrease in rainfall is still projected compared to historical baseline period. However, only average summer rainfall is mentioned, changes in extreme rainfall are not discussed in the report.

## **3.3 UKCP18**

UKCP18 will be the next set of climate change projections for the UK, replacing UKCP09. This work is currently being scoped and projections will not be released until 2018. It is likely to include greater emphasis on the spatial coherence of rainfall, but although short duration rainfall with high spatial resolution is known to be needed, exactly what will be produced is still being considered. It is thought that a 2.2 km model will be used to provide a 20 or 30 year time slice for the 2100s that uses the convective model and also a 4km model is used to provide output that is less dependent on convective processes.

Although UKCP18 is not due for release until 2018, there is a need to have a consistent approach for climate change in order to make decisions on infrastructure planning and design. An important issue will be the ability to map the results for the three scenarios used for UKCP09 (and in particular the High scenario) onto the four (different) scenarios being used for UKCP18.

In general, uplifts of rainfall intensities from climate models have been of the order of 25% to 40% over a number of modelling cycles UKCP98, UKCP02, UKCP09. It is unlikely that UKCP18 will be very much different in its projections. The consequences of uplifts of 40% to rainfall events on urban drainage system performance is considerable; a 20 year event now will become a 5 year event in 80 years' time.

## **4 Non-climate model rainfall predictions of future rainfall: the Clausius Clapeyron temperature – rainfall relationship**

It is always very useful to provide alternative cross-checks on hypotheses such as rainfall change predicted by models; particularly where it is acknowledged that the complexities of representing the rainfall processes is difficult to be sure about. As climate models are believed to be much more certain in their prediction of temperature, an alternative method of prediction can be made using the Clausius Clapeyron temperature – rainfall relationship.

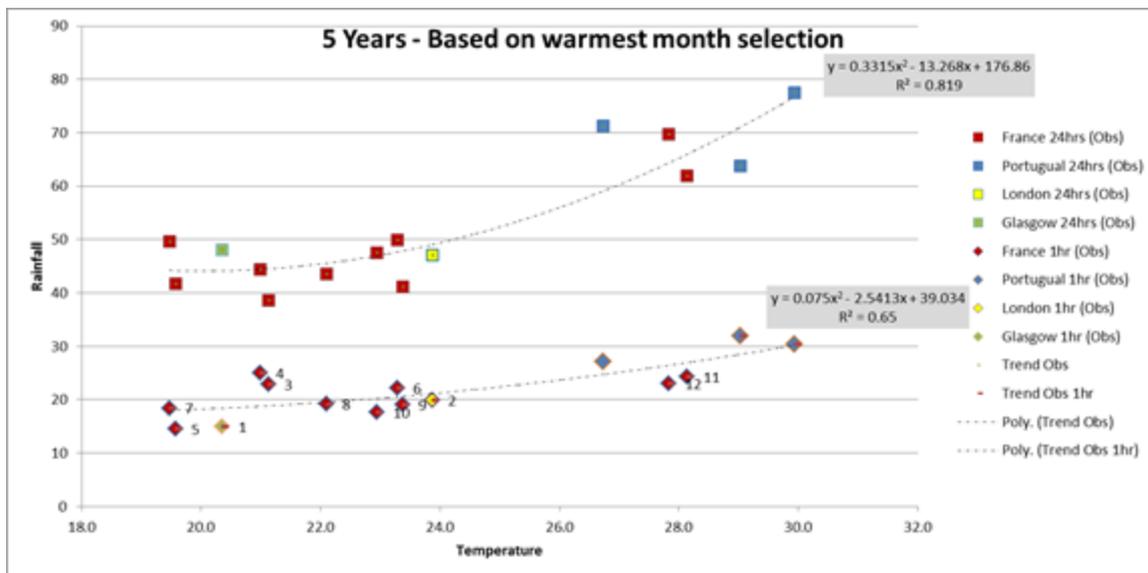
The link between warmer temperatures and more extreme rainfall relates to increased capacity of a warmer atmosphere to hold moisture and has been the subject of research. The

Clausius Clapeyron theoretical relationship has the hypothesis that for every degree Celsius increase in temperature there is an increase in rainfall intensity of 7%. This has been quite widely investigated and researchers have generally confirmed this relationship, although there is on-going debate over this relationship.

Blenkinsop et al. (2015) found that for heavy (99<sup>th</sup> percentile) summer rainfall in the UK the relationship in observed datasets is approximately 7%. Research by HR Wallingford (2013) confirmed this relationship by looking at Atlantic seaboard cities in south-western Europe. HR Wallingford also found the same relationship applied to both 1 hour rainfall and 24 hour duration events. However there have been some researchers who have come up with the suggestion that there might be a “super Clausius Clapeyron effect” where 10% or even 14% increase in rainfall for 1 degree rise in temperature may occur. Conversely, where humidity is limiting, uplift rates are found to be less than 7%. One of the findings of the CONVEX work is that there is a hypothesis that the UK future climate may have humidity limiting conditions due to the increasingly anticyclonic summer conditions that might occur, but this is largely conjecture at present (Chan et al. 2015).

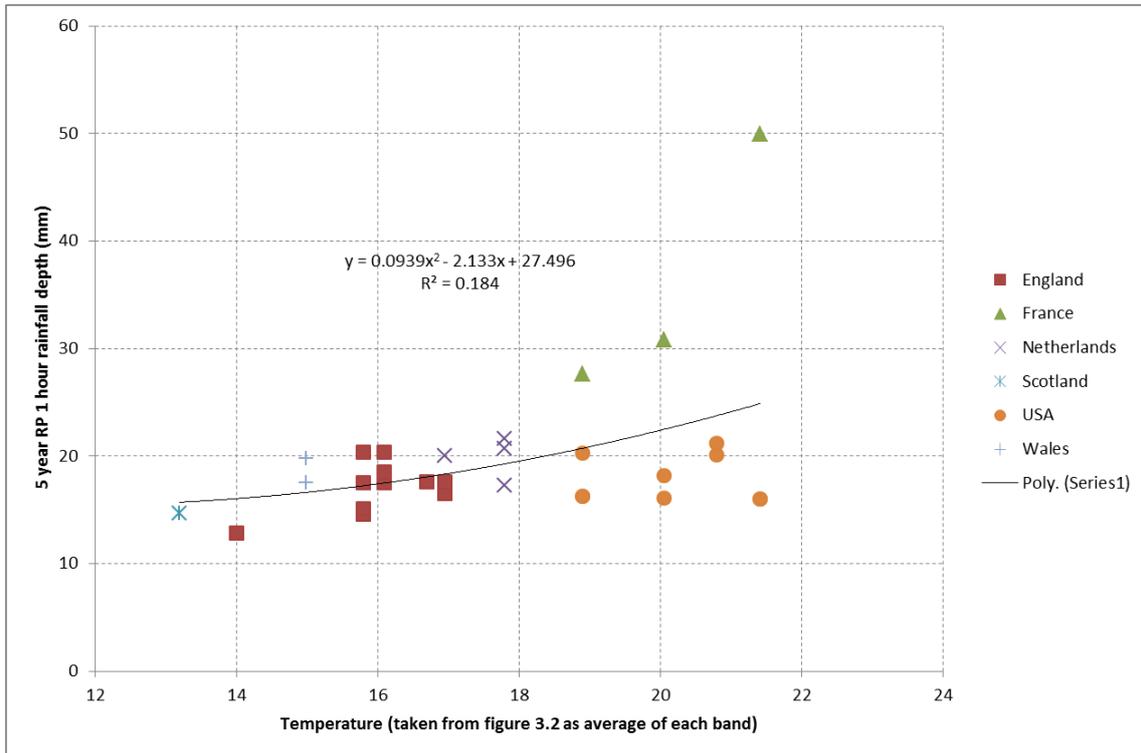
Figure 1 and Figure 2 illustrate the high degree of correlation of temperature and intensity found by the HR Wallingford analogue analysis, while Figure 2, which is based on analogue data used in the UKWIR (2015) study shows how poor correlations can result with inappropriate selection of gauges. In this case it is thought that all the American gauges are humidity limited. It is also likely that other climatic factors for these gauges are the cause for the poor correlation.

