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Increase in urban flood risk resulting from climate change – The role of storm temporal patterns

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Abstract

Warming temperatures are causing extreme rainfall to intensify resulting in increased risk of flooding in developed areas. Quantifying this increased risk is of critical importance for the protection of life and property as well as for infrastructure planning and design. The study presented in this manuscript uses a comprehensive hydrologic and hydraulic model of a fully developed urban/suburban catchment to explore two primary questions related to climate change impacts on flood risk: (1) How does climate change effects on storm temporal patterns and rainfall volumes impact flooding in a developed complex watershed? (2) Is the storm temporal pattern as critical as the total volume of rainfall when evaluating urban flood risk? The updated NOAA Atlas 14 intensity-duration-frequency (IDF) relationships and temporal patterns, widely used in design and planning modelling in the USA, form the basis of the assessment reported here. Current literature shows that a rise in temperature will result in intensification of rainfall. These impacts are not explicitly included in the NOAA temporal patterns, which can have consequences on the design and planning of adaptation measures. We use the expected increase in temperature for the RCP8.5 scenario for 2081-2100, to project temporal patterns and rainfall volumes to reflect future climatic change. The modelling analysis for a 22 km^2 developed watershed show that temporal patterns cause substantial variability in flood depths during a storm event. The changes in the projected temporal patterns alone increase the risk of flood magnitude between 1 to 35 % with the cumulative impacts of temperature rise on temporal pattern and the storm volume increasing flood risk by between 10 to 170 % across the locations that were referenced for a 50 year return period storm. The variability in catchment response to temporal patterns show that regional storage facilities are sensitive to rainfall patterns that are loaded at the latter part of the storm duration while the short duration extremely intense storms will cause extensive flooding at all locations. This study shows that changes in temporal patterns will have a

significant impact on urban/suburban catchment response and need to be carefully considered and adjusted to account for climate change when used for design and planning future stormwater systems.

Keywords: Storm Temporal Patterns, Urban hydrology, Climate Change, urban flood risk.

1 Introduction

Recent history shows that extreme weather events are occurring more frequently and in areas that have not had such events in the past (Hartmann et al., 2013). There are more land regions where the number of heavy rainfall events has increased compared to where they have decreased (Alexander et al., 2006; Donat et al., 2013; Westra et al., 2013a). A case study on the Oshiwara River in Mumbai, India has shown a 22 % increase in the overall flood hazard area within the catchment (Zope et al., 2016). Intensification of rainfall extremes (Lenderink and van Meijgaard, 2008; Wasko and Sharma, 2015; Wasko et al., 2016b) and their increasing volume (Mishra et al., 2012; Trenberth, 2011) has been linked to the higher temperatures expected with climate change. This increase in the likelihood of extreme rainfall and its intensification creates a higher risk of damaging flood events that cause a threat to both life and the built environment, particular in urban regions where the existing infrastructure has not been designed to cope with these increases. Adapting to future extreme storm events (i.e. flood events) will likely be costly in both economic and social aspects (Doocy et al., 2013). Properly addressing this increased flood risk is all the more important given the expectation that the urban population is projected to grow from the current 54 % to 66 % of the global population by the year 2050 (United Nations, 2014).

Adaptation as a way to address the effects of climate change has only recently gained attention (Mamo, 2015). The effectiveness of adaptation is dependent on the accuracy of simulating projected impacts, such as the effectiveness of a flood control structure to protect a city from flooding in the future, and, the uncertainty in projected impacts, as this will limit the amount of adaptation that society will accept (Adger et al., 2009). The foundation of adaptation measures to deal with flooding is typically based on flood forecasting and hydrologic/hydraulic (H/H) modelling (Thodsen, 2007). Prior to the advent of computers and the increase in computational power, drainage design was based on simple models of peak

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discharge rates using methods such as the rational formula in combination with Intensity/Duration/Frequency (IDF) curves (Adams and Howard, 1986; Nguyen et al., 2010). Consideration of the environmental impacts related to flow rates, volumes, water quality and downstream impacts requires more complex systems and ways to simulate the hydrologic and hydraulic processes in a more realistic manner (Nguyen et al., 2010). As such, the state of the art in modelling urban sewer and stormwater related infrastructure uses distributed, fully dynamic, hydrologic and hydraulics modelling software such as SWMM, infoWorks, TUFLOW and MIKE packages (Singh and Woolhiser, 2002). The dynamic approach and integrated nature of current modelling requires the use of temporal patterns to distribute rainfall and volumes that closely resemble actual storm events (Nguyen et al., 2010; Rivard, 1996).

Temporal patterns have typically been derived using the alternating block method from IDF curves where shorter storm durations are nested within longer storm duration design intensities (García-Bartual and Andrés-Doménech, 2016; Victor Mockus and E. Woodward, 2015) . However, this method does not represent a real storm structure. Alternatively, (Huff, 1967) presented the first rigorous analysis of rainfall temporal patterns (García-Bartual and Andrés-Doménech, 2016), where rainfall temporal patterns were derived from observations. Similar methods include the average variability method, where a storm is partitioned into fractions of equal time, and each fraction is ranked. The temporal distribution is then specified as the most likely rainfall order with the average rainfall used for the associated fraction (Pilgrim, 1997). NOAA Atlas 14 provides an updated set of temporal distributions and IDF curves for use in a major portion of the United States (Perica, 2013) that are now widely used for planning and design modelling analysis. These temporal distributions and rainfall depths are based on observed data and were generated using methodology similar to (Huff, 1967). The major concern is that the analysis and methods used in Atlas 14 assumes a stationary climate over the period of observation and application (Chapter 4.5.4 of Atlas 14 volume 8). This seems contrary to prevailing scientific thought (Milly et al., 2007) and can lead to inadequacies of future stormwater infrastructure as there is evidence to believe that warmer temperatures are forcing intensification of temporal patterns (Wasko and Sharma, 2015) and an increase in variability (Mamo, 2015). Several previous studies have examined the sensitivity of urban catchments to changes in intensity and temporal patterns with peak runoff rates and volumes modelled (Lambourne and Stephenson, 1987; Mamo, 2015; Nguyen et al., 2010; Zhou et al., 2016). For example, Lambourne and Stephenson (1987) presented a

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comparative model study to look at the impact of temporal patterns on peak discharge rates and volumes. However, these studies largely ignored the detailed hydraulic conveyance aspects of storage ponds, sewers, culverts, and flow control structures, with the exception of (Zhou et al., 2016), which play an important role in how the flow rates generated during runoff move through and impact on the built environment.

