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Understanding how changing rainfall may impact on urban drainage systems; lessons from projects in the UK and USA

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Abstract

Urban flooding and wet weather pollution are recognised as significant problems across the world, and changes in rainfall patterns arising as a consequence of climate change are likely to exacerbate these problems. This paper shares learning from a ground-breaking project led by CH2M for UK Water Industry Research and approaches used in other CH2M projects around the world. The UK project has explored the use of very high resolution (1.5 km) climate model output and climate analogues; other projects have used other methods to derive new design rainfall statistics commonly used in modelling wet weather collection systems for flooding and pollution investigations. Estimates of rainfall change have been used within collection system models to estimate the flooding and pollution impact of these changes. The methods applied in these projects can be replicated globally.

Key words: Climate change, flooding, resilience, stormwater, wet weather collection systems

INTRODUCTION

Flooding from wet weather collection systems and wet weather pollution are recognised as significant problems across the world. A key concern for many drainage operators and asset owners is whether today's drainage systems and pollution controls can cope with rainfall intensities in the future. 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.* 2014a). 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.

CLIMATE MODELLING APPROACHES

Research projects at CH2M have employed different approaches depending on the availability of climate models at appropriate resolutions and other data. The types of analyses undertaken include the first application of output from very high resolution climate models (resolutions of 1.5 km and 1-hour), regional and global climate model simulations and climate analogue approaches. In this

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paper we describe approaches employed in a project in the United Kingdom. CH2M has also undertaken estimates of future rainfall change in many locations in the USA and Canada, referred to later in this paper.

CLIMATE CHANGE & RAINFALL INTENSITY PROJECTS

United Kingdom rainfall intensity project

The water and sewerage companies in the United Kingdom are working hard to reduce incidences of flooding and pollution following periods of heavy rainfall. To plan for the future, these 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, localised rainfall events in the UK (Kendon *et al.* 2012).

UK Water Industry Research (UKWIR – www.ukwir.org) have commissioned CH2M to undertake research into this area. The first phase of this project used two approaches to derive changes in the 1-hour, 3-hour and 6-hour duration design rainfall estimates. It also examined pollution impacts using synthetic rainfall data from a very high resolution climate model run at the UK Met Office. The approaches summarised below are detailed more fully in Dale *et al.* (2015).

High resolution climate model approach

A dynamical downscaling approach was used through availability of the NERC-funded Newcastle University and Met Office project, CONVEX, which produced hourly rainfall simulations for 13-year periods for a current and future climate. This provided the first climate change simulation at convection-permitting scales; model details and related information on improved simulation of intense rainfall events are described in Kendon *et al.* (2012, 2014, 2015) and Chan *et al.* (2014a, 2014b) – critically, the convection-permitting model has much better simulation of the temporal evolution of convection.

In Phase 1 of the project, return period estimates were derived from 36 1.5 km cells from the climate model from four UK locations (centred on London, Cardiff (SE Wales), Glasgow (W Scotland) and Newcastle (NE England)) and 'uplifts' (percentage change values) were derived from comparing the results from the current and future model simulations. These are shown graphically in Figure 1. The results show a general increasing trend in rainfall depths for the 1-, 3- and 6-hour durations for all return periods.

Climate analogue approach

Several studies have demonstrated a scaling between extreme precipitation intensities and temperature on daily and sub-daily timescales (e.g. Lenderink & van Meijgaard 2008; Hardwick Jones *et al.* 2010; Utsumi *et al.* 2011) and recent evidence has indicated a Clausius-Clapeyron relationship for UK summer sub-daily intense precipitation (Blenkinsop *et al.* 2015). The underlying principle of the Clausius-Clapeyron relationship and associated empirical evidence demonstrates that temperature change is a significant driver of changes in rainfall intensity, such that locations with a similar climatic (temperature) regime can be expected to experience broadly similar rainfall event intensities. This evidence was used as a basis to derive estimates of precipitation intensity change using an analogue rain gauge approach. Change estimates were produced for the four UK locations

