Are you prepared for future rainfall? Results from the UKWIR rainfall intensity project.

Dale M.[1], Gill E.J.[2] Kendon, E.J[3], Fowler, H.J.[4]

[1] JBA Consulting, Exeter (formerly of CH2M)

[2] CH2M, Swindon

[3] Met Office Hadley Centre

[4] Newcastle University

ABSTRACT

Urban flooding and wet weather pollution are recognised as significant problems across the world, and changes in rainfall patterns due to climate change are likely to exacerbate these problems unless sewer systems adapt. This paper reports on a research project led by CH2M for UK Water Industry Research that has made use of very high resolution (1.5km) climate model output to derive change estimates for design rainfall and to develop a perturbation tool that allows time series rainfall data to be adjusted to reflect future rainfall intensities and patterns. Estimates of rainfall change have been used within sewer models to estimate the flooding and pollution impact of these changes.

KEYWORDS

Climate change, Flooding, Resilience, Rainfall, Urban drainage

INTRODUCTION

In 2014 UKWIR stated that "Water and sewerage companies (WaSCs) do not have a way of assessing the growing risk of customer flooding based on the climate science." Key to the problem was the spatial resolution of climate models – they were too course to resolve convective processes that lead to the highest rainfall intensities. Estimating these future rainfall intensities is challenging particularly because climate models typically have spatial and temporal resolutions that are coarser than is necessary to resolve convective rainfall processes effectively (Fowler & Ekström, 2009; Chan et al., 2014). Furthermore, climate models are known to be relatively poor at simulating precipitation extremes (Flato et al., 2013).

A significant challenge is, therefore, to estimate the impact of future rainfall intensities on drainage systems – particularly for heavier rainfall events that affect flooding and pollution from drainage systems.

UKWIR RAINFALL INTENSITY PROJECT

UK water and sewerage companies are working hard to reduce incidences of flooding and pollution following periods of heavy rainfall. To plan for the future, water companies want to have information on how rainfall depths and the frequency of heavy rainfall events are likely to change in future climates. As wet weather collection systems typically respond to very short duration rainfall (Digman et al, 2014), obtaining estimates of future rainfall intensity change is challenging since most climate models are at scales (spatial and temporal) that are too coarse to resolve convection – the principal cause of high intensity, localized rainfall events in the UK (Kendon et al, 2012).

UK Water Industry Research (UKWIR – www.ukwir.org) commissioned CH2M to investigate how new science can be used to develop better guidance on estimates of change in rainfall intensity affecting water and sewerage companies (WaSCs) for both flooding and pollution analyses and investment planning. Critical to its success is a new, very high resolution climate model for the United Kingdom, which is able to better simulate convective processes (Kendon, et al., 2012) (Kendon, et al., 2014) (Chan, et al., 2014). This is described in more detail below.

Our investigations found that UK water and sewerage companies do not have a consistent approach for applying climate change allowances in either design rainfall or for adjusting time series data. However, all twelve companies participating in this research are making some adjustment for climate change in the design storms used for modelling. One third of companies only are adjusting their time series rainfall for climate change, though by three different approaches. Hence, there was found to be a strong requirement for a consistent approach for applying allowances for climate change to both the design rainfall event (design storm) and to rainfall time series data that accounts for convective rainfall processes and is applicable at sub-daily durations.

Estimating change in intensities from a very high resolution climate model

The Met Office Hadley Centre has operated a very high resolution climate model in recent years (Kendon, et al., 2014). The UKWIR research examined all the 1.5 km land based cells over the UK from the climate model. The data analyzed are representative of two time periods:

1. A 'current climate' simulation representing the period 1996-2009 – a 13-year, 1-hour resolution time series
2. A 'future climate' centered on the year 2100 (RCP8.5 scenario) – also a 13-year, 1-hour resolution time series

Return period rainfall depths are estimated by extreme value theory (Chan et al, 2014; Coles, 2004). At each grid point, the extreme threshold is estimated; this is defined to be the 99th percentile of all "wet" hourly values (i.e. hourly precipitation rate above 0.1 mm/h). With thresholds at each individual grid point time series defined, we have fitted the Generalised Pareto distribution (GPD) with L-moment parameter estimation (Coles, 2004; Hosking & Wallis, 1987) for all values above the extreme threshold. Return period amounts have then been computed at each grid point using the fitted GPD parameters and the frequency that the extreme threshold is exceeded. As hourly precipitation time series display high degrees of auto-correlation, declustering (Ferro and Segers, 2003) has been conducted before GPD parameter estimation.

