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Disentangling the impacts of human and environmental change on catchment response during Hurricane Harvey

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Abstract

Flooding is a function of hydrologic, climatologic, and land use characteristics. However, the relative contribution of these factors to flood risk over the long-term is uncertain. In response to this knowledge gap, this study quantifies how urbanization and climatological trends influenced flooding in the greater Houston region during Hurricane Harvey. The region—characterized by extreme precipitation events, low topographic relief, and clay-dominated soils—is naturally flood prone, but it is also one of the fastest growing urban areas in the United States. This rapid growth has contributed to increased runoff volumes and rates in areas where anthropogenic climate changes has also been shown to be contributing to extreme precipitation. To disentangle the relative contributions of urban development and climatic changes on flooding during Hurricane Harvey, we simulate catchment response using a spatially-distributed hydrologic model under 1900 and 2017 conditions. This approach provides insight into how timing, volume, and peak discharge in response to Harvey-like events have evolved over more than a century. Results suggest that over the past century, urban development and climate change have had a large impact on peak discharge at stream gauges in the Houston region, where development alone has increased peak discharges by 54% ($\pm 28\%$) and climate change has increased peak discharge by about 20% ($\pm 3\%$). When combined, urban development and climate change nearly doubled peak discharge ($84\% \pm 35\%$) in the Houston area during Harvey compared to a similar event in 1900, suggesting that land use change has magnified the effects of climate change on catchment response. The findings support a precautionary approach to flood risk management that explicitly considers how current land use decisions may impact future conditions under varying climate trends, particularly in low-lying coastal cities.

1. Introduction

In 2017, global natural disasters and man-made catastrophes exceeded \$337 bn (all values are in 2017 USD) where \$217 bn has been attributed to three tropical cyclone events in North America alone: Harvey, Irma and Maria (Swiss 2017). In the US, floods and tropical cyclones account for over half of losses from extreme weather and climate events since 1980

and their financial impact of individual events has risen dramatically in recent decades (NCEI 2019). While several studies have indicated that the placement of people at assets in flood prone areas as the primary driver behind escalating losses (Changnon *et al* 2000, Wing *et al* 2018), climate change has also increased the intensity and frequency of extreme precipitation events across much of the US (USGCRP 2017). It is difficult to draw conclusions

about the extent to which climate change has impacted fluvial flooding at regional scales because observed gauge records are influenced by both climate change and urbanization (IPCC 2012). The widespread flooding caused by Hurricane Harvey in 2017 provides an opportunity to study the influence of both climate change and urbanization on flood response at a regional scale.

Harvey made landfall as a Category 4 storm near Rockport, Texas at 0300 UTC on 26 August 2017 (NWS 2017). Over the next 12 h Harvey rapidly deteriorated into a tropical storm. Weak atmospheric steering currents led Harvey to stall over coastal Texas and warm air from the Gulf of Mexico continued to fuel the storm, releasing unprecedented amounts of rain between August 26 and 30. Storm totals exceeding 76.2 cm (30 in) were observed across much of south-east Texas and a record-breaking 4 d rainfall of 153.9 cm (60.58 in) was measured in Nederland, Texas, making Harvey the largest rainfall event in US history and eliciting the largest disaster response in Texas history (FEMA 2017).

Several studies have attributed Harvey's extreme rainfall to climate change (Emanuel 2017, Risser and Wehner 2017, Van Oldenborgh *et al* 2017, Kossin 2018, Trenberth *et al* 2018, Wang *et al* 2018), further exacerbated by the urban heat island effect (Zhang *et al* 2018). While there are slight differences in their findings, likely related to event definition, there is consensus that anthropogenic climate change influenced the volume of precipitation observed and the frequency with which Harvey-like storms could occur. On the other hand, other researchers have argued that the primary drivers behind Harvey's flood impacts were the city's widespread urban sprawl and lack of zoning regulations (Vano *et al* 2019). It remains unclear the extent to which either climate impacts or urbanization, and their additive effects, worsened flooding during Hurricane Harvey. This demonstrates a need for a robust analysis in which the different contributors to flood flows during Hurricane Harvey are disentangled, and the effects of anthropogenic climate change on flood flows are isolated from other potential drivers.