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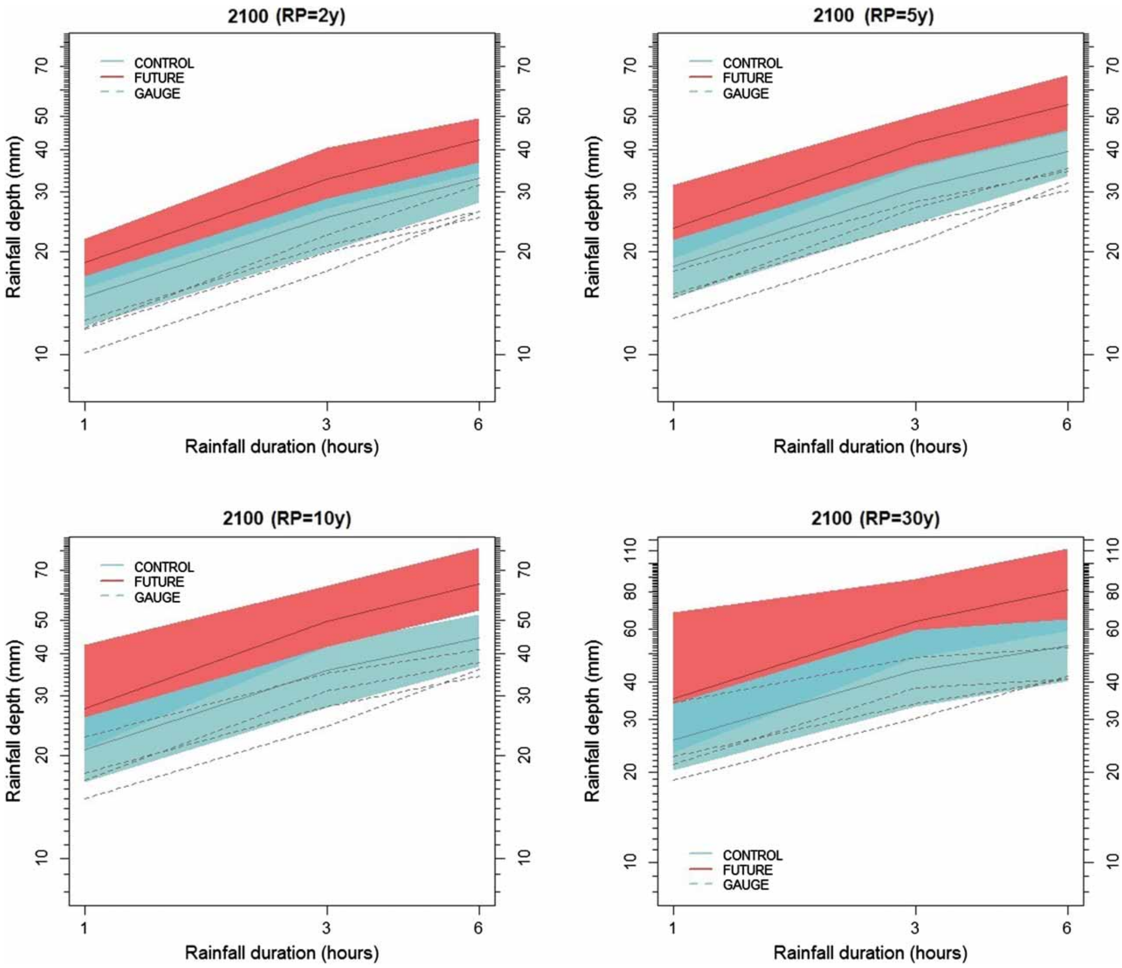

Figure 1 | Image showing projected change in rainfall depths from current climate to a future climate in 2100 using the 1.5 km climate model. Grey bands illustrate the range of rainfall depth estimates from the current climate simulation (a 13-year, hourly dataset) and the red bands show the range of rainfall depth estimates from the future climate simulation, centred on 2100 (also a 13-year, hourly dataset). The bold line within the red band represents the mean of the future depth estimates. The dashed lines represent the return period estimates of local rain gauges with long, hourly records (c. 20 years or more) – these give some confidence that the 1.5 km climate model's current climate simulation is realistic.

listed above, using long analogue hourly rain gauges representative of future warming from Europe and the USA.