In this study, we focus on the range of results generated from detailed H/H modelling arising from precipitation pattern variability and the impact of climatic change. In particular, we focus on the temporal distribution of rainfall to assess and illustrate the variability in how different catchments respond to different rainfall patterns. The primary questions that we address are;

1. What is the relative importance of the storm pattern and volume of rainfall on urban flood peaks?
2. How will climate change affect storm patterns and volumes and what are the impacts on urban flood peaks?

2. Impact of climate change on flooding in urban stormwater systems

Developed urban areas present the highest probability of causing damage and loss of life during flood events. There has been an increase in urban flooding in the past decade with densely populated developing countries like India and China coming into focus (Bisht et al., 2016; Zhou et al., 2017). In particular, flooding in Uttarakhand and Kashmir, which was caused by extreme rainfall coupled with inadequate stormsewer design, is blamed for 580 and 200 deaths respectively (Bisht et al., 2016). China has also experienced a devastating flood season in 2016 (Zhou et al., 2016) with the rapid increase in urbanization. Even with better planned and mature urban cities, Europe and North America are not immune to flooding in urban areas (Ashley et al., 2005; Feyen et al., 2009; Smith et al., 2016). The main characteristic of stormwater in urban areas is that the flows are predominantly conveyed in constructed systems, replacing or modifying the natural flow paths. Hence, the proper design of these conveyance systems becomes crucial in managing flooding during extreme storms. Impacts of climate change are expected to increase the risk of flooding and further exacerbate the difficulty of flood management in developed environments.

The number of studies investigating climate change impacts on urban flooding is increasing as the importance of this topic is more and more recognized. However, research focusing on

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the impacts of climate change on precipitation temporal patterns remains limited. The majority of available research use Global Circulation Models (GCMs) and Regional Climate Models (RCMs) combined with statistical downscaling techniques to project IDF curves to reflect future climate conditions (Mamo, 2015; Nguyen et al., 2010; Schreider et al., 2000). For example Mamo (2015) used monthly mean wet weather scenario data projected by four GCMs for the period 2020-2055, along with historic data from 1985 to 2013 to develop revised IDF curves , which were then used as weather generator input using LAR-WG, from which data was generated to develop the revised IDF curves. (Nguyen et al., 2010) used data sets generated by two separate GCMs are used to develop IDF and temporal patterns to reflect future rainfall patterns. The inconsistent results generated by the two different GCMs in the (Nguyen et al., 2010) study illustrate the challenge of forecasting future climate conditions with GCM generated results. It is recognized that GCM results form the largest part of the uncertainty in projected flood scenarios (Prudhomme and Davies, 2009).

Alternatively, research has shown that temperature, which influences the amount of water contained in the atmosphere, can have an impact on the patterns and total rainfall volumes of storm events (Hardwick Jones et al., 2010b; Lenderink and van Meijgaard, 2008; Molnar et al., 2015; Utsumi et al., 2011; Wasko et al., 2015; Westra et al., 2013a). In general, intensification of rainfall events is expected with a trend towards ‘invigorating storm dynamics” (Trenberth, 2011; Wasko and Sharma, 2015). Even though forecasts for climate change impacts on future flooding have a ‘low confidence’ global scale trends in temperature extremes are more reliable (Seneviratne et al., 2012). Following successful studies (Wasko and Sharma, 2017; Westra et al., 2013b) we take the approach of using temperature to project temporal patterns and rainfall volume to account for climate change impacts. As described in detail in section 3, we examine historical rainfall data coupled with daily average temperature to project temporal patterns and rainfall volumes to account for climate change impacts.

Flood risk assessment and communication depend on flood risk mapping, for which flood inundation areas are needed (Merz et al., 2010). Urban catchments are typically complex and need to capture the response of the system along with the interactions of the various components of the stormwater infrastructure (Zoppou, 2001) to provide reliable flood depths to develop inundation areas. Including the complex hydraulics and possible hydraulic attenuation and timing of congruent flows will have an impact on flooding, particularly in developed environments. As mentioned, there are an increasing number of catchment/basin scale and urban modelling studies that have been performed (Cameron, 2006; Graham et al., 2007; Leander et al., 2008; Zhou et al., 2016; Zope et al., 2016). However, there is a lack of a detailed study that looks at assessing future flood damage in a developed environment (Seneviratne et al., 2012). The majority of these past studies focus on either the hydraulics modelling component or the rainfall intensity aspect and mostly overlook the crucial detail of rainfall patterns. As discussed, temporal patterns of rainfall is now a critical aspect of design and planning of future storm systems. Research which uses temperature to project future rainfall and associated temporal patterns of rainfall, and then assesses impacts on flooding has not been performed. This study aims to fill this research gap through an elaborate analysis of how rainfall intensities and patterns impact urban flood risk in a warmer climate.

3. Study location, data and methodology

This section describes the data and methods used to evaluate the variability in flood risk as well as the impact to flood risk due to an increase in temperature. Broadly, the steps followed are:

1. Apply multiple temporal patterns and rainfall volumes with their associated confidence limits in the H/H model to establish the variability in the flood risk
2. Following (Lenderink and Attema, 2015; Wasko and Sharma, 2015) develop scaling factors for the volume and temporal pattern for future conditions using temperature as index
3. Evaluate impact of temperature rise on flood risk by scaling temporal patterns for a temperature increase
4. Evaluate cumulative impact of temperature rise on flood risk by scaling volume and temporal patterns

The hydrologic and hydraulic modelling presented in this paper was done using an EPA-SWMM model of an urban/suburban catchment in Minneapolis, Minnesota, USA. The SWMM software package was initially developed by the United States Environmental Protection Agency (EPA, 2016)and has since been used as the base engine for most of the industry standard H/H modelling packages.