Recent studies in the Houston region have cited urbanization as a major contributor to flood risk (Khan 2005). These studies vary in scope, methodology and scale. Several utilize statistical approaches to analyze observed stream flows (Olivera and DeFee 2007, Zhu *et al* 2015, Berg 2018) or flooded structures (Brody *et al* 2013, 2014, Blessing *et al* 2017) at regional or watershed scales, whereas others employ hydrologic and hydraulic models to quantify changes in peak flows or inundation extent at a watershed scale ($<700 \text{ km}^2$) (Doubleday *et al* 2013, Sebastian 2016, Munoz *et al* 2017, Gori *et al* 2018). Although land use impacts on flood hazard have been relatively well-studied across the Houston region, there has been much less focus on the impacts of climate change on evolving flood hazard, and to the authors'

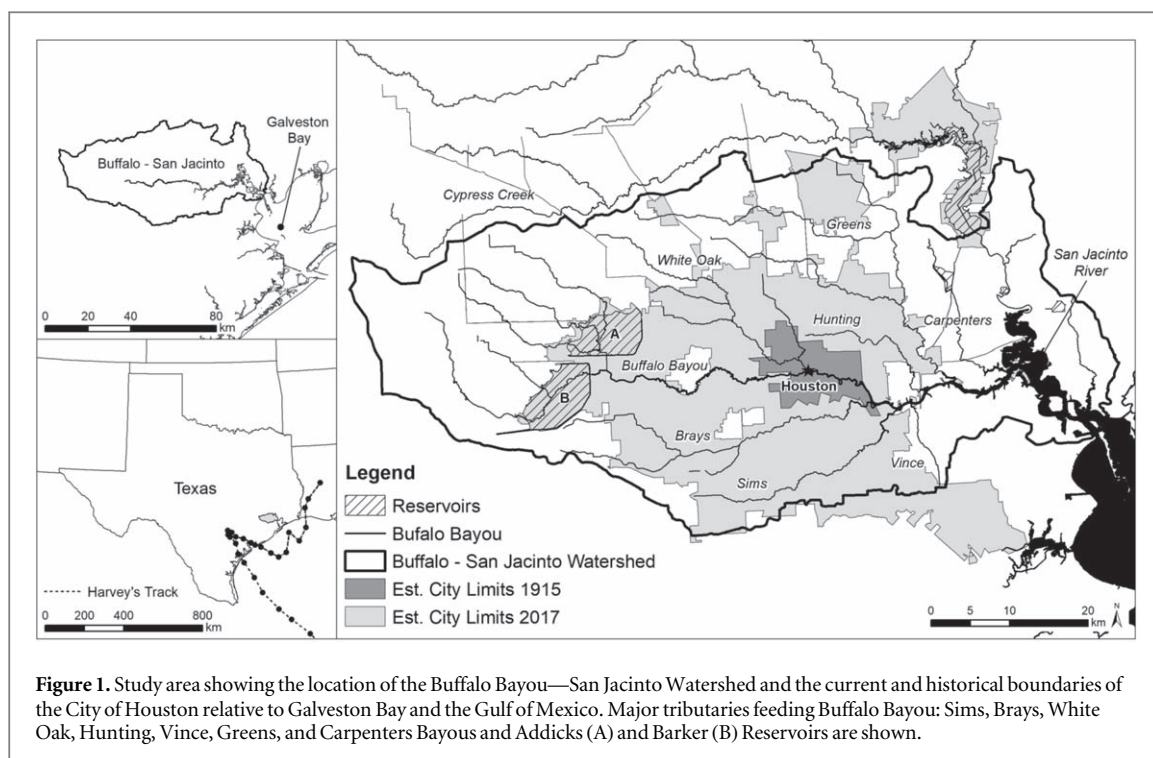
knowledge no studies in this region examining the joint impact of urbanization and climate change on catchment response.

More broadly, previous studies quantifying the impact of climate change and urbanization have been mostly carried out at the city or catchment scale (Jung *et al* 2011, Kaspersen *et al* 2015, Aich *et al* 2016, Pumo *et al* 2017). For example, Kaspersen *et al* (2015) input current and future rainfall extreme data in combination with historical and current land use data to a 2D flow model in order to quantify the relative contributions of climate and land use to flood hazard for a city in Denmark. They found that land use changes increased flood exposure by 6%–26%, while future climate impacts could exacerbate flooding by 40%–100%. These types of studies are useful since flood impacts from climate and land use change very widely based on local factors, such as soils, topography, and local flood infrastructure (Pelletier 2015). Previous studies have typically focused on return period storm analysis, but there has been less attention given to single-event attribution. Single event attribution can be valuable in cases where a storm event far exceeds typical design return levels, such as the magnitude of precipitation observed during Hurricane Harvey.