Rainfall uplift and urban flooding volume increase results

The two approaches summarised above produced two sets of rainfall change estimates. The results produced by the two methods were broadly similar, as detailed in the project technical report (UKWIR 2015). The two sets of results were combined (the two approaches were weighted equally) and low, central and high change estimates were derived for 1-, 3- and 6-hour rainfall durations.

The central change estimate was used in calibrated water company collection system models in the four locations referred to above. The results of this analysis are presented in Table 1. In general, the change estimates increase with time, as expected. However, the rainfall results for Cardiff do not follow the expected trend of increasing change with increasing temperature (temperature is projected to increase from 2030 to 2080). The explanation for this is the influence of data from different analogue gauges being used in the analysis at higher temperatures for this location in which drier summer climates were observed – this issued is discussed more fully in the project technical report (UKWIR 2015). Phase 2 of this project will aim to avoid such discontinuities, detailed below.

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Table 1 | Rainfall depth change estimates (central) for four UK locations and corresponding flooding volume changes when rainfall uplifts are used within calibrated collection system models

	Epoch					
	2030s		2050s		2080s	
UK location	Rainfall % change (*central* estimate)	Increase in flooding volume (%)	Rainfall % change (*central* estimate)	Increase in flooding volume (%)	Rainfall % change (*central* estimate)	Increase in flooding volume (%)
Glasgow	19	41	27	59	50	109
Newcastle	28	36	44	55	50	64
Cardiff	38	147	29	113	26	102
London	7	11	11	16	48	72

Implications of results

The results shown in Table 1 indicate that the percentage change of flooding volume is greater than the percentage change in rainfall depth. The estimated central estimates of rainfall change are, in general, higher than current flood risk guidance allowances in use in the United Kingdom (Defra 2006; Environment Agency 2011) – these allowances, expressed as a percentage for increasing design rainfall depths, are generally within the range of 10–30% for the 2030s to 2080s respectively[1]. Therefore, the research shows that future flooding could be more significant than existing rainfall change allowances suggest.

Organisations in the UK (the Committee for Climate Change and the Scottish Environment Protection Agency) have recognised and acknowledged the impact of these new rainfall change estimates and have used the information to inform guidance and information for flood risk management (Sayers *et al.* 2015; SEPA 2015).

On-going project (Phase 2)

UK Water Industry Research is currently planning a second phase to this project. This phase, to be undertaken by CH2M with contributions from Newcastle University and the UK Met Office, will develop the results from Phase 1 of the project in two ways. Firstly, high resolution climate model data will be analysed from all of England, Scotland and Wales' land-based cells using a newly available high resolution model simulation for the north of the UK, to give a more robust analysis of change estimates. Secondly, a tool will be developed allowing users to derive perturbed time series rainfall data with rainfall intensity and periodicity properties, for any location in the UK, that are broadly consistent with the Met Office's high resolution climate model's future data. The reason for using the high resolution climate model approach in Phase 2, and not that of the analogue approach, is that the analogue results in Phase 1 of the project showed a wide range of change estimates and the reliance placed on the Claussius-Clapeyron theory is regarded by the project team as resulting in less certain change estimates than those produced by the high resolution convection permitting climate model.

Phase 2 of this project will also address a need for deriving synthetic future time series rainfall data. Currently no suitable method exists for end-users (practising engineers) to derive and apply time series data representative of future climates at convective scale. Our team will use data from the 1.5 km climate model of the UK to develop a methodology for perturbing historic rain gauge time series to be

[1] The Defra and Environment Agency allowances apply to daily (24-hour) duration rainfall only, but are typically used for uplifting sub-daily duration design rainfall.

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representative of future climates. The perturbation methodology will ensure that the adjusted data represent characteristics of the future rainfall change that have been identified in the 1.5 km model. For example, if the future climate model run indicates a threefold increase in the number of 20 mm in 1-hour rainfall events by 2100, this characteristic will be preserved in the perturbed future time series.

