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Research papers

Sensitivity of peak flow to the change of rainfall temporal pattern due to warmer climate

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A B S T R A C T

The widely used design storms in urban drainage networks has different drawbacks. One of them is that the shape of the rainfall temporal pattern is fixed regardless of climate change. However, previous studies have shown that the temporal pattern may scale with temperature due to climate change, which consequently affects peak flow. Thus, in addition to the scaling of the rainfall volume, the scaling relationship for the rainfall temporal pattern with temperature needs to be investigated by deriving the scaling values for each fraction within storm events, which is lacking in many parts of the world including the UK. Therefore, this study analysed rainfall data from 28 gauges close to the study area with a 15-min resolution as well as the daily temperature data. It was found that, at warmer temperatures, the rainfall temporal pattern becomes less uniform, with more intensive peak rainfall during higher intensive times and weaker rainfall during less intensive times. This is the case for storms with and without seasonal separations. In addition, the scaling values for both the rainfall volume and the rainfall fractions (i.e. each segment of rainfall temporal pattern) for the summer season were found to be higher than the corresponding results for the winter season. Applying the derived scaling values for the temporal pattern of the summer season in a hydrodynamic sewer network model produced high percentage change of peak flow between the current and future climate. This study on the scaling of rainfall fractions is the first in the UK, and its findings are of importance to modellers and designers of sewer systems because it can provide more robust scenarios for flooding mitigation in urban areas.

1. Introduction

The accurate design of urban drainage networks requires the continuous simulation of long rainfall time series using an urban drainage model, which results in long computational times, and later the results need to be statistically post-processed (Willems 2013; Butler and Davies 2011). To overcome this problem, a design rainfall hyetograph with a specific temporal pattern, which is known as a design storm, is used instead in practice (Yen and Chow 1980; Wenzel 1982; Willems 2000; Madsen et al. 2002). Design storms can be derived by following one of two distinct approaches. The first approach is to extract the rainfall intensity from intensity–duration–frequency (IDF) curves and apply an arbitrary temporal distribution to that intensity to obtain the design storm (Kiefer and Chu, 1957; Desbordes, 1978). The second approach is to analyse specific storm events from the observed rainfall data to derive the temporal distribution (Huff, 1967; Nguyen et al., 2010). For both approaches a statistical analysis is performed before the hydrological model simulations. The statistical analysis has assumed that the frequency of urban drainage peak flow is equal to the corresponding frequency of the rainfall event. Such assumption is applied for areas that have a large proportion of paving, which is most often the case for urban runoff. Also, when the concentration time is almost constant for a specific location in the drainage system. In addition, such areas should have no strong seasonal variation such as watershed hydrology where the soil saturation level can affect the runoff. For the above conditions, the high rainfall intensities at a given location result in large peak sewer flows.

Different design storms have been derived, developed, and adopted around the world. Kiefer and Chu (1957) were the first to develop the Chicago storm in the USA, and later other alternative patterns were developed; for example, by Sifalda (1973), Pilgrim and Cordery (1975), the UK *Flood Studies Report* (FSR, 1975), Desbordes (1978), Yen and Chow (1980), and the UK *Flood Estimation Handbook* FEH (1999). The drawbacks of these

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approaches have been summarised in many previous studies (McPherson, 1978; Walesh, 1979; James and Robinson, 1982; Rivard, 1996). One of the shortcomings of these approaches that this study seeks to address concerns the fixing of the shape of the temporal pattern for rainfall storms regardless of changes in the climate. Using the current approaches, a specific current rainfall intensity is expected to appear in the future but with a shorter return period (IPCC, 2012). If we apply the temporal pattern of any of the abovementioned design storms for this rainfall intensity and for two different climates (i.e. current and future climates), the two storms will end up with exactly the same temporal distribution and peaks at the same location. However, Wasko and Sharma (2015) showed that the rainfall temporal pattern in Australia is changing with temperature due to climate change. The observed relation between rainfall and temperature, which is known as scaling, results from the natural variability in the present climate. The authors investigated the scaling values for each fraction of the rainfall temporal pattern and have found that the highest rainfall fraction scales positively, while the lowest fraction scales negatively with temperature regardless of the season and the type of event (see Fig. 1 in Wasko and Sharma 2015). The adjustment of the temporal pattern for a range of temperature changes using different scaling values for different locations (depending on the location of the station where the scaling is derived) was found to greatly affect the peak flood value in these locations (Wasko and Sharma, 2015). Another recent study by Müller et al. (2017) confirms the findings of Wasko and Sharma, 2015 in which changing the shape of rainfall event has a great effect on the peak flow of combined sewer system. However, the authors in Müller et al. (2017) study adopt a continuous rainfall time series instead of design storms.