3.1 Study Location and model

The H/H model used in this study was developed for the South Washington Watershed District (SWWD) in the State of Minnesota, USA for the management of surface water flows and as well as land use planning and management. The catchment area of the SWWD is a

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Discussion started: 30 June 2017

highly developed urban/suburban area and extends over 140-km^2. The model has extensive detail of all landuse types and stormwater infrastructures including sewers, culvert crossing, open channel reaches, and constructed as well as natural storages. For the purposes of this study and to reduce the complexity and model run times, the model was trimmed to the upper section of the SWWD representing an area of approximately 22 km^2. Figure 1 presents the focus area. An important feature of this particular model is the level of detail of the watershed storm sewer infrastructure as well as careful modelling of overflow routes to capture all the flow during the peak. Figure 1 also shows the schematic of the model network to illustrate the level of detail of the existing storm water infrastructure captured in the model. This level of detail results in accurately modelling the travel time of flows within the watershed and capturing all the runoff volume generated from the storm. The proper simulation of hydraulic attenuation and a variety of landuse types provide an ideal platform for this study.

Table 1 lists the primary reference locations that are used for this study. The locations have specifically been chosen to represent the range of possible conditions that are encountered in urban catchments. The sub-catchment sizes vary from less than 0.5 km^2 to approximately 2 km^2, with an overall catchment of 22 km^2. Different land uses such as commercial and industrial or different types of residential areas, as well as the amount of storage, have all been considered. It is important to note that these locations were selected prior to any model runs or availability of results and hence do not bias the results presented. Table 1 gives a description of the primary landuse type of the subwatershed that drains to each reference location along with the watershed area and the overall percentage of impervious surface area within that watershed. It also describes if there are local storage ponds, either natural or constructed, that provide rate and volume control.

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Discussion started: 30 June 2017

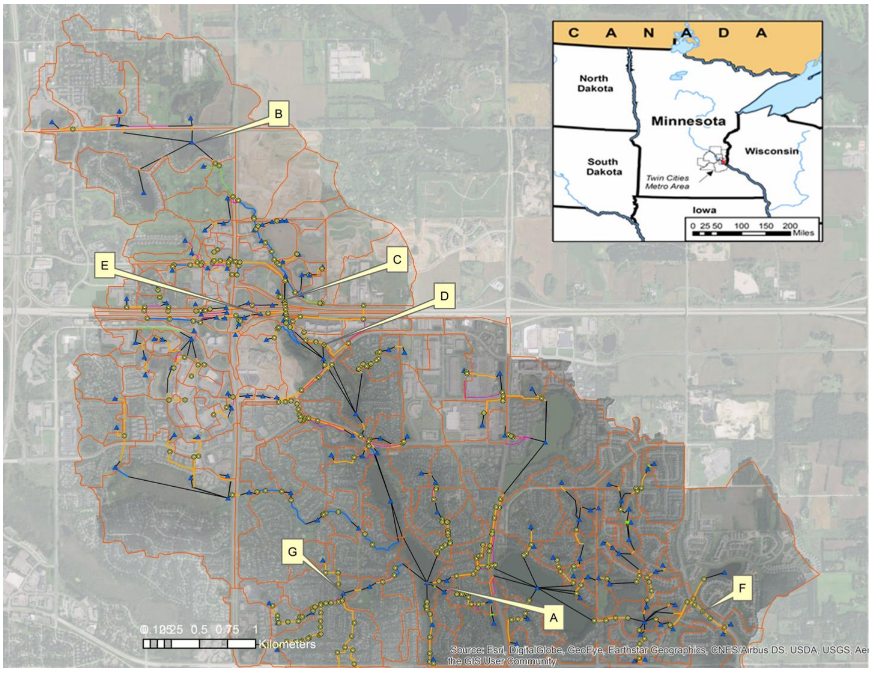

Figure 1 Location of the model and the sub-watersheds along with the reference points used in the discussion below. The details of the reference points and further explanation are presented in Table 1

Table 1. Description of reference locations presented in Figure 1 and used to present results. Each location represents a variation of landuse within the watershed

Reference point for results presented in figures	**Landuse types and description**	**Watershed Area (km^2)**	**Average Percent impervious**
(A) Wilmes	Natural lake and downstream limit of watershed.	~ 22	-
(B) Upstream	Predominantly rural, lower density residential landuse with good tree canopy and green spaces. Natural wetlands to mitigate flow with minimal to constructed storage	2.2	32
(C) Business park	Office space and parking lots with green space mixed in. Constructed storage and infiltration to help mitigate runoff	0.5	42
(D) Commercial 1	Retail and parking dominates this area with some green spaces added in. Minimal constructed storage. Two	.25	60

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Discussion started: 30 June 2017

	sub-surface infiltration basins installed under parking lots		
(E) Commercial 2	Retail and parking dominates this area with substantial constructed storage to help mitigate runoff rates and volumes. Part of the highway also drains through this point.	.75	48
(F) Residential 1	Medium density residential landuse with minimal constructed storage.	.35	24
(G) Residential 2	Medium density residential landuse with constructed storage.	1.05	39

3.2 Precipitation and Temperature Data

The precipitation and temperature data used in the analysis were sourced from the National Centers for Environmental Information hosted by the National Oceanic and Atmospheric Administration (NOAA). Both hourly and daily rainfall data were downloaded from the climate data online site for Minneapolis and St Paul (MSP) International Airport gauge, which is the closest major airport to the study area. Daily data for the MSP airport was available from 1901 through 2014, while hourly data was available from 1948 through 2014. Daily maximum, minimum and average temperature data was also downloaded for the site for the period from 1901 through 2014. For this analysis days that did not have precipitation data were assumed to have no rain.

The temporal patterns for storms and the depths of rainfall were taken from NOAA ATLAS 14 volume 8 – the current state of the art design standard for this location. The modelling analysis centred on the 50-year (2% exceedance probability) storm, which is a total rainfall volume of 160 mm in 24-hours, for the area within the SWWD in the USA. The 90 % confidence margin storm depths were added to the analysis to look at how flood depths modelled vary with total precipitation (Table 2). Six temporal distributions (two patterns with their associated confidence margins) were chosen from NOAA ATLAS 14 volume 8 to investigate how flood depths are impacted by the shape of storm over a 24-hour period for each of the above mentioned total rainfall depths. Table 2 describes the different storm temporal patterns and each of the precipitation volumes modelled.