To obtain estimates for the epochs of the 2030s, 2050s and 2080s, a pattern scaling approach was adopted that was based on global mean temperature through the 21st century. This assumes that the local response of a climate variable is linearly related to the global mean temperature change, with the geographical pattern of change independent of the forcing. The technique is discussed in more detail by Tebaldi and Arblaster (2014).

Analysis of the uplift values shown graphically at different spatial resolutions led the project team to decide that three regions of the UK would best represent the uplift changes. The three regions are shown in Figure 1 and Figure 2 and can be described as UK south, UK north-east and UK north-west. For Northern Ireland, the results for the north-west region are most applicable.

Table 1 Mean uplift results for each region for different rainfall durations (30-year return period) between the control climate (1996-2009) model run and future climate model run (2100)

30Y RP mean uplift – control to future climate (2100)						
Region	**1 hr**	**3 hr**	**6 hr**	**12 hr**	**24 hr**	**Mean across all durations**
North West UK	65%	73%	74%	78%	76%	73%
North East UK	39%	45%	47%	48%	45%	45%
South UK	34%	26%	26%	28%	34%	30%

Two features of the results for the 30-year return period analysis shown in Table 1 are that there are relatively similar levels of uplift (rainfall depth change) across the various rainfall accumulation periods of 1-hour to 24-hours, though distinct differences in uplift from region to region. For this reason, and for simplicity in application in sewer modelling applications, the researchers decided to provide uplift values applicable to all storm durations. These are shown in Table 2. Uplift factors were shown to vary with return period (Figure 3). Using a 12-year record length we have not extended return periods beyond 30-years - as the standard of service for flooding, due to hydraulic overloading, provided by new build and upgraded sewerage is typically 1 in 30 years, the uplift values proposed for use by the water industry are those derived from the 30-year return period results, shown in Table 2.

Use of central and high estimates of design storm uplift

Central estimates of change are derived from using the mean of the distribution across the region (see Table 2). The high estimate values shown in Table 2 are 90th percentile values derived from sampling the range of estimates across each region, rather than giving an estimate of the uncertainty in the mean. We propose that the central estimate is applicable for the majority of urban drainage network modelling analyses, though we recommend use of the high estimate value for sensitivity testing and in cases of high flood impact. This approach is risk-based, where risk is defined by impact multiplied by likelihood. Where impact is higher a lower probability (more extreme) estimate of rainfall change would be more suitable, and vice versa. Inevitably, selection of such impact levels is subjective and will require user judgement and local knowledge.

