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Monitoring the future behaviour of urban drainage system under climate change: a case study from north-western England

Abstract: Catchments hydrological conditions and responses are anticipated to be affected by the changes in weather patterns, increasing in climate variability and extreme rainfall. Thus, engineers have no choice but to consider climate change in their practices in order to adapt and serve the public interests. This paper is an exploration of the impacts of climate change on the hydrology that underlies the hydraulic design of urban drainage system. Future rainfall has been downscaled from the Global Climate Model (GCM) employing a hybrid Generalised Linear Model (GLM) and Artificial Neural Network (ANN) downscaling techniques under different greenhouse emission scenarios. The output from this model is applied to a combined sewer system of an urban drainage catchment in the Northwest of England during the 21st Century to monitor its future behaviour in winter and summer seasons. Potential future changes in rainfall intensity are expected to alter the level of service of the system, causing more challenges in terms of surface flooding and increase in surcharge level in sewers. The results obtained demonstrate that there is a real chance for these effects to take place and therefore would require more attention from designers and catchment managers.

Keywords: Urban drainage, Climate change, Combined Sewer System, Artificial Neural Network, Storm water, InfoWorks CS

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1 Introduction

Drainage systems have been utilised to maintain health and safety of urban populations for centuries and are in large part, responsible for supporting continuing economic development [1]. In some cities the systems are more than 150 years old and replacement or renewal rates are very low. Although the annual average for the UK is currently 0.4%, investment in sewer renewal is, by some estimates, not going to replace some of the current assets for more than 1000 years [2]. The 21st Century brings fresh challenges to the field of urban drainage in form of climate change. The anthropogenic impact on our global climate now seems to have been demonstrated conclusively, but the implications are not fully understood.

It is well documented that climate change would lead to changes in the physical processes forming the natural hydrological cycle in a catchment and their interactions [3]. One of the key processes that would severely be affected is rainfall or precipitation which is the driving force for operation of urban drainage systems. Many studies predict that there will be significant changes to the rainfall regime ([4] and [5]), especially the extreme events which need to be taken into account while designing new systems.

One of the most serious implications of climate change is the increased potential for sewer flooding. In urban areas, the impact can be very high because the areas affected are densely populated and contain vital infrastructure. It has become possible to carry out approximate national-scale analysis of risk from sewers flooding due to insufficient capacity in urban drainage system, where urban models can be scaled- up to generate national estimates of the risks of urban flooding [6]. Given the stochastic nature of rainfall and potential for more extreme events in the future, this is an area that is likely to require careful attention by urban drainage researchers and practitioners.

Therefore consistent versions of the future are required in order to examine and monitor the future behaviour of the drainage system in a logical manner. These consistent versions are known as climate change scenarios based primarily on estimates of greenhouse gas emissions [7]. In this paper two emission scenarios have been used, the high (A1FI) and the low (B1) emission scenarios of greenhouse concentration. The implications of these two scenarios were used as input in a global climate model (GCM)

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to simulate the future rainfall at coarse scale. Downscaling techniques have been used to obtain this future rainfall at a local scale from the GCM (Had CM3) as their coarse scale limits their usefulness for hydrological impact study [8]. Then monitoring of future behaviour was conducted using the downscaled rainfall to understand, and where possible to quantify, the extent and scale of risks of flooding for an urban drainage system in north-western England.

2 Case study

Windermere drainage area is located in Cumbria in north-western England (see Figure 1); the drainage area covers 425 hectares and has a residential population of 8,500. The InfoWorks CS model of the area has 173 sub-catchments and a total number of pipes totalling 633, which connects 655 manholes and 4 outfalls. The receiving water for wastewater discharges from the catchment is Lake Windermere. The lake receives direct storm discharges from the two Combined Flow Overflows and also receives the final effluent from Windermere Wastewater Treatment Work (WwTW). The catchment contains two main (and adjacent) settlements of Windermere and Bowness-on-Windermere together with small localised areas. It is served by predominantly combined gravity and pumped sewerage systems which drain in a southerly direction along the eastern shore of Lake Windermere to the receiving WwTW at Tower Wood. In the Windermere area, the larger developments were judged to be redevelopments in existing developed areas and would contribute little additional area to the wastewater network [9].