This study aims to address the limited understanding of the interactions between urban development and climate change on flood risk over long time scales and presents new estimates of anthropogenic influences on peak discharge in Houston, Texas. In order to disentangle their relative impacts and influence on flooding during Harvey, we model the interplay between urbanization and anthropogenic climate change using a physics-based, distributed hydrologic model and land use/land cover (LULC) datasets representing historical (c. 1900) and current development conditions. The results of our analysis indicate that urbanization significantly increased the flood flows observed during Hurricane Harvey and decreased the capacity of the watershed to adapt to changing climate conditions over the previous century.

2. Data and methods

We develop four scenarios to assess the relative contribution of climate change and urban development to flood risk over the past century: (i) a baseline scenario that represents pre-development conditions circa 1900, (ii) a climate change-only scenario, (iii) a development-only scenario, and (iv) current conditions scenario. These scenarios are represented and modeled using a fully distributed, physics-based hydrologic model, and their peak discharge, runoff volume, and time-to-peak are compared. The following sections present the data and methods used to develop the scenarios and the hydrologic model.



2.1. Study area

As a study location for this paper we selected the larger Buffalo-San Jacinto watershed (USGS HUC8 #12040104). The watershed has an area of 2531 km² and features over 2591 km of open drainage channels (HCFCD 2018). The elevation of the watershed ranges from approximately 0–5 m above mean sea level (msl) to 60 m above msl. Buffalo Bayou serves as the primary channel for the watershed (figure 1) and is fed by several major tributaries, including: Sims, Brays, White Oak, Hunting, Vince, Greens, and Carpenters Bayous. In addition, due to flat topographic slopes in the north-western part of the watershed and limited conveyance capacity of the neighboring Cypress Creek, significant volumes of water can spill over the watershed divide during intense rainfall events (HCFCD 2015, Gori *et al* 2018). To accommodate this overflow and protect downtown Houston from flooding, two large dry reservoirs—Addicks and Barker—were built in the 1940s. For the purpose of this study we focus on the developed areas in Buffalo Bayou and its tributaries upstream of its confluence with the San Jacinto River. A full description of the study area can be found in the supplementary material, which is available online at stacks.iop.org/ERL/14/124023/mmedia.

2.2. Hydrologic model

To examine the relative impacts of climate change and urbanization on catchment response in Houston during Hurricane Harvey, we simulate flood hydrographs for four LULC and climate scenarios using the computationally efficient physics-based, distributed hydrologic model *Vflo*[®]. *Vflo*[®] was chosen because it has been widely applied and validated in hydrologic

studies in the Houston region (Fang *et al* 2010, Fang *et al* 2011, Doubleday *et al* 2013, Torres *et al* 2015, Sebastian 2016, Juan *et al* 2017, Blessing *et al* 2017, Gori *et al* 2018), and its efficient implementation of the Kinematic wave analogy (KWA) which is a simplification of the 1D Saint-Venant equations, allows high-resolution simulations to be efficiently conducted over large model domains. The flow direction network was constructed using a 10 m digital elevation model (DEM) from the US Geological Survey (USGS) 3D Elevation Program (3DEP) National elevation dataset (NED) and is made up of approximately 65 910 cells, each 300 by 300 m. Infiltration parameters were derived from the US Department of Agriculture (USDA) Gridded Soil Survey (gSSURGO). Infiltration is estimated using the Green and Ampt equation and runoff is routed through the flow-direction network using the KWA (Vieux *et al* 1990, 2004). Where slopes are mild, Modified Puls routing, also known as the storage-indication method, can be employed to route water between channel cells using channel cross-sections extracted from the DEM. The incorporation of spatially-diverse soil and land cover characteristics provides an accurate representation of the physical parameters of the watershed and makes *Vflo*[®] a powerful tool for understanding the impacts of land cover changes on catchment response (Sebastian 2016, Gori *et al* 2018, Juan *et al* n.d.). For a full description of the model and the computational solver, we refer the reader to Vieux *et al* (1990, 2004).

2.2.1. Current conditions model

Two LULC scenarios were used to generate two different models: a current conditions model and a

Table 1. Description of model scenarios.