The perturbations will be undertaken at an hourly resolution because the 1.5 km climate model does not produce results at sub-hourly timesteps. However, the perturbations will be possible with sub-hourly data, though the distribution of the data at sub-hourly scales will not change from the base data. Our project team will develop a software tool that facilitates the perturbation process. We propose to test the software tool and run perturbed time series data through existing wet weather collection system models to summarise the changes to pollution spill frequency and volume.

Other approaches taken to derive future rainfall estimates

Where high resolution climate model outputs are not available, it is still possible to develop locally specific projections of potential future rainfall using 'downscaling' techniques based on a combination of the locally observed data and the outputs from global climate models. CH2M have applied this approach in many locations, including Alexandria, VA, Miami-Dade, FL, Los Angeles, CA (all United States) and Vancouver, Canada.

These analyses have employed SimCLIM (Warrick 2007) – a computer model system for examining the effects of climate variability and change over time and space on a personal computer developed by CLIMsystems (www.climsystems.com). SimCLIM integrates historical observations with complex arrays of data and general circulation model (GCM) results in order to assess the impacts of climatic variability, change, and extreme climatic events on natural and manmade systems as user selectable target years; e.g. 2025, 2050, 2100. The SimCLIM system allows the generation of site specific, climate change-perturbed, historical time series that can be used as input to hydrologic, ecosystem, and any number of climate-driven natural resource models. The system supports analysis of historical and projected changes in extreme values such as precipitation intensity, duration, and frequency, using the generalized extreme value distribution.

SimCLIM supports a variety of downscaling approaches including 1) pattern scaling, 2) self-organizing maps – statistical downscaling, and 3) bias-corrected statistical downscaling to meet specific requirements. SimCLIM allows selection of the IPCC-sanctioned representative concentration pathway (RCP) greenhouse gas scenarios as input to GCM model results, allowing a full exploration of boundaries of projected changes in temperature, precipitation, and sea level change. Site-specific analysis examples include projected changes in precipitation intensity, duration and frequency, projected sea level rise and projected changes in extreme temperature threshold exceedance as shown in Figure 2, in a study undertaken for Los Angeles airport.

Alternatively, it is possible to simply adjust the design criteria, by a 'change factor' based on the published climate science where peer-reviewed research provides projections of 'change' in the climate metrics relevant to rainfall intensities. Following this approach, the design storm values, depth, intensity, etc for a given event can be simply adjusted by a given percentage in line with the published research. This approach was adopted by CH2M in developing future rainfall intensities to inform climate resilience planning for New York City's stormwater system. This was a component of the analyses undertaken to develop future design storm metrics and future typical years to inform planning. Within this project, estimated change in rainfall intensity for individual events was derived from research by Zhu *et al.* (2012), using results from seven regional climate models. This research derived potential changes in intensity–duration–frequency (IDF) curves, which are often used for assessment of extreme rainfall events, using historic data and future climate projections. Zhu *et al.*'s approach incorporated projected changes in rainfall intensity at a range of locations in the United States, including projections for New York. Their results highlighted strong regional patterns