**Figure 1 Temperature rainfall correlation. Warmest month based on maximum daily values, Rainfall based on 5 year return period (1 hour and 24 hour rainfall depths)**



Source: HR Wallingford (2013)

**Figure 2 UKWIR CL10 analysis analogue gauges correlation relationship between temperature and 5 year return period 1 hour rainfall depth**



Source: HR Wallingford (2016) based on UKWIR CL10 data (2015)

Although the Clausius Clapeyron relationship is considered relatively robust, only Australia (Bates et al. 2015) is known to have formally used it in defining its guidance on rainfall uplifts and uses a 5% increase per 1°C increase in temperature. The advantage of this approach is that temperature model predictions are considered to be inherently more accurate than the modelling of rainfall. It does however assume that humidity levels are sufficiently high to allow this relationship to hold true, but if this assumption is made, it provides a good check against which to assess model outputs.

For the summer season (June, July, August) a comparison with a temperature-based scaling approach has been carried out by HR Wallingford using UKCP09 information applying a 7% rainfall increase per degree for the 2030s and 2080s Medium and High scenarios (for the UKCP09 cell 1625) in the south east of England. This is shown in Table 1. This shows that a temperature based uplift tends to give higher values than the rainfall information derived directly from UKCP09. It also illustrates the large differences between P50 and P90 predictions, which creates difficulties for decision-making if a risk-based approach is taken on the possible range of future climate.

**Table 1 Summary of climate change projections for JJA mean temperature and corresponding changes in rainfall depth based on 7% increase in rainfall per degree in temperature**

	<b>50th percentile temperature increase (°C)</b>	<b>90th percentile temperature increase (°C)</b>	<b>50th percentile rainfall increase (based on 7% per 1°C) (%)</b>	<b>90th percentile rainfall increase (based on 7% per 1°C) (%)</b>
2030s medium emissions	2.0	3.5	15 %	26 %
2030s high emissions	2.1	3.5	15 %	27 %
2080s medium emissions	4.0	6.5	31 %	56 %
2080s high emissions	5.0	8.2	40 %	74 %

*Source: UKCP09 sampled data (from UKCP09 archive)*

## **5 Uncertainties on projected rainfall change due to climate change**

Uncertainties on the accuracy of climate models should be considered as a separate and distinct issue from the range of uncertainty associated with the future.

When considering the accuracy of climate models, it is important to recognise that not only are there generic processes that need to be represented accurately, but many relationships are based on approximations or are empirically derived from observed information. In the case of rainfall for urban drainage analysis, the issue of not analysing convective processes (which really require a resolution of the order of 1.0 km<sup>2</sup> and temporal resolution which is preferably less than 15 minutes to be accurate) means that current models are unable able to predict these conditions properly due to the computational effort required. Model developers recognise these limitations and provide warnings on inappropriate use of model information. Even where rainfall or other parameters are considered to be more appropriately represented (non-convective events) there is still an issue of accuracy to consider.

There are four actions that can be taken to assess this to some degree. These are:

1. Assess the control data against observed data;
2. Use an alternative method to check on the predicted differences in the results;
3. Look at the absolute predictions as well as the differences between present and future to see what the difference in predicted future conditions might be.

4. Where there are models that are considered to be equally robust and accurate, the differences in the predicted absolute values of the projected future for the relevant parameters can provide an indication of uncertainty.

The first and third points are related. The second point might have a number of options, though the Clausius Clapeyron method (discussed in Section 7.1.3) is the only one known (to the author) that provides a way of arriving at a cross-check based on a completely different set of data. There is no way that the issue of uncertainty on extremes and temporal resolution can be examined by looking at climate change model data, but the degree of extrapolation and the validity of assumptions used can be assessed.

In summary, it is very difficult to assess the accuracy of climate models. Although work in this area has been carried out, it is not proposed to carry out a quantitative evaluation of uncertainty in this project of climate model accuracy for assisting in understanding the range of possible future conditions. A simple approach of using 30% sensitivity testing on the projected most likely change is considered to be sufficient in providing an indication of future uncertainty.

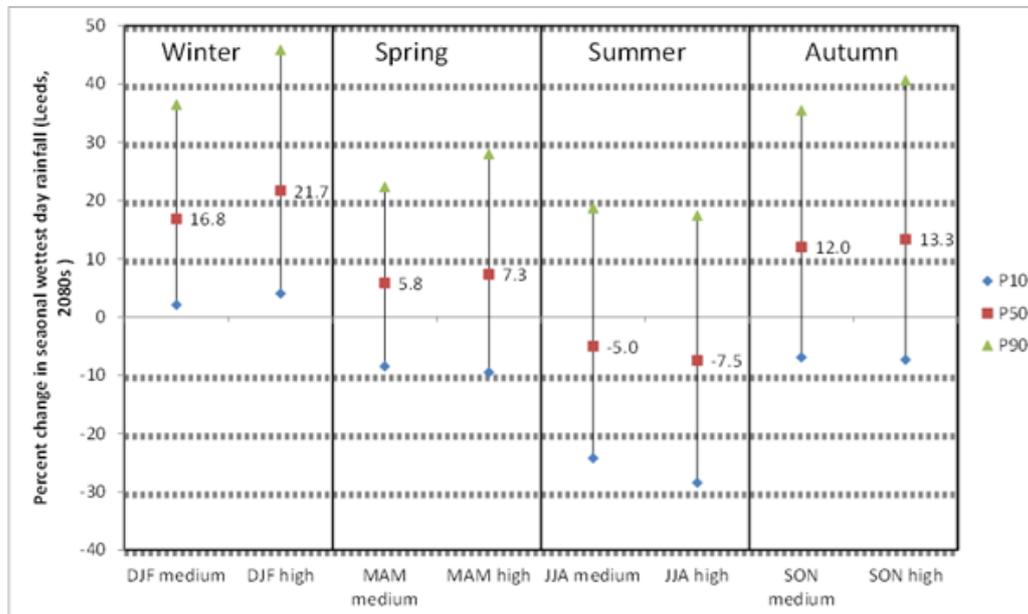
## **5.1 Future scenarios and probabilistic ranges**

The fact that there are three emissions scenarios of High, Medium and Low would seem to imply that the differences between them are likely to be large compared to the range of uncertainty within each scenario. In fact the contrary is true. Figure 3 and Figure 4 from an HR Wallingford project for Yorkshire Water (HR Wallingford, 2012) show the projected change for a location in the UK based on the mean and seasonal ranges (P10, P50, P90) for each scenario. These shows that differences in projections depending on scenario are quite small while the ranges across a scenario are large.