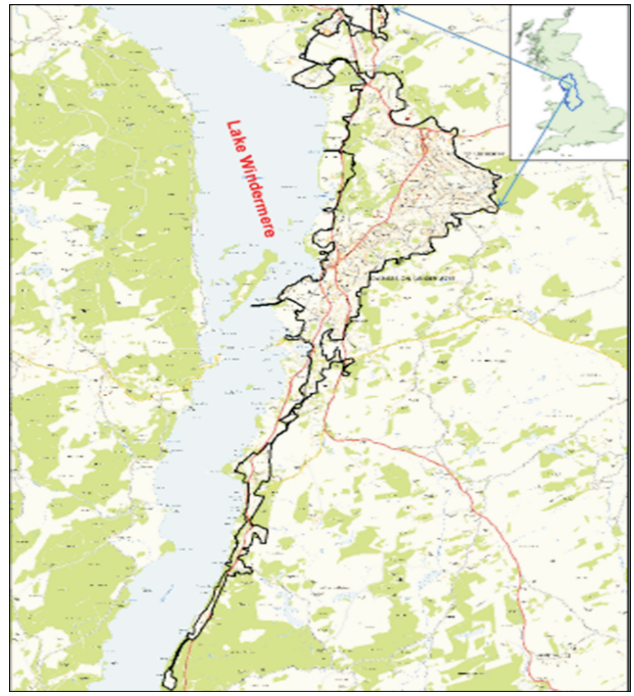

Figure 1: Location of Windermere in northwestern England.

3 Methods

3.1 Rainfall downscale model

A hybrid Generalised Linear Model (GLM) and Artificial Neural Network (ANN) approach, developed in study [10], was used to downscale rainfall from coarse global climate model (GCM) (HadCM3) outputs to finer spatial scales. More on information on model and how it has been applied can be found in the given reference and will not be repeated here.
The developed GLM-ANN model was then used to simulate daily future rainfall in the studied catchment using a set of input variables generated by global circulation models, for scenario emissions A1FI and B1, as predictors. The outcome is a time series of daily rainfall for the future 2080s period (2079-2099).

3.2 Future design rainfall

Design rainfall for certain return periods was produced using frequency analysis carried out on the downscaled future rainfall from the Global Climate Model (Had CM3). Summer and winter profiles design rainfall events were generated for 5 year return period for a duration of 1440 minutes (24 hours) using the Peaks over Threshold (POT) method.
The frequency analysis was carried for the baseline period (1961-1990) and the future period (2080s) extreme rainfall series. By employing an uplift percentage for the future on the current design rainfall in the network model, it would be possible to project the performance of the Windermere sewers network model in the future period.

3.3 Generation of future runoff

The transformation of rainfall hyetograph into surface runoff involves two principal steps. Firstly, losses due to antecedent conditions (surface wetness of catchment and in-depth wetness of catchment), areal reduction factor and evapotranspiration are deducted from the rainfall. Secondly, the resulting effective rainfall is transformed by surface routing into an overland flow hydrograph. The two steps simultaneously take place within the drainage modelling software used (i.e. InfoWorks CS).

In the current study the antecedent rainfall depth from surface wetness was set to 99 mm to eliminate initial losses. Evapotranspiration was not applied to the design rainfall as it was not used in the original model build and verification or in any subsequent re-verification of the model due to the insignificant value even with the climate change in the Northwest England during the summer.

For urban catchments in the UK, the percentage runoff coefficient can be estimated from Wallingford or New UK volumetric models. The effective rainfall hyetograph can be transformed into runoff after accounting for all the above-mentioned catchment losses (overland flow). In this process the runoff moves across the surface of a subcatchment to the nearest entry point to the drainage system using the unit hydrograph method [4]. For the purpose of simulation of the current drainage system, InfoWorks CS Software (version 12; Innovyze Ltd, http://www.innovyze.com) has been used and results have been processed employing specialist Data Manager Software (version 3.9, MWH UK Ltd, http://www.mwhglobal.com). The design storm uplifts found in Section 3.2 are used as inputs in the existing InfoWorks CS model of Windermere to simulate the future behaviour of the drainage system.

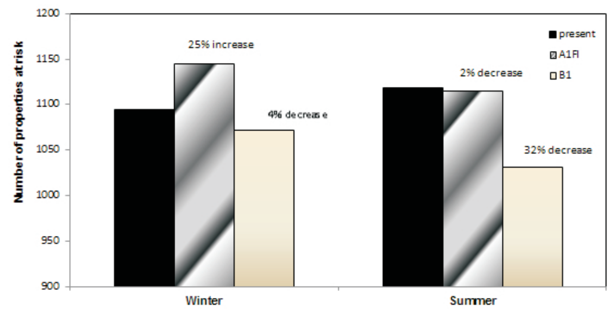

Figure 2: Surface flooding volume spilling from manholes in the present and future 2080s under scenario AFI (high) & B1 (low) for winter and summer. N.B. The percentage shown in the bar chart indicates a decrease and/or increase in design storm of the drainage system in the future compared with the baseline design storms.