For the UK climate, all the previous studies have investigated the scaling relationship concentrated on the scaling of the overall storm event intensity, termed as storm volume, and the most recent of these studies have investigated such a relation for subdaily data, and more specifically for extreme hourly data (Jones et al., 2014; Blenkinsop et al., 2015; Chan et al., 2016). However, none of the previous studies examined the scaling values for the UK climate for the individual fractions of storm event (i.e. rainfall temporal pattern) (see Section 3.1 for the definitions and more details of rainfall volume and rainfall fractions). It would be of interest to the hydrological community to explore such an issue besides Australia so that a more complete pattern around the world could be derived.

Thus, the objectives of this study are to: (1) study the scaling relationship for both the storm volume and the individual fractions of the storm event, termed the temporal pattern; for storms with and without seasonal separation and (2) investigate how a change in the temporal pattern can affect the peak flow of the sewer system of a particular urban area for the future climate.

2. Catchment and observed data

The study area, which is a small urban catchment with an area of approximately 12 km × 5 km, is located in West Yorkshire in the north of England. The UK Environment Agency (EA) provides rainfall data at a 15-min temporal resolution from tipping bucket gauges that cover large parts of the UK. However, all the gauges provided by the EA were located outside the study area, thus only the 28 closest gauges were used for this study (Fig. 1). As shown in Fig. 1, some of the gauges are located far away from the catchment at distances of more than 40 km. Thus they may not seem relevant to the study area. However, these gauges were included in order to investigate whether there is a link between scaling values and altitude, as concluded by Wasko and Sharma (2015) for Australia, or not as found by Blenkinsop et al. (2015) for the UK. A quality check of the gauges was performed by using the procedure in Fadhel et al. (2016). The procedure consists of two steps: First, the spatial consistency between nearby gauges is tested (i.e. the gauge being tested is compared with neighbouring gauges). Second, the gauges that are flagged up as a result of the first check are subjected to another test using radar data. This is because rainfall is highly variable in space and time, so the performance of a gauge during a convective storm is not necessarily consistent spatially with that of neighbouring gauges. It should be noted that when the period of rainfall data for the gauges was not covered by the radar data (i.e. before 2006 in this study) only the first quality check was used. The temporal coverage for each gauge is shown in the table in Fig. 1.

The daily temperature data used in this study was the gridded temperature data provided by the climate hydrology and ecology research support system meteorology dataset (CHESS-met) (1961–2015) and was at the 1-km space scale. The CHESS-met air temperature was derived by Robinson et al. (2015) for a reference height of 1.2 m. The authors interpolated the MORECS air temperature from a scale of 40 km to a 1-km resolution based on the bicubic spline method. Later, the integrated hydrological digital terrain model was adopted to adjust the elevation for each pixel of the 1-km grid interpolated data. The 1-km spatial resolution of temperature data may be too high for daily data and lower resolution data could also (or better) be used. Further studies are needed based spatial correlation or semivariograms in order to work out the spatial variability of temperature distribution in the study area. A suitable spatial temperature resolution could then be derived.

The CHESS-met temperature data for the period 2004–2015 was used alongside the rainfall data to derive the scaling values.

3. Methodology

3.1. Scaling for rainfall volume and rainfall temporal pattern

The procedure in Wasko and Sharma (2015) was adopted to study the scaling relationship for both the storm volume (which is defined as the total rainfall depth in mm for a given storm event duration) and the storm fractions for five different durations. The largest 500 storm events in terms of volume for each rain gauge within the common period for all gauges (2004–2015) and a given duration were chosen (Wasko and Sharma, 2015). Extracting such a high number of events ensures that all the heavy rainfall events that occur over the year are considered. Independent events were identified by using the criteria defined in Willems (2000), where two extreme events should be separated by at least a 12-h time interval if the duration is less than 12 h, while for longer durations a time interval larger than the considered duration should be used to delineate the independent events.

Various storm event durations, ranging from 1 h to 24 h, were included in the study (the values of the durations are shown in Fig. 3). Since the gauge network used in this study has a 15-min resolution, the maximum number of fractions for a storm duration of 1 h can only be four (i.e. each fraction has a timescale of 15 min). Thus, to be consistent with storms of other durations the fractions also need to be four in number as well. Therefore, for each duration, the precipitation records were accumulated to ensure that the storm events were grouped in exactly four periods in length. For example, to analyse a 3-h storm event, the rainfall was accumulated into durations of 45 min to end up with a storm of four increments of equal duration. Similarly, a 6-h storm event was split into four increments consisting of four 90-min increments. Later, each storm event was matched to its concurrent temperature.

Most of the previous studies adopt the binning method to derive the scaling values for the rainfall-temperature relationship. The method involves binning rainfall data in temperature bins so