It can be seen from Figure 3 and Figure 4 that the P10 – P90 range can be up to a 50% different in the projection of change. The differences between the P50s of the two scenarios - Medium and High - often appear to be minimal. It can also be seen that there are considerable differences between the changes in seasonal total rainfall depths and the extremes of the wettest day; both in terms of ranges and the mean predictions. It can be seen that extreme events are always wetter in the predicted change than the total change in total depths. This is an important aspect which needs to be captured in any methodology for developing climate change rainfall data for modelling analysis, as the performance of drainage systems to extreme rainfall conditions is usually what needs to be assessed.

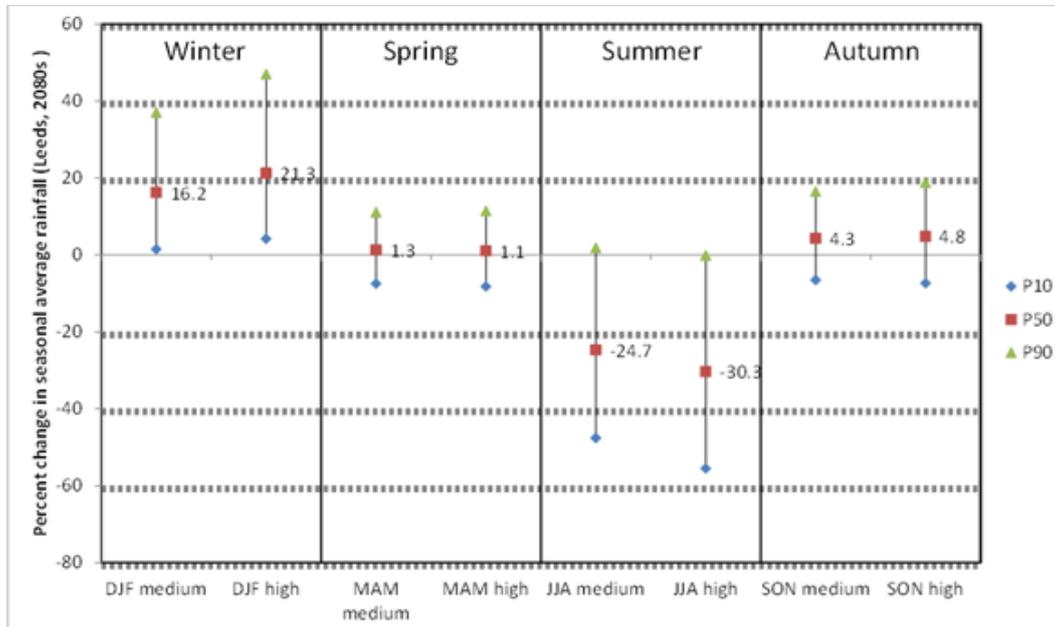
The conclusion that can be drawn from this is that use of the High scenario should probably be considered as the precautionary position without incurring a significant cost implication over using the Medium scenario, but the choice of P50 or P90 as part of a risk assessment process is a much more significant decision.

**Figure 3 Comparison of changes in wettest day of the season rainfall for the Leeds grid cell, 2080s for medium and high emissions scenarios**



Source: HR Wallingford 2012. Courtesy of Yorkshire Water

**Figure 4 Comparison of changes in seasonal rainfall for the Leeds grid cell, 2080s for medium and high emissions scenarios**



Source: HR Wallingford 2012. Courtesy of Yorkshire Water

## 6 National guidance on climate change rainfall

There is no consensus on climate change rainfall uplifts for design events or methods for creating TSR data. The following is a summary of the different guidance that currently exists in the UK.

### 6.1 Environment Agency guidance for flood risk assessment

The Environment Agency (EA) has produced guidelines for peak rainfall intensity climate change allowances (EA, 2016 and EA, 2011) for Flood Risk Assessment (FRA) which is primarily aimed for use by the development community, but is also applicable to government projects. These factors are used for planning control purposes as precautionary allowances for FRAs. These factors are heavily caveated in the covering report (EA, 2011), which notes that “Developing quantitative predictions of future changes for such extreme rainfall at the local scale remains a key challenge for climate scientists”. The factors are advised for return periods greater than 5 years, as a precautionary position, while direct analysis of UKCP09 outputs are recommended for more frequent events. It also notes that the information and estimates are based on daily rainfall models, as the climate models outputs do not provide shorter duration information even though the models use a sub-daily time step in carrying out the analysis.

The current guidance is summarised in Table 2, which mirrors the general view that a probabilistic approach should be used when assessing climate change impact. It remains to be seen how this advice is applied in practice by the planning community.

**Table 2 Environment Agency guidance on climate change uplifts for rainfall (England only)**

	<b>Total potential change anticipated for '2020s' (2015-39)</b>	<b>Total potential change anticipated for '2050s' (2040-2069)</b>	<b>Total potential change anticipated for the '2080s' (2070-2115)</b>
Upper estimate	10%	20%	40%
Central estimate	5%	10%	20%

*Source: Environment Agency (2016)*

### 6.2 The CONVEX project and UKWIR guidance

The CL10 UKWIR analysis (2015) (the third time UKWIR has looked at climate change in the context of its impact on sewerage systems in 15 years) is based on the CONVEX model and varied quite significantly with return period, duration and location in the country. This information is produced here for completeness as it will soon be superseded by the latest CL10 study due out in summer 2017.

The guidance, which was issued in 2015 along with the project analysis report, modified these outputs and removed the relationship with return period and smoothed some of the results for the four locations selected. To avoid confusion by reporting all of the uplift factors, only