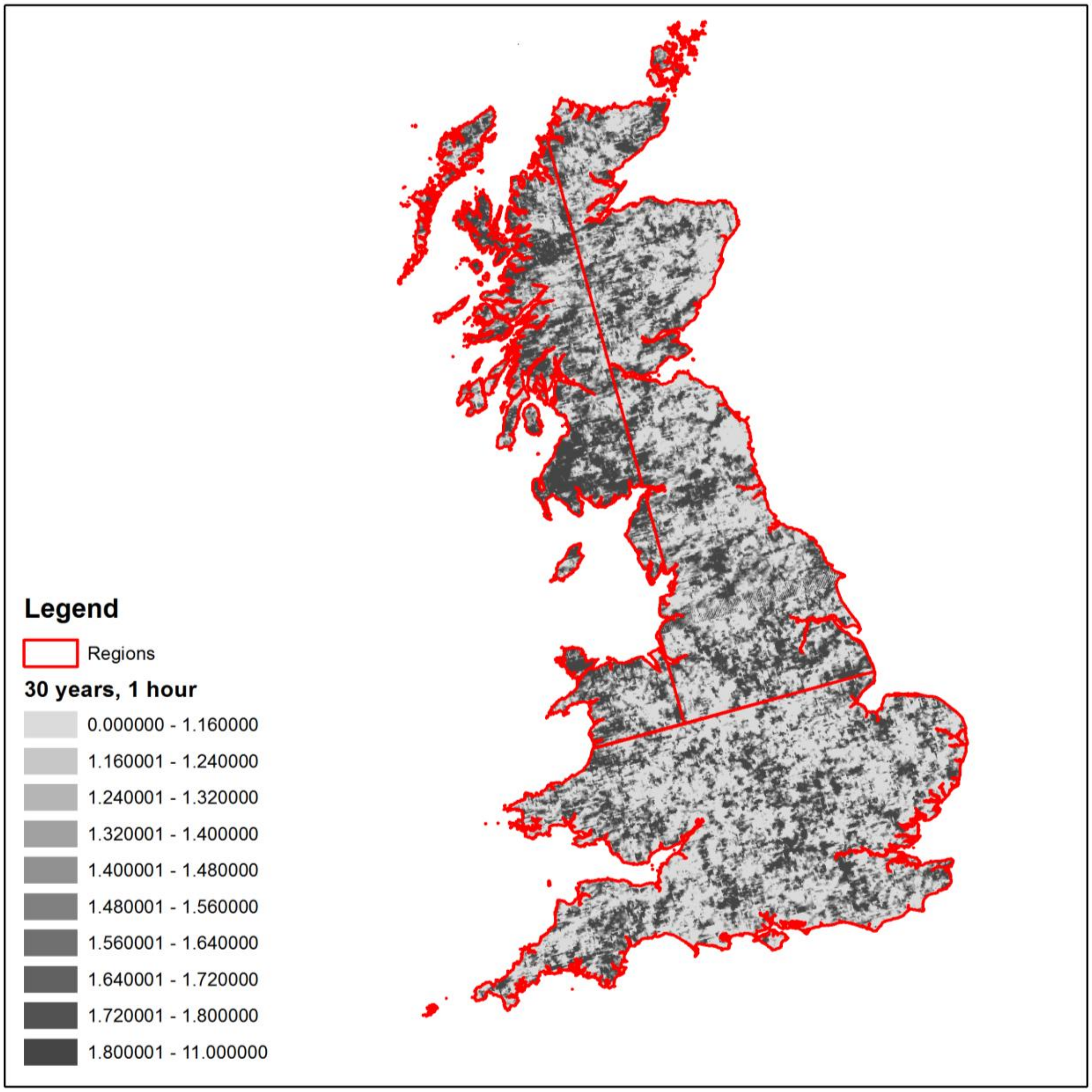

Figure 1 Map of uplift values (current to future climate) for the 1-hour, 30-year return period case. The cell resolution in this image is 1.5km, the same as for the climate model.