Table 2. Description of notation used in reference to the modelled storm depths and temporal distributions (NOAA Atlas 14 volume 8 appendix 5)

Design Rainfall	Description
160 mm 24 hour	2 % exceedance 24-hour duration (50-year return period) rainfall depth
12.5 cm 24 hour	Lower margin of the 90% confidence interval of the 2 % exceedance 24-hour duration (50-year return period) rainfall depth-Approximately Equivalent to the 20-year 24 hour ARI
21 cm 24 hour	Upper margin of the 90% confidence interval of the 2 % exceedance 24-hour duration (50-year return period) rainfall depth-Approximately Equivalent to the 200-year 24 hour ARI
Temporal pattern	**Description**
Q1-10 - (a)	NOAA Midwest region, 1st quartile 10th percentile temporal distribution
Q1-50 - (b)	NOAA Midwest region, 1st quartile 50th percentile temporal distribution
Q1-90 - (c)	NOAA Midwest region, 1st quartile 90th percentile temporal distribution
Q3-10 - (d)	NOAA Midwest region, 3rd quartile 10th percentile temporal distribution
Q3-50 - (e)	NOAA Midwest region, 3rd quartile 50th percentile temporal distribution
Q3-90 - (f)	NOAA Midwest region, 3rd quartile 90th percentile temporal distribution

The SWMM model was run for each of the precipitation amounts for the six temporal patterns, a total of 18 model runs, to generate the base dataset for current conditions and establish the variability in the current climate. The impact of climate change due to changed temporal patterns was assessed by modelling the 2% exceedance rainfall value (160 mm) with the temporal patterns that were scaled for an expected temperature increase (Section 3). Finally the cumulative impacts of changed temporal patterns and volume were evaluated by scaling both the rainfall volume and temporal patterns with temperature. An important point to note is that only the rainfall time series was changed appropriately for each model run. All the boundary conditions such as initials water levels at storage locations and all hydrologic parameters for each of the above model runs were kept the same for every model run.

3.3 Temperature scaling of temporal patterns and rainfall volume

To assess the impact of climate change, design storm temporal patterns and rainfall volumes need to be projected for a future warmer climate. Most methods that project rainfall for future climates focus on downscaling output from general circulation models to those required for hydrological applications (Fowler et al., 2007; Maraun et al., 2010; Prudhomme et al., 2002) through either dynamical or statistical models (Wilks, 2010). Downscaling methods however will not replicate design rainfall (Woldemeskel et al., 2016), so an attractive alternative is that proposed by (Lenderink and Attema, 2015) whereby historical temperature sensitivities (scaling) are directly applied to the design rainfall.

Using established methods (Hardwick Jones et al., 2010a; Utsumi et al., 2011; Wasko and Sharma, 2014), the volume scaling for the 24 hour storm duration was calculated using daily rainfall paired with daily average temperature. The rainfall-temperature pairs were binned on 2 degree temperature bins and a Generalized Pareto Distribution fitted to the rainfall data in each bin above the 99th percentile (Lenderink et al., 2011; Lenderink and van Meijgaard, 2008) to find extreme rainfall percentiles. A linear regression was subsequently fitted to the fitted extreme percentiles and used as the rainfall volume scaling.

Temporal pattern scaling was calculated using hourly data, again paired to the average daily temperature and followed the proposed methodologies in (Wasko and Sharma, 2015). The largest 500 storm bursts of duration 24 hours were identified in the hourly data, with each storm burst independent (not overlapping). The 24-hour duration storm bursts were divided into 6 fractions, each fraction with duration of four hours. Each fraction was divided by the rainfall volume and ranked from largest to smallest. An exponential regression was fitted to the fractions corresponding to each rank and their corresponding temperature to produce a temporal pattern scaling. The scaled temporal patterns were then applied and run through the H/H models.

4 Results and Discussion

The results as discussed in the following section show that the variability in temporal distributions of rainfall within a storm event can have significant impact on the level of flooding. We show that the current industry standard temporal distributions need to be adjusted to account for climate change impacts as do design rainfall volumes. The following sections provide a detailed discussion of each step of the analysis.

4.1 Temporal patterns and volume scaling

The scaling of the temporal pattern fraction for Minneapolis is presented in Figure 2. Table 3 provides the scaling that results from the fitted regression in each of the panels in Figure 2. A temperature change of 5^{0}C was selected to determine the percentage change based on temperature increases estimated for the RCP8.5 scenario in Figure SPM7(a)(IPCC 2014) projected for 2081-2100. As the slopes in Figure 2 and factors in Table 3 show, only the first fraction scaled positively, which means that the 4 hours that included the highest amount of rainfall scale up while the remaining rainfall fractions scale down. The results are consistent with "invigorating storm dynamics" that are discussed in the literature (Lenderink and van Meijgaard, 2008; Trenberth, 2011; Wasko and Sharma, 2015; Wasko et al., 2016b) resulting in a less uniform, more intense storm. The percentage adjustments were normalized to make sure that total rainfall amount did not change from the current value of 160 mm in 24-hours. Figure 3 shows (Q1-50 and Q3-50 shown as an example) the changes to the temporal patterns when the scaling percentages calculated above are applied. Figure 3 illustrates the change to the highest peak rainfall rate and the decrease in the rest of the rainfall fractions. Similar scaling was applied for all six temporal patterns that were used in the H/H modelling analysis. As an additional verification, a similar analysis was completed for two neighbouring locations (Sioux Falls South, Dakota and Milwaukee, Wisconsin). The fraction and volume scaling results for both Sioux Falls and Milwaukee were consistent with those discussed in this paper.

Figure 4 presents the precipitation volume temperature pairs, the extreme percentiles generated based on the temperature bins, as well as the resulting scaling for the 24 hour rainfalls. The daily total rainfall of 160 mm fell into the 99.99th percentile based on a cursory ranking of the daily precipitation data. Hence, the 99.99th percentile 2.92 % scaling was selecting for the 24 hour volume. This is broadly consistent with (Utsumi et al., 2011) and (Wasko et al., 2016a) who present scaling between 2 and 5 % for the central north of the U.S for the 99th percentile and throughout Australia. This value is less than the scaling found by (Mishra et al., 2012) who used hourly precipitation, which is consistent with the expectation that shorter duration extremes scale more (Hardwick Jones et al., 2010a; Panthou et al., 2014; Wasko et al., 2015). This scaling converts to an approximately 20 % increase in the volume of rainfall for a 24 hour period for a five degree increase. Applying the 20 % increase to the

160 mm in 24-hours gives a rainfall depth of 208 mm in 24 hours. Coincidentally, 208 mm(~210 mm) in 24 hours is the upper margin of the 90% confidence interval for the 160 mm event based on the margin provided in NOAA Atlas 14.