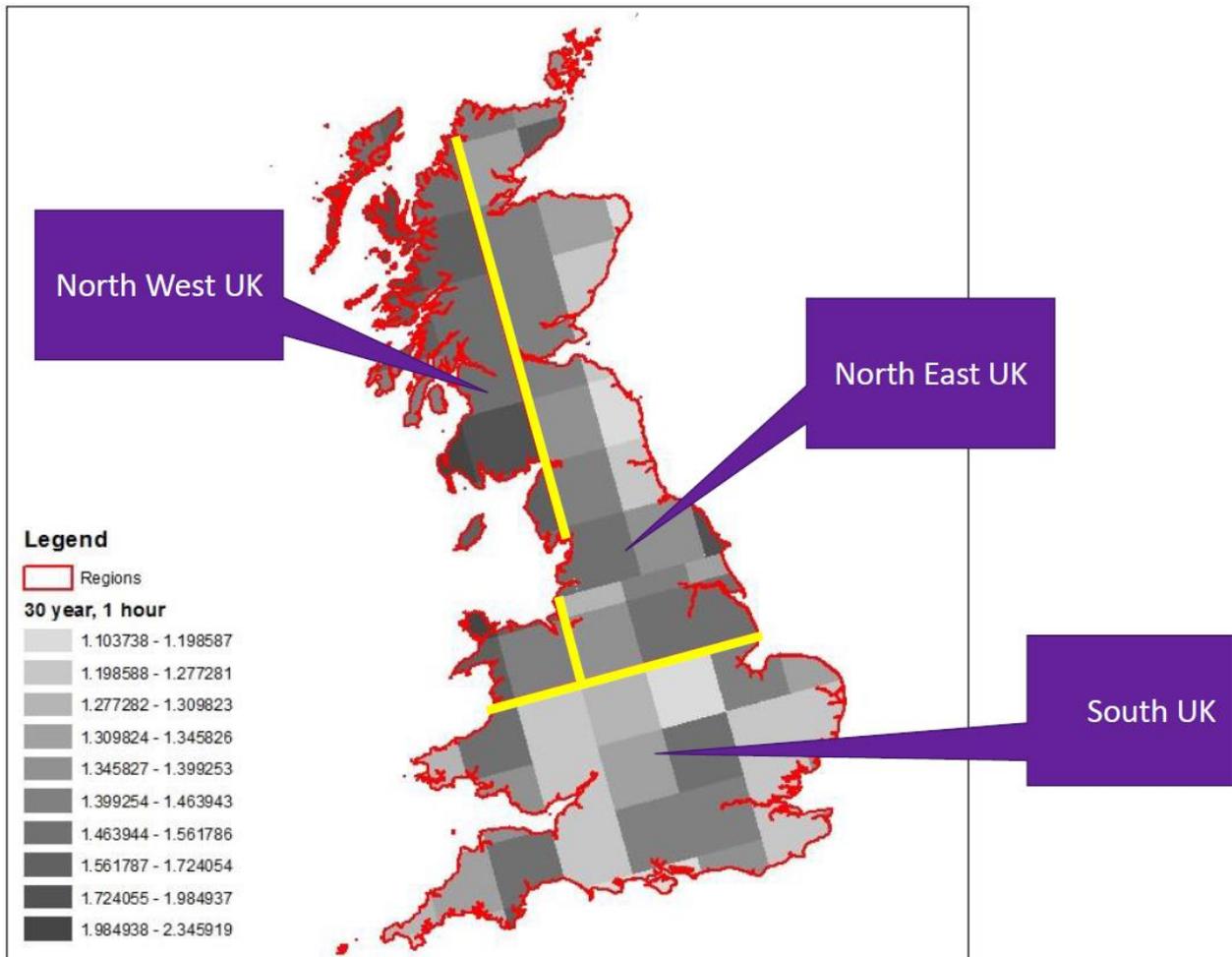
two values are used for the comparison in the next section of climate change uplifts provided by various guidance. The CONVEX model results were extracted for several locations across the UK and averaged. The 1 hour duration 2 year return period, and 6 hour 30 year return period factors are reported, as these provide an envelope for the range of growth factors suggested (2 year 1 hour being the smallest, and 30 year 6 hour being the largest).

The 2 and 30 year return periods are plotted in Figure 6 and Figure 7. As the CONVEX simulation only ran for 13 years, the estimates of 30 year return period are effectively extrapolated well beyond that normally applied when carrying out statistical analysis of a data set of only 13 years. As there is a substantial increase in the projected uplift factor associated with the higher return periods, this needs to be treated with caution; both because of the extrapolation of the data and the fact that there is limited support elsewhere for such a rapid growth in the uplift factor with return period. Because of this uncertainty, the 2 year return period is considered to be far more robust as an indication of the climate change factor than the higher return periods.

The fourth UKWIR CL10 analysis, which is due for completion in summer 2017, has carried out the analysis on uplift factors for design storms. It has provided a central and higher estimates based on a comparison of uplifts for grouped cells across the whole country. As a result of the analysis, a recommendation has been made to divide the country into three regions; each with their own central and higher estimates. Figure 5 shows the three regions.

As the report has not been issued yet, the actual recommendations associated with the analysis are not given here, but in general terms it can be stated that the higher estimates are considerably greater than the recommendations made in this statement, but the central estimates are broadly in alignment.

**Figure 5 Climate change factors derived from CONVEX analysis (2017), UKWIR project CL10 – courtesy of CH2M**



### 6.3 UKCP09 wettest day of the season

UKCP09 data are widely used for UK climate projections. One of the rainfall indicators that is most commonly quoted is that of the ‘wettest day of the season’. It is defined as the 99th percentile of daily maximum precipitation on a seasonal basis. Assuming each season is 100 days long, the 99th percentile roughly corresponds to 1 day per season<sup>2</sup>.

Although the indicator is targeted towards heavy rainfall events (one per season), it does not specifically address events that typically form design criteria for drainage such as the 30 year return period. The change in wettest day of the season for summer (JJA) and winter (DJF) have been extracted from UKCP09 for cell 1625 in the south-east of England for comparison purposes (see Figure 7).

<sup>2</sup>UKCP09 website <http://ukclimateprojections.metoffice.gov.uk/23134> accessed 1 July 2016

## 6.4 Comparison of climate change uplift factors

Table 3 compares the various sources of information on climate change for storm rainfall.

Figure 6 presents climate change factors from:

- The EA guidance (EA, 2016),
- The UKWIR project using the CONVEX modelling (UKWIR, 2015) and
- A temperature scaling approach using Clausius Clapeyron.

Figure 7 presents climate change factors derived from UKCP09 'wettest day of the season' indicator for summer (JJA) and winter (DJF) rainfall. These have been plotted separately to ensure legibility of the figures and also because the UKCP09 wettest day indicator is not considered particularly relevant for low frequency short duration storms.

The EA and UKCP09 based factors consist of a central and an upper estimate, with upper estimates shown as dashes. The CONVEX derived factors are only provided as a single central estimate (which is based on the High scenario).

Figure 6 shows that uplift factors are typically between 5% and 15% for the 2030s with upper bound estimates at around 25% for both Medium and High emissions scenarios. For the 2080s the uplift factors range from 20% to 45%, with upper bound estimates at over 70%. These high values are derived from temperature scaling, and with the very high temperatures projected, this provides a warning that the climate models may be under-predicting future rainfall conditions.

Figure 7, which shows information on the wettest day, shows the opposing trend in projections between summer and winter heavy rainfall in UKCP09. Winter rainfall is projected to increase over time and with increasing emissions. However, summer heavy rainfall is shown to decrease over time and with higher emissions, which would seem to disagree with the evidence in Figure 6. However if the P90 values are evaluated the summer events do still show positive rather than negative factors.

UKCP09 indicates drier summers on average, and this appears to be reflected in the changes in heavy rainfall in summer. However, the reductions in seasonal average rainfall are greater than the reductions in heavy rainfall, for example at the P50 level for 2080s High emissions, the reduction in average rainfall is ~30% while the reduction in heavy rainfall is ~10%, indicating more of the rainfall is falling in heavy events. Based on the UKCP09 sampled data it is difficult to comment on more extreme rainfall than wettest day of the season. As pointed out previously the low 25km resolution RCM used in UKCP09 is unable to represent convection events and therefore the results for intense rainfall in summer are not considered to be particularly reliable.