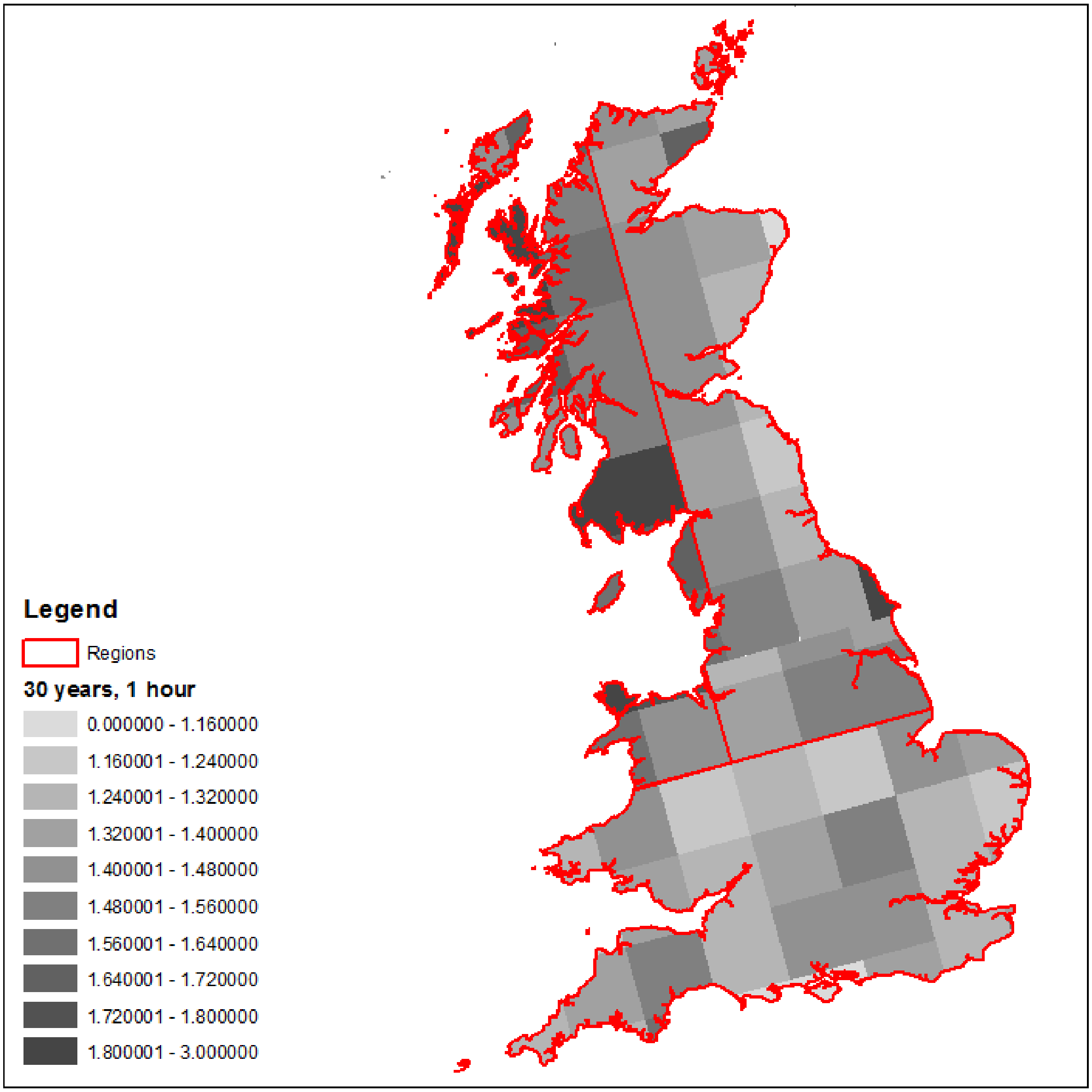

Figure 2. Map of uplift values (current to future climate) for the 1-hour, 30-year return period. 1.5km cells have been aggregated over a 75km grid in this image.

Table 2 Design storm uplift values by region applicable for all storm durations from 1-hour to 24-hour and for the 30-year return period.

		2030s	2050s	2080s
North West UK	Central estimate	20%	35%	55%
	High estimate	*35%*	*65%*	*110%*
North East UK	Central estimate	10%	20%	35%
	High estimate	*30%*	*50%*	*85%*
South UK	Central estimate	10%	15%	25%
	High estimate	*20%*	*35%*	*65%*