Scenario	Description
Baseline	1900 development and Harvey's rainfall decreased by 15%
Baseline + Climate change	1900 development and Harvey's rainfall
Baseline + Development	2017 development and Harvey's rainfall decreased by 15%
Current conditions	2017 development and Harvey's rainfall

pre-development (i.e. baseline) model (section 2.2.2). To build the current conditions model, overland roughness and impervious parameters were derived at 30 m resolution from the 2011 Multi-resolution land characteristics (MRLC) Consortium's National Land Cover Database (NLCD). The LULC categories were converted to roughness and imperviousness parameters using the Manning's roughness coefficients presented by Kalyanapu *et al* (Kalyanapu *et al* 2009) and percent imperviousness was assigned using NLCD guidelines. Significant hydraulic structures (e.g. reservoirs and large detention ponds) are represented in the model as reservoir outlets using stage-storage and stage-discharge curves derived from observed data. Interbasin transfers from the Cypress Creek watershed are incorporated explicitly as weirs in the model based on the method described in Gori *et al* (2018). Multi-radar/multi-sensor system (MRMS) gauge bias corrected, 1 h precipitation was obtained from the Iowa State Repository of National Severe Storms Laboratory (NSSL) and used to calibrate the model to three recent storm events: Memorial Day Flood (25–26 May 2015), ($R^2 = 0.94$), Tax Day Flood (16–17 April 2016) ($R^2 = 0.86$), and a smaller event which occurred 27–28 May 2016 ($R^2 = 0.55$). The model was also validated for Hurricane Harvey (26–30 August 2017) ($R^2 = 0.71$). A discussion of the calibration and validation can be found in the supplementary material.

2.2.2. Pre-development conditions model

To build the baseline model for pre-development conditions, early 1900s LULC and channel conditions were reconstructed by changing overland and channel roughness and imperviousness parameters in the model based on historical maps and topographic surveys completed by the US Geological Survey in 1915 and 1916 (USGS 1923) and aerial imagery from 1944 obtained from Google Earth. Developed areas beyond city limits were converted to prairies, agricultural, or forested land cover types using the 1970 NLCD Historical Reanalysis Dataset compared against aerial imagery. Roughness and impervious values were assigned to the resulting land use classes as described above and exported as a 30 m raster dataset. Large detention ponds and reservoirs were removed from the model and channel roughness values were set to 0.068 to represent heavily wooded streams based on descriptions of the historical channel conditions (Dalrymple 1937). The baseline model was validated

using 24 h gauge-measured precipitation from National Climatic Data Center (NCDC) and reported peak discharge from a flood event which occurred 6–8 December 1935 ($R^2 = 0.96$). A discussion of the model validation can be found in the supplementary material.

2.3. Climate conditions

Anthropogenic climate change is represented in the model as a 15% increase in precipitation relative to the 1900s. Justification for the anthropogenic climate change effect on rainfall totals during Harvey is discussed in detail in Van Oldenborgh *et al* (2017). This attribution study provides an estimate of the increase of extreme three-day rainfall events on the US Gulf Coast from 1900 to 2017 based on two observational datasets and experiments with two independent global climate models. The authors conclude that global warming made Harvey's precipitation 15% (8%–19%) more intense or, equivalently, made Harvey three (1.5–5) times more likely. Because the estimate is based on dynamical climate model experiments, it incorporates both dynamic as well as thermodynamic changes, i.e. the full effect, of global climate change. Similar values were reported by Risser and Wehner (2017).

2.4. Experimental set-up

The validated pre-development and current condition models were used to simulate four climate change and urban development scenarios: (i) baseline; (ii) baseline + climate change; (iii) baseline + urban development; and (iv) current conditions (table 1). Each of the scenarios was designed to disentangle one of the drivers of flooding from another by comparing it against the baseline (pre-development, pre-climate change) condition. For example, to represent scenarios (ii) baseline + climate change and (iv) current conditions, the model was forced using Hurricane Harvey's rainfall and 1900 and 2017 land use conditions, respectively.

In addition to the four scenarios described above, the effects of the two large reservoirs west of Houston—Addicks and Barker—on peak discharge, volume and time-to-peak at gauges downstream of their outlets (i.e. Buffalo Bayou reach) were also considered. The reservoirs were modeled using stage-storage and storage-discharge relationships fit to the observed data collected during Hurricane Harvey at gauges 8073100 (Addicks) and 8072600 (Barker) and included in the