**Table 3 Summary of the information sources used in the comparison between climate change factors**

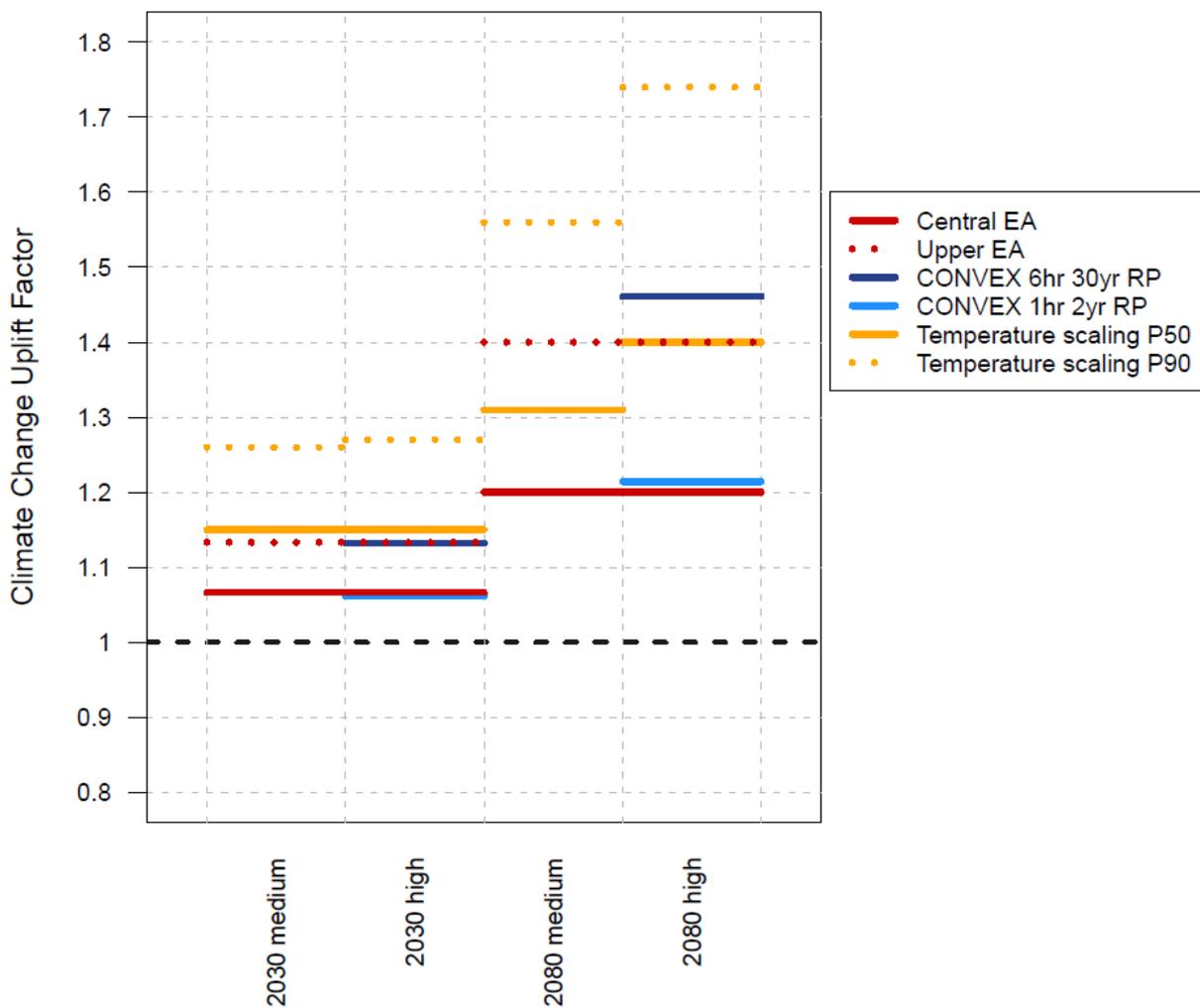
	<b>EA climate change factors</b>	<b>UKWIR CONVEX factors</b>	<b>Temperature scaling</b>	<b>JJA Wettest day of the season</b>	<b>DJF Wettest day of the season</b>
<b>Baseline Period</b>	1961-1990	1996-2009	1961-1990	1961-1990	1961-1990
<b>Future period<sup>3</sup></b>	2030s and 2080s	2100, scaled back linearly to 2030s and 2080s	2030s and 2080s	2030s and 2080s	2030s and 2080s
<b>Geographical Range</b>	Small and Urban Catchments across all of England	England and Wales	South-east England (UKCP09 Cell 1625)	South-east England (UKCP09 Cell 1625)	South-east England (UKCP09 Cell 1625)
<b>Return Period</b>	Unspecified	2, and 30 years to give the total envelope of factors	N/A	Wettest day of the season	Wettest day of the season
<b>Season</b>	Annual	Annual	JJA	JJA	DJF
<b>Emission Scenario</b>	Unspecified	RCP <sup>4</sup> 8.5 (High emissions CMIP5)	UKCP09 Medium and High	UKCP09 Medium and High	UKCP09 Medium and High
<b>Baseline Period</b>	1961-1990	1996-2009	1961-1990	1961-1990	1961-1990

<sup>3</sup> UKCP09 data refers to time periods of 30 years for control and future modelled climate. For example, the '2030s' refers to the period 2020-2049, with a mid-point in 2025. These 30 year epochs are used to allow the calculation of change factors between baseline and future periods removing natural variability between individual years.

<sup>4</sup> For further information on the IPCC CMIP5 Representative Concentration Pathways see [http://sedac.ipcc-data.org/ddc/ar5\\_scenario\\_process/RCPs.html](http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html)

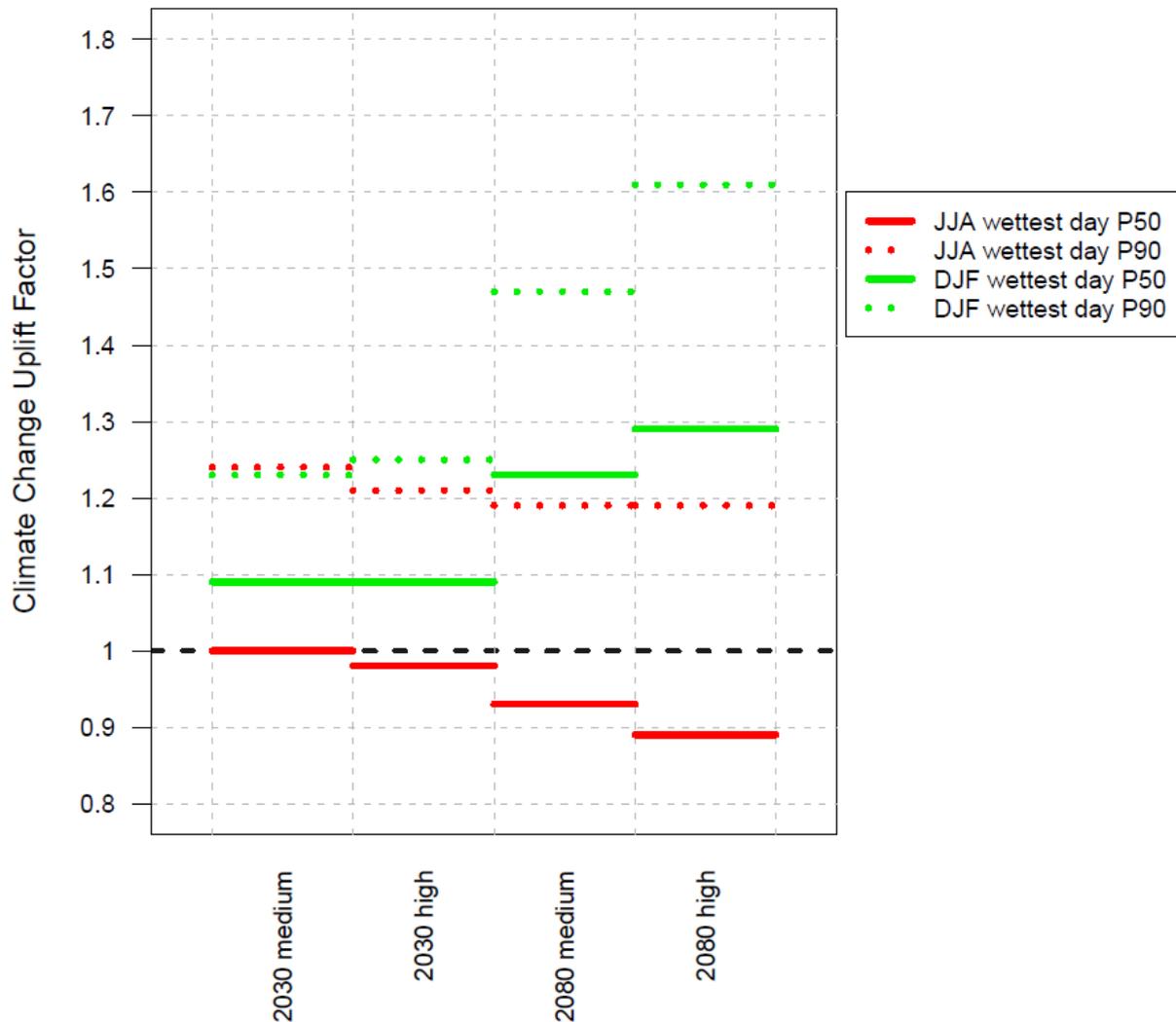
	EA climate change factors	UKWIR CONVEX factors	Temperature scaling	JJA Wettest day of the season	DJF Wettest day of the season
Future period <sup>5</sup>	2030s and 2080s	2100, scaled back linearly to 2030s and 2080s	2030s and 2080s	2030s and 2080s	2030s and 2080s