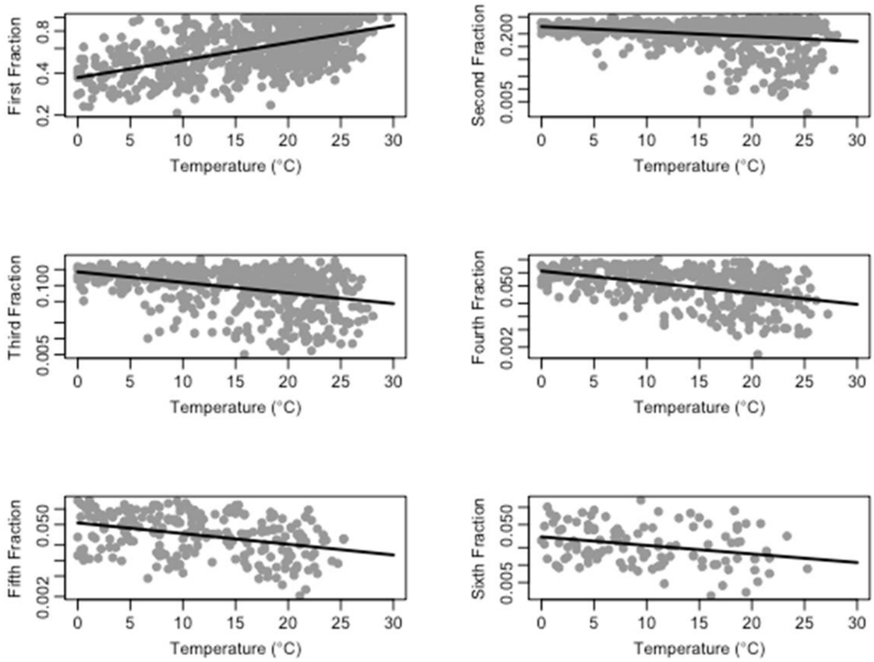

Figure 2. Scaling temporal pattern fractions with temperature for Minneapolis (1948-2014 hourly data). Black lines represent the fitted exponential regression.

Table 3 Temporal pattern scaling factors for each of the fractions

Fraction	Scaling factor
F1	0.029
F2	-0.026
F3	-0.045
F4	-0.057
F5	-0.047
F6	-0.033

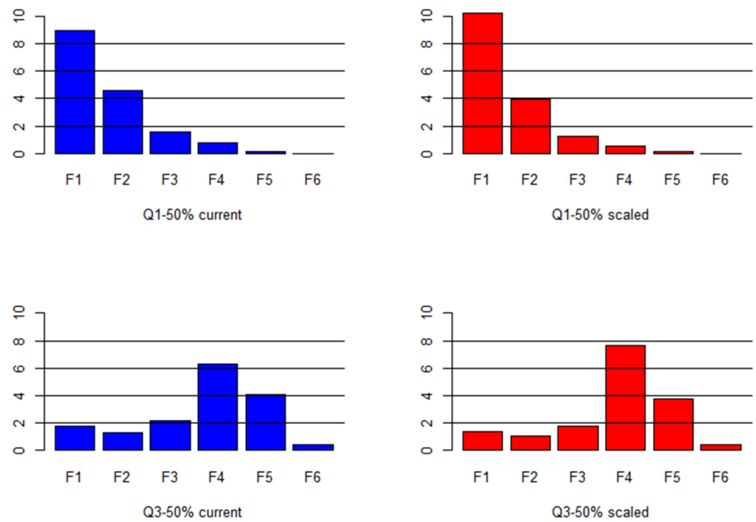

Figure 3 Q1-50 and Q3-50 temporal patterns projected for temperature rise of 5^{0} C. Total rainfall of 160 mm over 24 hours with each fraction representing accumulated rain for 4-hour periods.

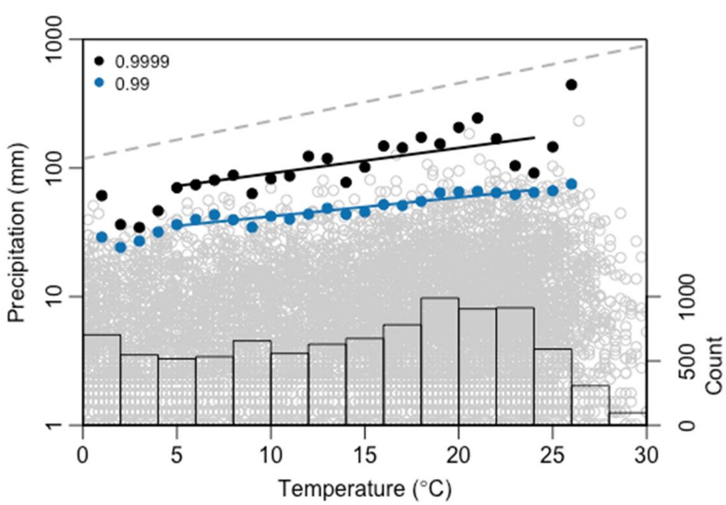

Figure 4 Scaling total volume of rainfall with temperature for Minneapolis (1901-2014 daily rainfall data). The grey dashed line represents a scaling of 7 %. The histogram represents the number of precipitation-temperature pairs.

4.2 Flood depth response to temporal patterns and total rainfall variability.

The hydrologic/hydraulic model was run for the 18 different combinations of rainfall volumes and temporal patterns. Results are presented for the five reference locations throughout the watershed that represent different landuse types that are typical in a developed area as described in Table 2. The flood depths extracted from the model were first analysed to compare variability between temporal patterns and total rainfall depth. The selection of the reference points essentially provides results at different sub-catchments, or different sub-models. These sub-models show the variation in catchment response to runoff generated by different land use types as well as how the flows then move through the different stormwater infrastructure.