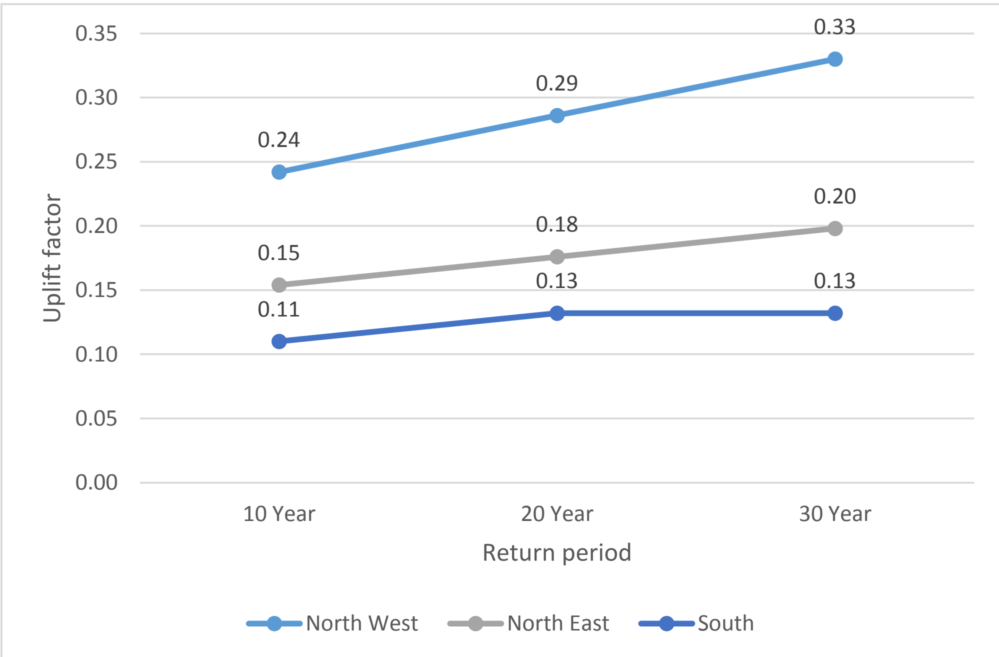

Figure 3 Variation in design rainfall uplift factor with return period for different UK regions

Development of a time series perturbation tool

Currently, no suitable method exists for engineers to derive and apply time series data representative of future climates at convective scale. Within the UKWIR research we have made use of the very high resolution Met Office climate model to derive rainfall characteristics from which to perturb historic rainfall data. The perturbation ensures that the adjusted data represent characteristics of the future rainfall change that have been identified in the 1.5km model.

The perturbations are undertaken at an hourly resolution because the 1.5km climate model produces results at an hourly output frequency. Sub-hourly data can be used, however, through aggregating this to hourly data for perturbation – the perturbation tool then returns the perturbed data in the same temporal resolution.

The perturbation tool was developed from examining trends in the 1.5km resolution climate model data for the current and future climate runs. The climate data were available for a period of almost 12-years from 01/12/1997 to 30/11/2009 covering the current climate and an equivalent length time series centred on 2100 representing the future climate. Nine-cell data clusters were extracted for the following UK cities that have been used as index locations in the perturbation tool: London, Glasgow, Aberdeen, Plymouth, Newcastle, Liverpool, Leeds, Cardiff, Cambridge and Birmingham. This provides 103,680 hourly rainfall values per cell for each climate run, and 933,120 hourly values in each nine-cell cluster.

The perturbation tool, RedUP, has been developed as a standalone desktop interface (see Figure 4). The tool undertakes three perturbations: hourly intensity perturbations, fitting to dry period statistics and fitting to total rainfall depth statistics. For all three steps, the tool uses factors derived from the current and future climate model runs. These factors relate to the change in frequency of rainfall values within the same depth range, or ‘bin’. In Figure 4, the ‘raw bin count’ and the ‘target bin count’ relate to the number of hourly values in the original data and the number that are required in the perturbed data. The ‘Uplift Factor’ shown in this image is the ratio of event frequencies from current to future climate.