**Figure 6 Climate change factors derived from the EA guidance (EA, 2016), UKWIR project using the CONVEX modelling (UKWIR, 2015) and a temperature scaling approach (2030s, 2080s, Medium and High emissions scenarios)**



<sup>5</sup> UKCP09 data refers to time periods of 30 years for control and future modelled climate. For example, the '2030s' refers to the period 2020-2049, with a mid-point in 2025. These 30 year epochs are used to allow the calculation of change factors between baseline and future periods removing natural variability between individual years.

**Figure 7 Climate change factors derived from UKCP09 ‘wettest day of the season’ indicator for summer (JJA) and winter (DJF) rainfall (2030s, 2080s, Medium and High emissions scenarios)**



## 7 Methodology for developing climate change rainfall data

The approach to assessing design storm uplifts compared to time series rainfall is different as in the latter case there is the need to capture total rainfall depths, number of events and also extreme intensities. In the case of design storms the approach is much simpler and uses a standard approach to extreme value analysis.

As there are two different sources of information (UKCP09 and CONVEX) each with their own limitations, careful use of the data and comparison of results from both sources will help in establishing an understanding of the robustness of the method.

It is also possible to make a cross-check against a temperature based approach, depending on the weight that is attributed to the Clausius Clapeyron rule.

All three methods of assessment could be used to provide a comparison of the three approaches.

## **7.1 Design events**

Design events are, by definition, extreme events. It is important to note that these are annual rainfall return period depths, but need to take into account the fact that both summer and winter profiles are used. The increase in rainfall intensity/depth in summer due to climate change may not be the same as in winter. Therefore design storm uplifts should be based on an analysis of climate model seasonal data.

The main concern with design storm event uplifts is the uncertainty associated with modelling the complex processes of rainfall and insufficient length of data to provide an assessment of frequencies up to the 30 year event.

### **7.1.1 Method based on CONVEX**

Access to CONVEX is limited to those organisations that the Met office are prepared to give access to the data. Comments on the use of CONVEX made here therefore presume that access to data is available. Also, this section is, to some extent, redundant as the UKWIR project has carried out this analysis.

As CONVEX data is based on hourly information the 13 years of data can be used by extracting hourly and multiples of hourly durations for seasonal and annual maximum depths, or 'Peaks-over-threshold' approach. Due to the stochastic nature of the model, more than one cell in the region needs to be interrogated to provide an indication of the variability of the model predictions and to obtain a mean uplift value.

An extreme value curve fitting exercise should be carried out for both the control data and the 2080s. Differences between the control and future state for each spatial cell should be made for the 2 year and 5 year event. More extreme projections of the curve are not robust when using only 13 years of data. Where there is a clear trend with return period it is possible to extrapolate the results to say 10 years, but it should be recognised that extrapolation to longer return periods should only be considered to be indicative.

Analysis of summer, winter and all year should be carried out. Where there is a marked difference between the seasons, then different uplifts can be proposed. The variability of the uplifts across all cells can be used as an indication of the probabilistic range, providing an indication of climate variability.

The extreme value analysis should be carried out for several durations ranging from 1 hour to 24 hours. Although there may be a trend in the results, it is expected that spatial variability will be greater than a trend with event duration. This has been found to be the case by the current CL10 UKWIR project.

The CONVEX model control run was based on 20 years for the period 1989 – 2008. Interpolation for other epochs would use the periods of 2000 and 2100 for providing the start

and end points for estimating the uplift factor. This could be based simply as a linear function of time or use predicted temperature change.

### 7.1.2 Method based on UKCP09

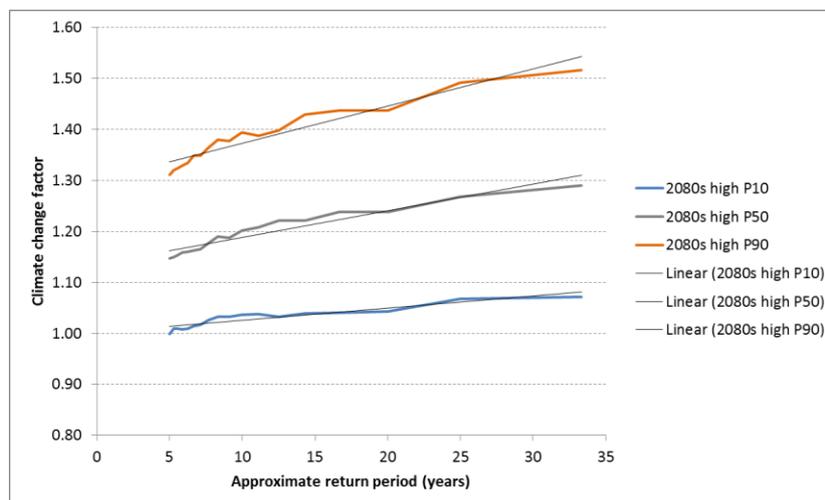
UKCP09 has to assume that the uplift(s) derived from daily rainfall analysis is applicable to all sub-daily durations. This is because the Weather Generator has been shown that it does not capture climate effects in the hourly information. Even at the daily scale there has to be a degree of caution about the predictions as convective processes are still relevant at the daily scale and the climate model is only approximating to the hydrological processes.

In principle, the approach is very similar to that for the CONVEX analysis except that instead of hourly data used to consider a number of different durations, daily data is used. The advantage of the Weather Generator is that it produces 30 years of information for each run. This means that the extreme value analysis can be extended to look at the 10 year return period for assessing trends in the frequency of rare events.

In the same way that 100 cells might be used to provide an indication of the possible range of uplift values, the Weather Generator can be run 100 times to provide a way of obtaining the P10, P50 and P90 uplift values.