Figures 5(a) shows the depth/time curve at Wilmes Lake (location A) which is the main regional collection point and the downstream end of the model. Each curve represents change in depth versus time for the six temporal patterns distributing the same total rainfall volume of 160 mm. The differences in shape, peak flood depth and the time to peak illustrate the variability of flooding that can result purely due to variation in in-storm rainfall pattern. A striking result is the approximately 30 % (1.3 m) variation in flood depth (relative to mean flood depth) at Wilmes Lake purely due to variation of how the rain falls within the duration of the storm. Not surprisingly, the highest flood depth curve is a result of the most intense storm event pattern which is the Q1-10 distribution. The depth at Wilmes Lake rises quickly during the Q1-10 event and then stays high for the longest duration. The high intensity of the Q1-10 pattern can overwhelm local conveyance and storage structures, resulting in uncontrolled overflow along city streets that flushes flow down to the low lying areas very quickly, causing the water level at the lake to rise. Interestingly the next highest peak flood level results from the Q3 pattern which has the majority of the precipitation loaded at the latter half of the storm event. This type of pattern results in higher runoff volume as the soil saturates and infiltration rates are reduced as well as local storage structures and ponds fill up by the time the bulk of the storm occurs. This suggests that, on average, regional storage facilities such as Wilmes Lake within the SWWD are more sensitive to the runoff volume than the instantaneous peak flow rate, and thereby more sensitive to end loaded temporal patterns during storms.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-352
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Discussion started: 30 June 2017

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Figure 5(b) illustrates the same type of variation of peak flood depth due to the different temporal patterns at each of the reference points. There is appreciable variation in peak flood depths at all locations with the smallest range at location B. As described in Table 1, location B has more rural landuse with local natural storage, which can explain the lack of variability in flood depth relative to changes in temporal patterns. The range of variation in flood peaks at locations C and D suggest that catchments with higher impervious have a higher sensitivity to rainfall patterns. Locations F and G are both residential catchments though the area draining to location G is larger. Additionally, locations F is a manhole within the storm sewer system while location G is local constructed pond, which suggests that variation in flow rates, or peak runoff from a catchment, does not always translate to higher variation in flood depths. In general, Figure 5(b) illustrates that temporal patterns of rainfall can lead to substantial variability in flood depths.

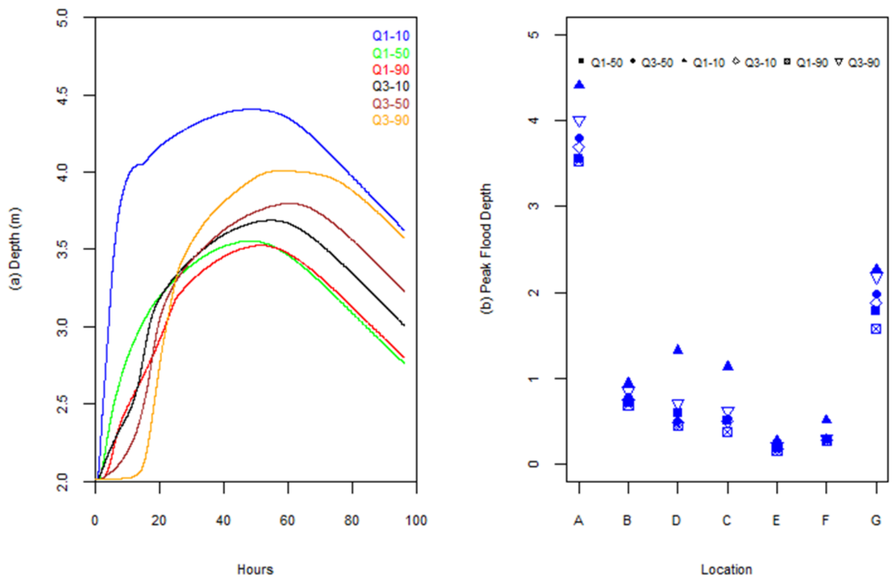

Figure 5 (a) Depth over time at Wilmes Lake (Location A), which is the downstream regional reference point in Figure 1. Depth vs time curves are plotted for 160 mm of total rainfall over 24 hours with the six temporal patterns. (b) Presents the variation of peak flood depth at reference locations throughout the watershed (ref to table 1) with variation of temporal patterns for a total of 160 mm of rainfall over 24 hours.

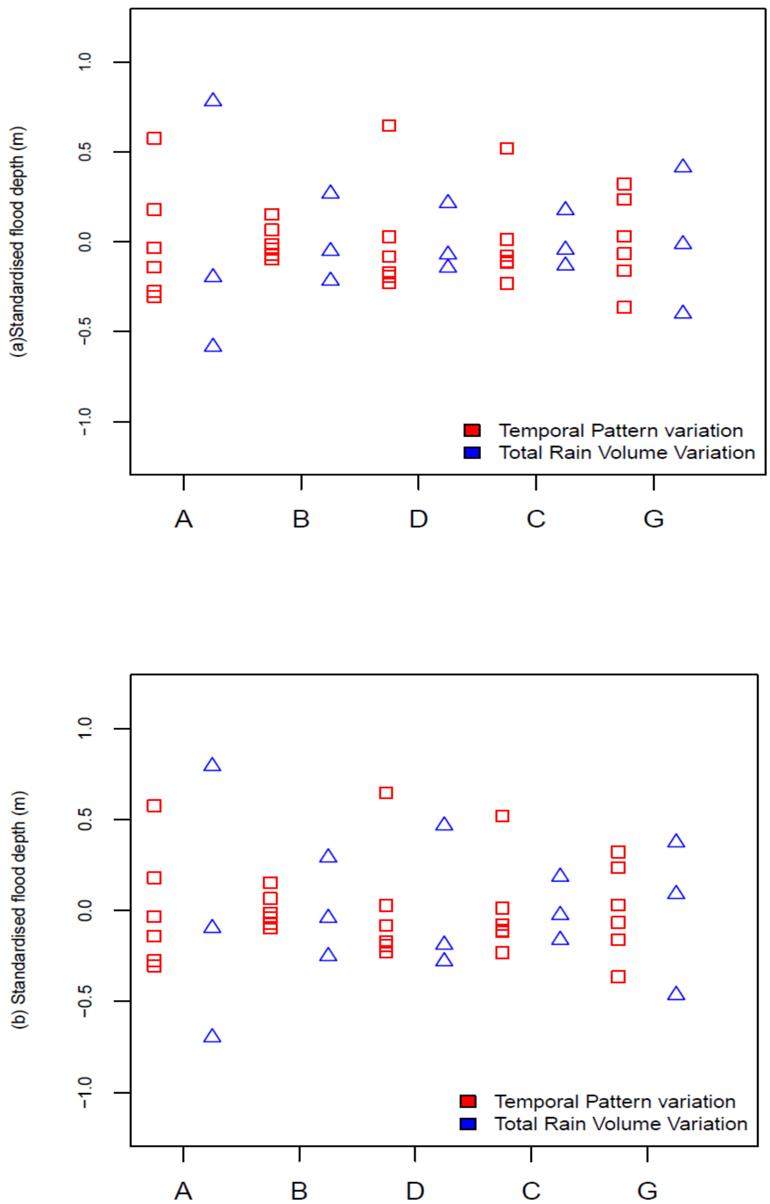

Figure 6 Comparison of total volume of rainfall and temporal patterns variability impact on peak flood depth (a) Flood depth variation due to the 6 different temporal patterns with 160 mm of rain compared to 110, 160 and 210 mm of total rainfall over 24 hours distributed over a Q1-50 temporal pattern. (b) Flood depth variation due to the 6 different temporal patterns with 160mm of rain compared to 110, 160 and