The following observations were made from analysis of the time series data used to develop the perturbation tool:

1. **Increased hourly intensities.** There is a general increase in hourly rainfall depths >4mm per hour in all of the UK locations. This is most notable in the higher hourly totals >16mm per hour, where there is generally a doubling or trebling in frequency of such events. However, the detail shows there is a reasonably wide regional disparity in the increases.
2. **Regional similarities and differences**. Consistent with the findings of the increases in the 30-year return period design event uplifts, the change ratios in event frequencies are highest in the north west of the UK and least in the southern part of the UK, though the changes are similar in all regions in the 4mm – 12mm / hour range.
3. **Reduced low-intensity rainfall events.** There is a general reduction in the frequency of the lowest order events (<4mm / hour) across the UK on an annual basis (only Liverpool shows a modest increase in the 2-4mm events).
4. **Increased dry days in all quartiles and all locations.** For all the quartiles of the year and in all locations the number of dry days is estimated to increase in the future. There is a general trend of dry day increase throughout the year.
5. **Reduction in average annual rainfall.** Average annual rainfall is estimated to reduce in almost all locations to 2100. The mean change in annual average rainfall is 88% from current climate to 2100 and 65% in the bathing seasons.

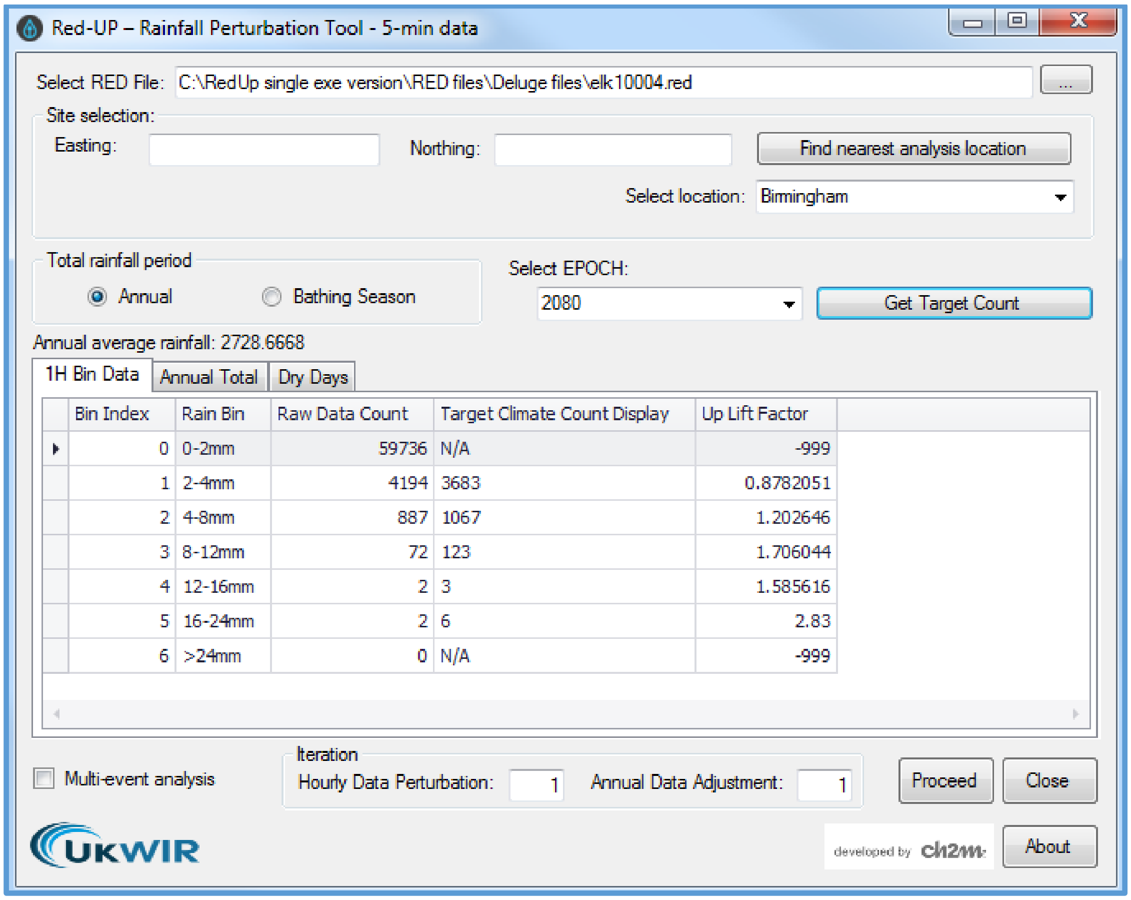

Figure 4 User interface for RedUP rainfall perturbation tool

CONCLUSIONS

Estimating changes in short duration rainfall in the future is challenging and new technology and approaches are evolving rapidly. We see an important technological development in this area coming from climate models that run at convection-permitting scales, addressing a significant limitation of standard resolution models; however, these are not available worldwide. In the UK, we have demonstrated how a 1.5km very high resolution model can be used to provide estimates of future rainfall intensity for different epochs in the 21st century. We have also demonstrated how a time series perturbation software tool can be developed to perturb historic rainfall data series that uses change relationships derived from detailed analysis of the 1.5km climate model current and future simulations.