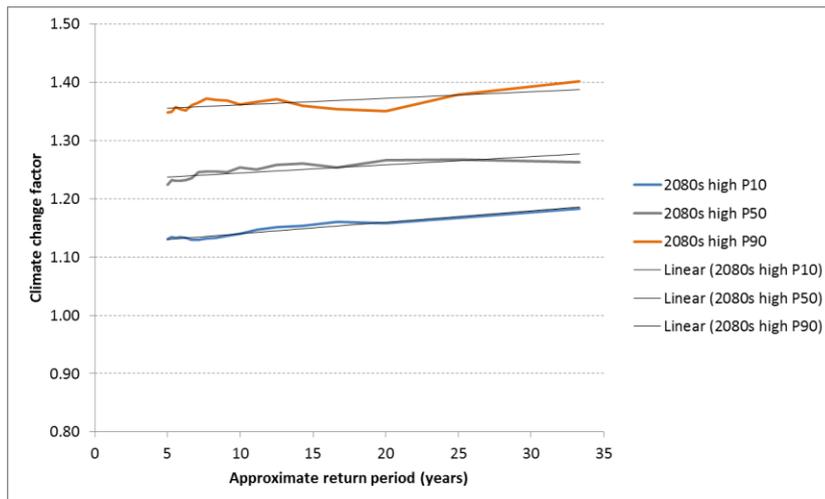
Figure 8 and Figure 9 illustrate the results from a study carried out by HR Wallingford for Yorkshire Water. It can be seen that the summer data appears to give a steeper trend line with return period for design storm uplifts than winter, but that the respective values of the uplifts for both seasons are fairly similar.

**Figure 8 Changes in extreme rainfall depth, 2080s high emissions, summer**



Source: [\\hrw-uk.local\mar5027\\$\Work\Phase 3\Alternative CC factors\Alternative Extreme value analysis\Alternative Extreme value factors summary.xlsx](#) – courtesy of Yorkshire Water

**Figure 9 Changes in extreme rainfall depth, 2080s high emissions, winter**



Source: [\\hrw-uk.local\mar5027\\$\Work\Phase 3\Alternative CC factors\Alternative Extreme value analysis\Alternative Extreme value factors summary.xlsx](#) – courtesy of Yorkshire Water

As with the CONVEX data, the analysis should be carried out for summer and winter seasons as well as all year.

Because CONVEX and UKCP09 models are based on the same scenarios with the same target epoch, it is extremely useful to make an assessment of these uplifts using both methods to see how similar the predictions are. If there is a significant difference there might be a preference to use the CONVEX information due to its convection modelling. However, as it is known to be a ‘wet’ model and over-predicts extreme rainfall depths, a degree of caution should be applied to both sets of results obtained.

### 7.1.3 Method based on Clausius Clapeyron

The advantage of using the Clausius Clapeyron approach is that the climate model is believed to be far more robust for estimating the change in temperature. However there are two main points of caution in using this approach for generating rainfall uplifts:

- The assumption that the 7% per degree rule is an accurate relationship and applies to the UK of the future; and
- This rule holds true for different seasons, rainfall durations and return periods.

The approach taken is exactly the same as for the use of UKCP09 rainfall data in assessing the change in temperature for the year and the seasons. The analysis can be made for different return periods of temperature change but also the mean monthly change. This information can be compared to assess whether there is a trend with return period. The uplift factor would then be calculated as:

$$\text{Uplift} = 1.07^T$$

where T is the change in temperature between the Control and 2100.

## 7.2 Time Series Rainfall events

Time series data has a number of difficulties in addition to those discussed for design events. These include:

- The number, duration and intensities of all events needs to be correctly developed for the future series;
- A median (P50) year is unlikely to have a median summer or winter period. Similarly a P90 year or set of years will not comprise a set of P90 seasons, as this would constitute a more extreme probability condition than a P90 set of years.

Theoretically the output from a cell for the 13 year period of the CONVEX could be used as hourly information, which could then be disaggregated to provide 5 minute information. However 30 years of daily information is not advised for disaggregating to 5 minute data, so CONVEX information has a distinct advantage over the UKCP09 data for doing this. But on the basis that the view that has always been taken is that the difference between the control and the epoch data should be preferred, then the use of the absolute values for carrying out this disaggregation is not recommended.

Because the UKCP09 method is based on daily data, the suggested approach is described first, and then the refinement (and limitations) of the CONVEX approach is detailed.

As with the design events uplift, there is the opportunity for the Clausius Clapeyron rule to be applied, but this should only be made as a check for the predicted change for extreme events.

### 7.2.1 Method based on UKCP09

As with the design event analysis, 100 runs of the Weather Generator can be used. Instead of doing an extreme value analysis on annual maximum depths, factors are derived for the differences in ranked daily depths for all 30 years and plotted on a frequency curve. This is done 100 times and an envelope of rainfall depth factors is produced. From this a mean curve can be produced for P50 (as well as P90 and P10).

However, it is known that winters are projected to get wetter and summers drier, so if this is done on a whole year basis this curve would average out the seasonal changes and provide an incorrect interpretation of the rainfall depth changes through the year. To address this the analysis can be carried out for each of 12 months or the four seasons. This should capture the climate changes accurately.

Selecting the median curve from this is statistically fairly robust, but selecting the four seasons of P90 curves is, theoretically, a more extreme frequency than P90 for the whole year, unless each season is considered to be independent in its impact on the analysis being made. This may be a reasonable assumption; for instance an analysis of Bathing Beaches may not be unreasonable using this approach. However assessment of total spill volumes in the year would probably not be considered appropriate. To carry out an analysis as to what would

constitute P90 from four seasons (say P75 for each season) would require too many assumptions and not worth discussing further here. The view taken is that P90 is such a significant increase over the P50 curve that the more extreme results might be put down to being a precautionary approach.

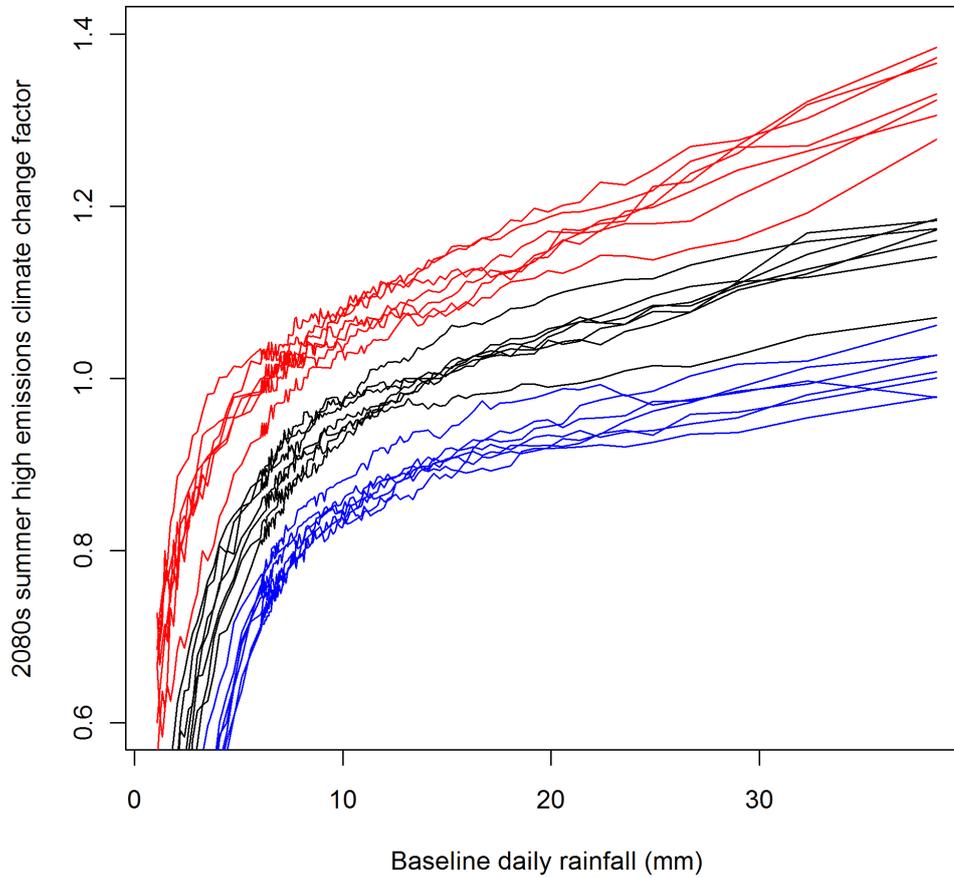
Figure 10 illustrates a typical set of summer curves produced for a summer analysis for 7 locations across Yorkshire, and Figure 11 a similar set of winter curves.