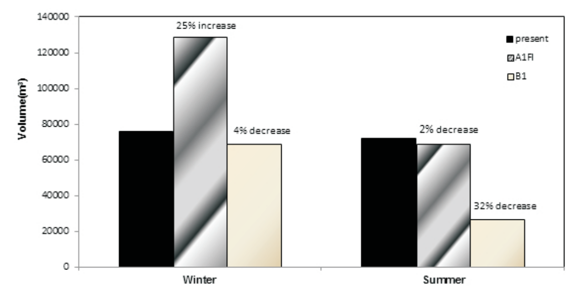

Figure 3: Number of Properties at risk of flooding due to surcharged sewers in the present and future 2080s under scenario AFI (high) & B1 (low) for winter and summer. N.B. The percentage shown in the bar chart indicates a decrease and/or increase in design storm of the drainage system in the future compared with the baseline design storms.

4 Results and discussion

The current study used downscaled future rainfall for the 2080s (2070-2099), resulting from scenario emissions A1FI and B1, into existing urban drainage system of Windermere in North-western England to monitor its future behaviour. The future behaviour has been assessed based on the change in manholes flooding volumes, surcharge in sewers and the number of buildings at risk of flooding.

The number of manholes where water exceeding the ground level in the baseline period climate is predicted to increase in the future time period (2080s), for scenario A1FI. Subsequently, the spilling volume is projected to increase 1.6 times that of the baseline period which due a 25% increase in the design storm during winter (see Figure 2). However, under the low scenario B1, there would be a slight decrease in spilling volume from manholes.

In the summer, under both scenarios, the spilling volume is predicted to reduce, especially under the low scenario B1, due to an expected reduction in the greenhouse emission.

The increase in design storm intensity in winter under the high emission scenario (A1FI) indicates there might be more damage to properties due to surcharged sewers when the hydraulic gradient is increased above the property level as shown in Figure 3. In the winter of the low scenario (B1) and summer of both scenarios, a drop in the number of properties at risk is predicted with a significant reduction under the summer of the low scenario (B1) which is predicted to be around 60% less than the situation in the baseline period (Figure 3).

The geographical distribution of the flooding in the sewer system can vary and the flooded manholes are more spread out in the future (2080) under the winter of the AFI scenario compared with the baseline situation (Figure 4). Although the number of flooding manholes is predicted to increase by only 27%, the corresponding total spilling vol-

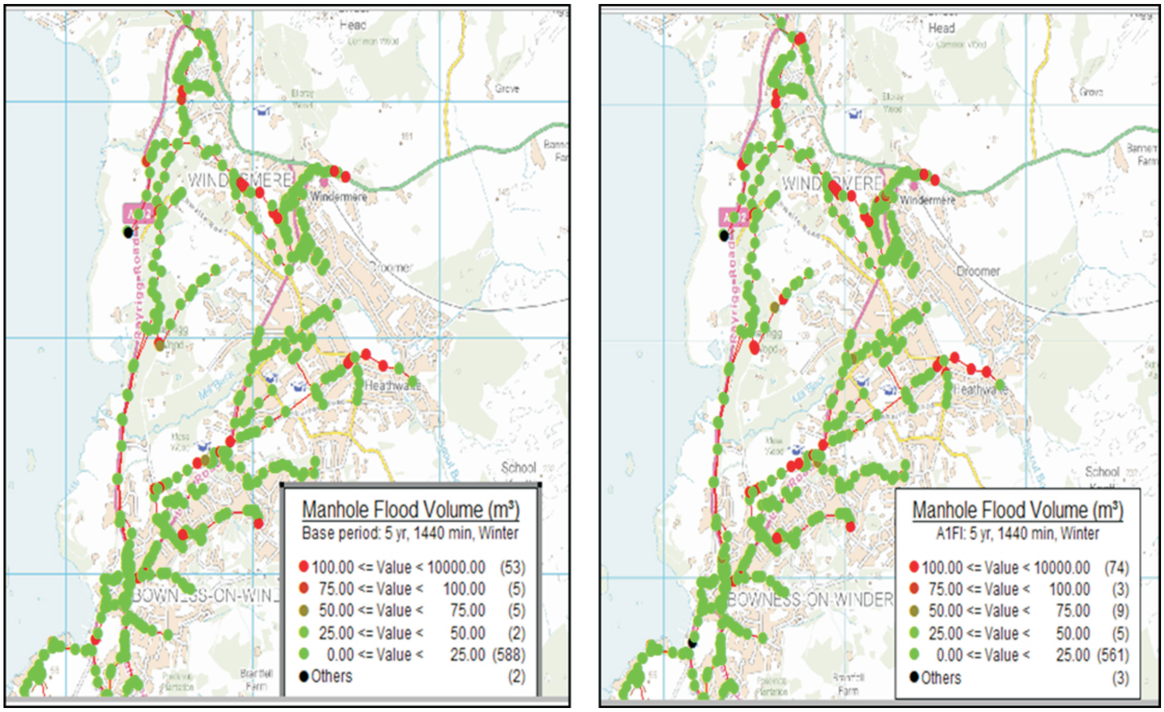

Figure 4: Location of flooding manholes in part of Windermere catchment in the present (left) and future 2080s in winter under scenario A1FI (right); where the number of flooding manholes is 94 and 120, respectively.