Estimates of rainfall intensity change are inherently uncertain. Uncertainties exist within the selection of future greenhouse gas emission scenario, in climate models' ability to represent both current and future rainfall depths accurately (modelling uncertainty) and due to natural variability in current and future climates. Managing the uncertainties in the projections can be done in different ways. We always provide projections as a range of plausible values but usually define within that range a central and precautionary estimate – these could equate to a 50% and 90% value from a probabilistic distribution for example. These estimates can then be used in a risk-based decision making framework to ensure the uncertainty in projections is managed appropriately.

ACKNOWLEDGEMENTS

The authors acknowledge the funders of the research, UK Water Industry Research (UKWIR). The Met Office has been actively involved in the UKWIR Rainfall Intensity project and use of its high resolution climate model is grateful acknowledged, facilitated through Dr Elizabeth Kendon. Professor Hayley J. Fowler is funded by the Wolfson Foundation and the Royal Society as a Royal Society Wolfson Research Merit Award (WM140025) holder.

REFERENCES

Chan, S. C., Kendon, E.J., Fowler, H.J., Blenkinsop, S., Roberts, N.M., Ferro, C.A.T. (2014). The value of high-resolution Met Office regional climate models in the simulation of multi-hourly precipitation extremes. *Journal of Climate*, 27, 6155-6174.

Coles, S. (2004) *An introduction to statistical modeling of extreme values* (Springer, 370 London)

Dale, M., Luck, B., Fowler, H.J., Blenkinsop, S., Gill, E., Bennett, J., Kendon, E., Chan, S. (2015). New climate change rainfall estimates for sustainable drainage. *Proceedings of the Institution of Civil Engineers Engineering Sustainability.* DOI: http://dx.doi.org/10.1680/jensu.15.00030 Published Online: October 30, 2015

Digman, C.J., Ashley, R.M., Hargreaves, P. and Gill, E. (2014) Managing urban flooding from heavy rainfall - Encouraging the uptake of designing for exceedance – recommendations and summary, CIRIA, C738a.

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason and M. Rummukainen (2013). *Evaluation of Climate Models.* In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fowler, H. J., Ekström, M. (2009). Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *International Journal of Climatology*, 29, 385–416.

Hosking JRM, Wallis JR (1987) Parameter and Quantile Estimation for the Generalized Pareto Distribution. *Technometrics* 29:339–349.

Kendon EJ, Roberts NM, Senior CA and Roberts MJ (2012) Realism of rainfall in a very high resolution regional climate model. *Journal of Climate 25(17): 5791–5806.*

Kendon EJ, Roberts NM, Fowler HJ et al. (2014) Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change 4: 570–576*, http://dx.doi.org/10.1038/nclimate2258.

Tebaldi, C. & Arblaster (2014). Pattern scaling: Its strengths and limitations, and an update on the latest model simulations *J.M. Climatic Change* 122: 459. doi:10.1007/s10584-013-1032-9

UKWIR (2015) *Rainfall Intensity for Sewer Design.* UKWIR, London, UK, Ref. 15/CL/10/16. Available at: www.ukwir.org