210 mm of total rainfall over 24 hours distributed over a Q3-50 temporal pattern. Flood depths were standardised by subtracting the mean at each location for ease of comparison

One of the primary questions that we set out to answer was the comparison of "how it rains" versus "how much it rains". For clarification, "how it rains" refers to the variation of temporal patterns during a storm event with the total rainfall volume for the storm event held constant. The term "how much it rains" refers to different volumes of rainfall for each storm event with the temporal pattern held constant. Figure 6 (a) and (b) make the direct comparison between the variations of peak flood depth between "how it rains" versus "how much it rains". The range in peak depths at the reference locations indicates how the different catchments respond to variability in storm volume and pattern.

Location A is the regional concentration point and as shown in Figure 5(a), flood depths here are more sensitive to total rainfall volume. It is interesting that the different temporal patterns did generate a comparable range in variation of flood depths at location A. Locations C and D have higher impervious surface area within the sub-watershed and show a wider range in flood depths due to temporal patterns. Location G, which represents a residential area responds more to variation in total rainfall volume. One of the interesting observations from Figure 6 is that the change in rainfall volume results in a larger variability when applied to a Q3 temporal pattern (Figure 6(b)). The general variability due to temporal patterns is higher when compared to a total rainfall volumes distributed over a Q1 temporal pattern. Combining these observations suggests that the changes in total rainfall volume have a bigger impact when the peak of the storm arrives at the latter half of the event. The results in Figure 6 clearly indicate that temporal patterns of storms play a significant role in watershed response to storm events. It is also clear that temporal patterns have to be carefully considered when looking at flood depths and extents, especially in complex and developed watersheds. In addition the range in the results shown in Figure 4 and 5 illustrate the importance of considering "how it rains" when trying to quantify uncertainties related to H/H modelling. This is especially a concern given the evidence to date that systematic change is occurring to rainfall patterns across climate zones, making them more intense and impactful in derived flood estimations (Wasko and Sharma, 2015).

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4.3 Impact of applying temperature scaling to temporal patterns and rainfall volume on flood depths

Figure 7 compares the results for projected temporal patterns with results from the base simulation. Both scenarios are based on the 50 year return period event which is 160 mm distributed over the six base and projected temporal patterns. The depth results shown in Figures 7 are variation of the peak flood depth around the mean of the results from the base conditions models. In other words, the depth results were standardized by subtracting the mean of the base conditions results from the results at each location.

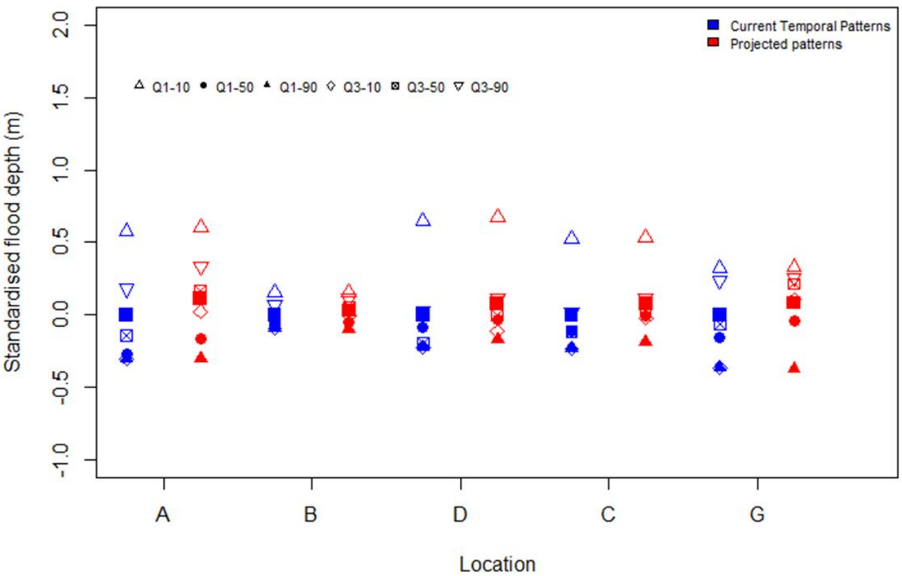

Figure 7. Impact of rise in temperature on the peak flood depth variation at reference locations within the watershed when scaling applied only to temporal patterns. The peak flood depths at each reference point are based on 160 mm of total rain distributed over the 6 temporal patterns used. Temperature scaling (T/S) for the temporal patterns are based scaling fractions presented in Figure 4. Flood depths were standardised by subtracting the mean from the base simulations presented in Figure 6 for each location.

There is an increase in peak flood depth with the projection of temporal patterns alone (Figure 7). Unsurprisingly, the highest flood depth results from the Q1-10 pattern for both current and scaled conditions. But the results at the highest depths show little change due to temperature scaling of the Q1-10 pattern. The Q1-10 pattern is an extremely high intensity event with majority of the rainfall occurring in the first fraction of the event. Applying the scaling to this fraction makes minimal changes to the overall pattern of rainfall. Interestingly, there is minimal to no change in the range of flood depths at each location due to the different projected temporal patterns when compared to the current conditions results. The change in mean flood depth is within the current overall variability of the results. Alternatively, if we take the extreme Q1-10 event out of consideration, one can say that qualitatively the mean of the flood depth for projected events does exceed the upper limit of the variability in flood depths for the base scenario.

The important fact is that these plots are based on the same total rainfall volume of 160 mm. All the variability is purely due to the differences in temporal patterns. The increase in mean flood depth in the projected condition is purely due to changes to the base temporal patterns and not due to any increase in rainfall volume. The mean of the peak flood depths does shift up at each location even with the differences in catchment characterises. This clearly provides the answers to the questions that were initially set, that the temporal patterns are an important factor that needs careful consideration and that climate change impacts on these temporal patterns will increase the likelihood of flooding in the future.