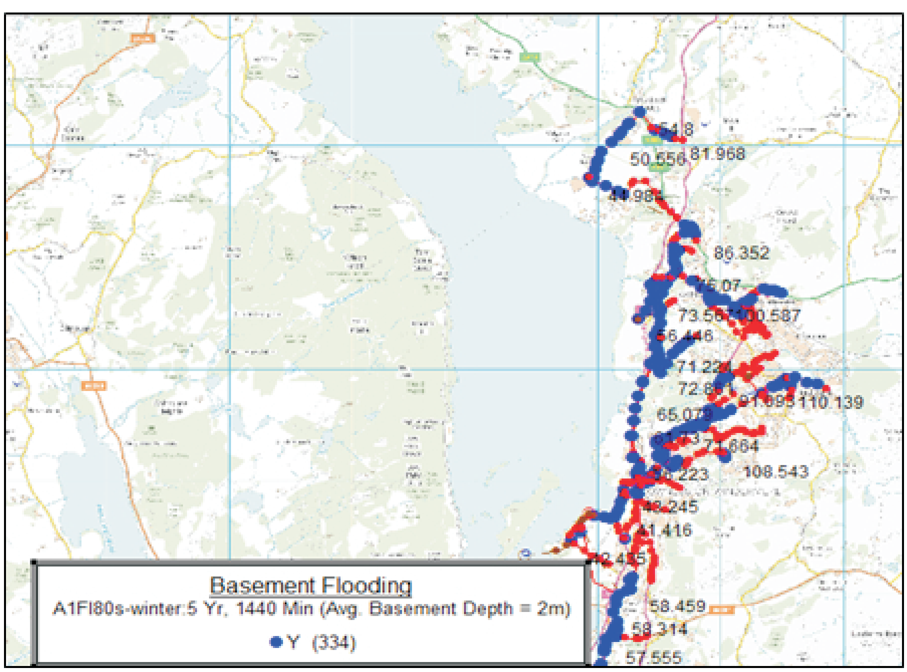

Figure 5: Location of properties (Basement only) at risk of flooding due to surcharged sewers in Windermere in Future 2080s (2070-2099) in winter under AFI (worst scenario).

umes from these manholes are very significantly different from the baseline situation (the total spilling volume is increased by 70%) as depicted in Figure 2.

Figure 5 is another demonstration for the distribution of surcharge flood risk to properties and is based solely on the flood/surcharge levels in the sewer relative to property level. Flood risk to properties is categorised using the following depth bands:

- VHI-very high impact: water level greater than 200 mm above property level
- HI-High impact: Water level between 0 mm to 200 mm above property level (Red)
- MI-Medium impact: Water level between 0 and 200 mm below property level (Blue)
- NI-No impact: Water level greater than 200 mm below property level (Green)

The finding presented in this paper reflects the potential future behaviour and flood risk but does not give a definite answer of what the future consequences of climate change will be. This is due to uncertainties over the magnitude and timing of climate change impacts, especially at regional and local levels. This is partly because of GCMs limitations and inability to model the climate system, biophysical impacts and the social and economic responses to changes in climate ([11] and [12]). Despite these uncertainties related to future climate change and its impacts, the fact that the climate change has already started is sufficient evidence for the outcome of the impact studies. Thus it is possible to identify a range of possible outcomes that can inform adaptation and planning policies.

5 Conclusion

Changes in rainfall magnitude and pattern due to climate change will have impact on future behaviour of urban drainage systems. Increased intensity and amount of rainfall may, for example, cause increase in flow volumes entering the system and will also be likely to introduce hazardous substances into receiving waters, which would have impact on the drinking and bathing waters. The present paper highlights an example of increase in spilling volume trough manhole flooding which is likely to cause more surfaces flooding in the future. Moreover, the number of properties at risk of flooding, including basements, was also identified. On the other hand, decrease in amounts of rainfall, as shown during summer, may cause high pollutant loads in storm water during a rainfall event due to urban build-up of pollution and could also cause severe problems connected to drinking water quality. The monitoring results showed that the urban drainage system of Windermere could behave differently in the future in terms of increase in number of surcharged sewers and from manholes surface flooding.

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