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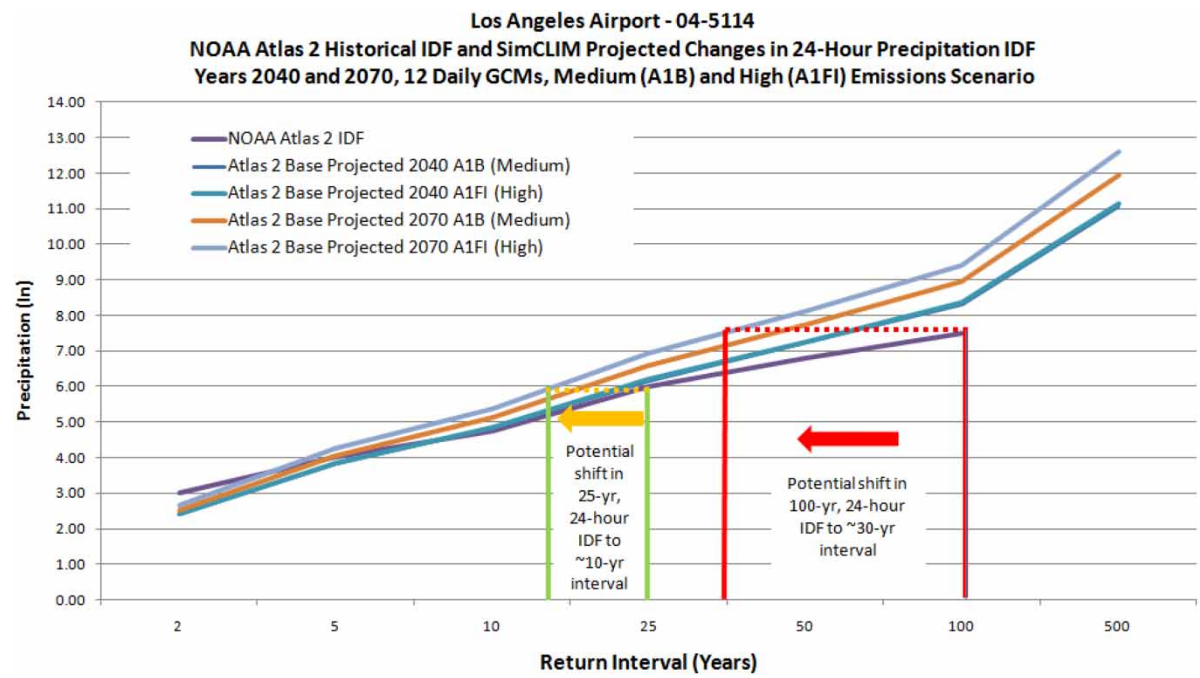

Figure 2 | Example of projected changes in precipitation intensity, duration and frequency for Los Angeles Airport using SimCLIM.

in projected changes in rainfall intensity, which are influenced by the rainfall characteristics of the region.

DISCUSSION

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. Of relevance to the Singapore International Water Week, however, we are aware that the Meteorological Service Singapore (MSS) Centre for Climate Research Singapore (CCRS) has used such a high resolution model within its Second National Climate Change Study (MSS, 2016), projecting among other things, more extreme rainfall for Singapore and the surrounding region.

Where such high resolution models are not available, other techniques can be used that can make combined use of both regional climate models and climate analogue approaches. A pitfall to avoid, however, is inferring that short-duration intensities in rainfall might be reduced in a drier seasonal climate because daily precipitation totals might be reduced in such a climate. For example, the drier, warmer summers projected for the United Kingdom in the 21st century (Murphy *et al.* 2009) may not in fact lead to reduced hourly intensities of rain on wet summer days (Kendon *et al.* 2014) and output from standard resolution RCMs cannot be used reliably for estimating changes in convective rainfall.

This paper has highlighted that, in general, asset owners, planners and engineers need to allow for increases in short duration rainfall intensities in the future. The amount of these increases can be informed by different methods as has been described above. The change estimates 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

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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.

CONCLUSIONS

- Climate science suggests that in many parts of the world, extreme rainfall events (used as drainage design events) are likely to become more intense in the future, with likely increased frequency of urban flooding and pollution events as a consequence.
- The planning and design of new drainage infrastructure should take account of potential future climate change to ensure delivery of required service standards throughout asset design life. Drainage authorities can use scenarios and/or probabilistic decision-making to address the uncertainties regarding future rainfall values.
- The application of high resolution climate modelling, at convection-permitting scales, suggests a greater increase in intensities than is typically projected using regional climate model downscaling approaches in the UK. Where such models are available, it would be advisable for authorities to consider their outputs when assessing their wet weather collection systems' performance. Where these climate models are not available, it may be appropriate to use values from the upper range of downscaled data in recognition of this potential under-representation. In this case an assumption is made that current relationships between daily and sub-daily durations will be preserved in the future.
- Currently, all national climate scenarios are based on coarse resolution model runs which do not simulate realistic changes to convective rainfall frequencies and intensities, indicating that all current national climate scenarios would benefit from convective-scale climate model analyses.

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