Figure 8 shows the same comparison as in Figure 7 when temperature scaling is applied to both the temporal pattern and rainfall volume. Hence Figure 8 presents the cumulative impacts of temperature scaling to the base conditions. As in Figure 7, the results in Figure 8 show the variation of results for both scenarios around the mean of the base condition flood depth at each location.

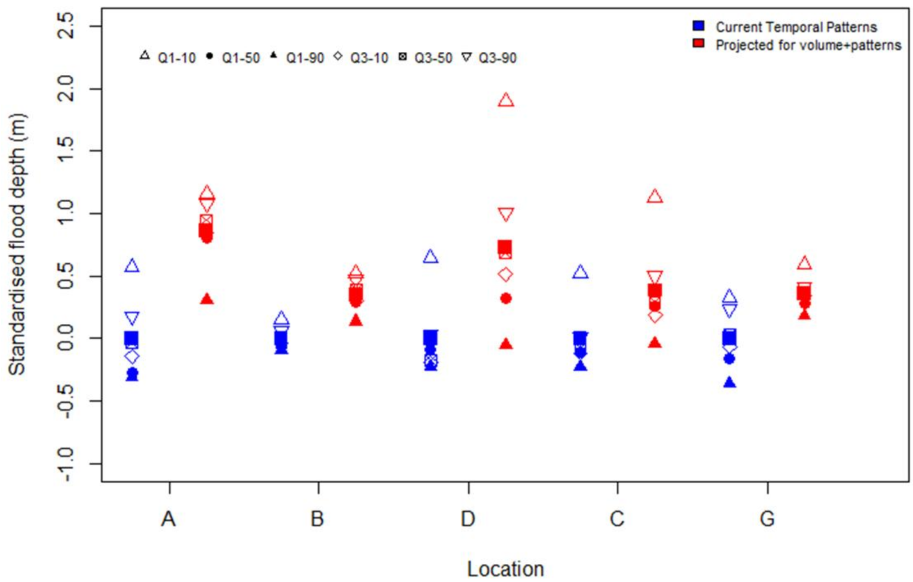

Figure 8. Impact of rise in temperature on the peak flood depth variation at reference locations within the watershed, when scaling applied to both rainfall volume and temporal pattern. The peak flood depths at each reference point are based on 210 mm of total rain distributed over the 6 temporal patterns used. Flood depths were standardised by subtracting the mean from the base simulations presented in Figure 6 for each location.

As expected, substantial increase in flood risk is seen when the cumulative impacts of changes to temporal pattern and increase in precipitation volume due to temperature rise are modelled. The mean flood depth is outside the upper margin of the highest flood depth for base conditions except at the business park (C). The business park location (C) comes close to meeting this threshold as well. The mean flood depth at Wilmes Lake (A) increases by approximately 1 m, which translates to a significant increase in the extent of flooding. The biggest change due to cumulative impacts occurs at the upstream location (B) were previously, when only the temporal patterns were scaled, minimal impact was shown. Additionally, the range of the results and the overall variability has increased at the commercial and business park areas (C, D) locations when compared to Figure 7. The higher intensity and the larger total volume of rainfall overwhelm the existing infrastructure with much larger surface overflows that increase the flood risk.

The increase in flood depth at the reference locations due to changes to temporal patterns alone range from 1 % to 35 %, while the cumulative impacts increase flood depth from 10 % to as much as 170 %. When considering all the nodes in the model, the average increase in flood depth due to changes in temporal patterns was 6 %. Similarly the average increase in flood depth throughout the entire model due to cumulative impacts of both changes to temporal pattern and rainfall volume is 37 %. The percentage increase shows that there is a significant impact to overall flood risk throughout the catchment and that it is not isolated to the reference points that are discussed in detail.

As mentioned above, the process of characterizing the way a catchment responds during a storm event and how the flows interact with the built environment in an urban setting is highly complex and variable. The variation of reference locations selected for this study provides a reasonable assessment of how the flows interact with the physical features of the catchment and how the results differ based on the location and features. This study clearly shows the sensitivity of the catchment to variation in how it rains, in particular the areas that are more impacted by volume as opposed to flow rate. Explicitly including intensification of rainfall patterns and volume due to climate change along with detailed H/H modelling to assess the variability in catchment response makes this study unique among available literature. The methodology presented here is universally applicable and the benefits of correctly designing infrastructure are likely to far outweigh the cost of the added effort, even in industry applications

5 Conclusions

The significance of temporal patterns and how climate change impacts on rainfall patterns affect flooding in developed environments was investigated using detailed hydrologic and hydraulic modelling. Climate change impacts were undertaken by projecting historical precipitation-temperature sensitivities on storm volumes and temporal patterns. The following conclusions can be drawn from the results presented;

1. The response of a complex catchment is sensitive to variability in rainfall temporal pattern. The flood depths varied in excess of 1 m at Wilmes Lake when different temporal patterns were used with a constant volume of precipitation.

2. The variability due to temporal pattern had similar magnitude when compared to variability due to total rainfall volume, which clearly shows that the temporal pattern of rainfall is as important as the volume of rainfall for the purposes of H/H modelling.
3. The temporal patterns intensified when scaled based on estimated temperature increases due to climate change.
4. A 1 % to 35 % increase in flood depth resulted when the scaled temporal patterns were used in the H/H model, suggesting an increase in potential flood risk purely due changes to "how it rains" as a result of climate change impacts.
5. A 10 % to 170 % increase in flood depth resulted when the projected rainfall volume was added to the projected temporal patterns.
6. The variability of flood depth at each location also increased suggesting that H/H modelling for future planning and design needs to give serious consideration to the aspects of variability of rainfall patterns as well as increase in rainfall amounts.
7. The study shows that regional storage facilities are sensitive to rainfall patterns that are loaded at the latter part of the storm duration while the extremely intense storms will cause flooding at all locations.

The effect of projected intensification of storms due to climate change impacts suggests that action needs to be taken promptly to prevent flood damages and possible loss of life. The two most important points that can be derived from this study is that temporal patterns and storm volumes need to be adjusted to account for climate change when applying to models of future scenarios. The general application of H/H modelling analysis needs to adopt an ensemble approach rather than a single event model to consider the significant variability in rainfall patterns that can generate a substantial range in results in order to make a properly informed decision as shown in this paper.

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Technical details of EPA-SWMM can be found at https://www.epa.gov/water-research/storm-water-management-model-swmm.

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