Figure 10 shows that the largest daily events are more extreme in the future, while there are fewer events in summer. Subsequently using this curve to factor a present day series based on ranking of daily rainfall depths results in factoring small events from present day rainfall with a value of zero, thus removing them from the series. This approach therefore preserves both the volumetric effects of total rainfall depth, the number of events and the rainfall intensity. The only thing that is not explicitly captured (and cannot be) is any change in the duration of different types of events.

As an existing time series can be generated for a 100 year series, this curve can be applied to the whole series. The upper end of the factoring curve will need to be extrapolated and checking that the maximum uplift of the largest event is not significantly more than the equivalent Clausius Clapeyron derived uplift factor.

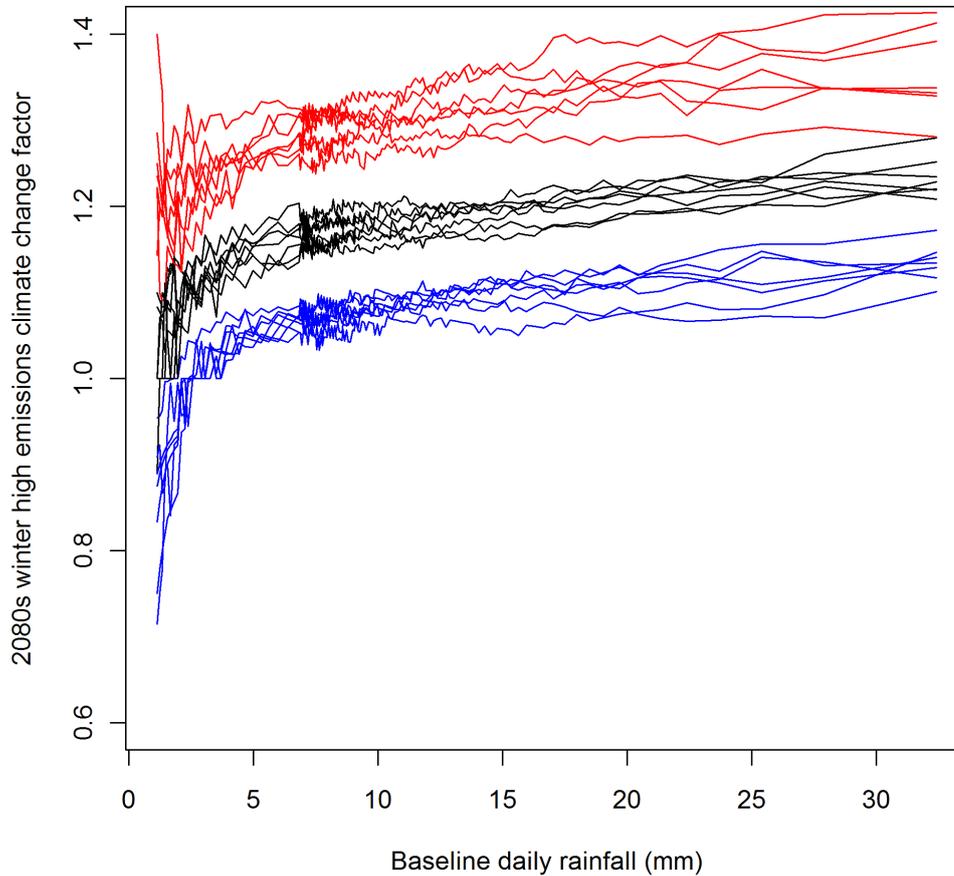
However there can be difficulties with the analysis for winter data. Instead of the curve tending to zero for small events, the P90 curve can show an increase in factor tending to infinity for the smallest events. What this means is that there are a few more events in the future than at present. Creation of extra events is not practical (although some methods recommend this approach). In practice the number and size of these events are sufficiently small that they can probably be ignored. An assessment can be made of how many events are missing in an average year and a decision can be made as to whether the result of the smallest event in the series should be assumed to take place a number of additional times when an analysis of a system is made with the series.

**Figure 10 Climate change factors for 2080s high emissions, summer for seven locations across Yorkshire and three levels of uncertainty 10th, 50th and 90th percentiles**



*Source: \\hrw-uk.local\mar5027\$\Work\Phase 3\Climate change factors\Comparison across sites v2.xlsx – courtesy of Yorkshire Water*

**Figure 11 Climate change factors for 2080s high emissions, winter for seven locations across Yorkshire and three levels of uncertainty 10th, 50th and 90th percentiles**



*Source: \\hrw-uk.local\mar5027\$\Work\Phase 3\Climate change factors\Comparison across sites v2.xlsx – courtesy of Yorkshire Water*

### **7.2.1.1 Short duration extreme events**

However carrying out this approach on factoring all events based on total rainfall each day, does not address the fact that short high intensity events will be treated as relatively small events and therefore always factored by a value less than 1.0 (for summer series). As the summer curve is far more pronounced than in winter, this assumption is inappropriate. Although the curve is derived using daily data, if one makes the assumption that it is true for any duration (large events are more extreme than at present), then a refinement can be made to process the present day time series into a range of durations based on their return period and then apply this curve factor to each set of events. Because the method does not exactly replicate the derivation of the curve in the first instance, there will be some repercussions on preservation of total rainfall depth, but it is not thought to be particularly significant.

## 7.2.2 Method based on CONVEX

The limitations of the UKCP09 method due to working with daily data can be addressed by carrying out the analysis based on the duration of storms and repeating the analysis in three or four groups of durations between 1 hour and 24 hour. The limitation of the 13 years means that the extreme event part of the uplift curve has to be extrapolated further, but a sense check can be made. Also there is the cross-check of comparing the curves for the four different durations.

As for the design storm method, it would be appropriate to carry out a factoring curve analysis for at least 10 spatially distributed cells for the region of interest. A probabilistic approach of using 100 cells is again an option for deriving P10 and P90 data though the same assumptions on independence between seasons apply.

## 8 Conclusions

It is important to note the following key aspects of climate change:

- Recognise that the predictions for change in the climate are uncertain, but that there is projected to be a significant shift in hydrological characteristics, particularly in summer.
- Models do not provide outputs that address the need for sub-hourly rainfall for urban drainage analysis. The creation of time series and design storm uplifts requires a number of assumptions and methods to be used to enable suitable rainfall data to be developed.
- Interpolation of the impact of design storms can be made from predicted uplifts for the end of the century. However interpolation of model results for intermediate epochs could be carried out on a seasonal basis, but it is probably best to create individual time series data sets for any epoch of interest.
- Climate change allowances used in this Framework and the methods of deriving the data sets will need revisiting when the UKWIR CL10 report comes out in summer 2017 and again in 2018 when UKCP18 becomes available.

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