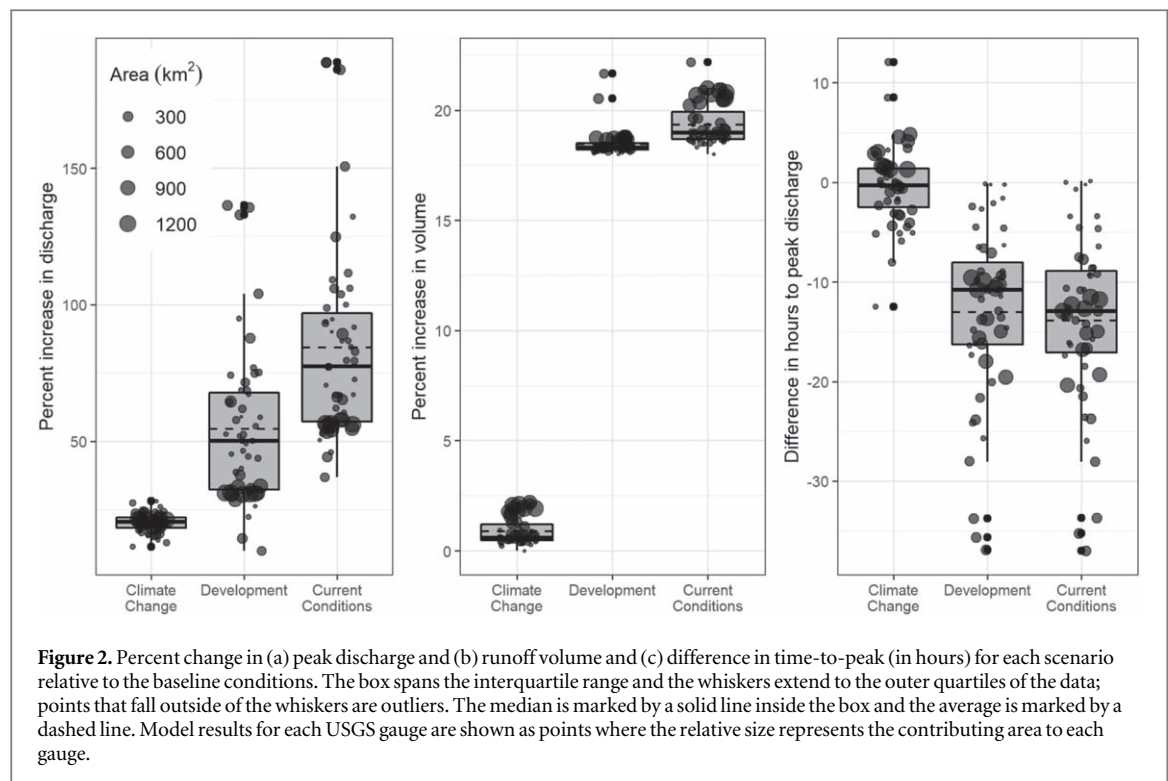


Table 2. Average increase in peak discharge, runoff volume, and time-to-peak for the climate change (only) scenario, development (only) scenario, and current conditions relative to baseline conditions. The standard deviation is given in parenthesis.

Scenario	Peak discharge	Runoff volume	Time-to-peak
Baseline + Climate change	20.2% ($\pm 3.44\%$)	0.88% ($\pm 0.60\%$)	-0.39 (± 3.95) h
Baseline + Development	54.4% ($\pm 28.7\%$)	18.5% ($\pm 0.59\%$)	-13.0 (± 8.72) h
Current conditions	84.4% ($\pm 35.4\%$)	19.4% ($\pm 0.93\%$)	-13.9 (± 8.50) h

supplementary material. For the purpose of this study, it is assumed that the operation of the reservoirs (i.e. the activation levels which determine when water should be released from the reservoirs) would have remained the same across all four scenarios. The scenario results were also compared to baseline conditions with and without the reservoirs in place.

3. Results

The model output was compared at 51 USGS gauge locations within the Buffalo-San Jacinto Watershed and the contributing overflow area in Cypress Creek. The percent change in peak discharge, volume of runoff, and time-to-peak are plotted in figures 2(a)–(c) and the results are reported in table 2 for model runs without the two large reservoirs—Addicks and Barker—in place. When comparing the baseline + development model to the baseline + climate change model, figure 2 illustrates that: (1) the impact of development on all catchment response variables is much greater than the impact of climate change relative to the baseline conditions; and (2) the impacts of development on peak flows are more pronounced in smaller catchments than in larger catchments.

Relative to 1900 conditions, the combined impact of urbanization and climate change led to 84.4% ($\pm 35.4\%$) higher peak discharge and 19.4% ($\pm 0.93\%$) larger runoff volume and caused peak flows to arrive more than half a day (13.9 h) earlier on average. When considered as independent drivers, climate change increased peak discharges by 20.2% ($\pm 3.44\%$), increased runoff by 0.88% ($\pm 0.60\%$) and decreased time-to-peak by 0.39 (± 3.95) h relative to baseline conditions; whereas urbanization increased peak discharges by 54.4% ($\pm 28.7\%$), increased runoff by 18.5% ($\pm 0.59\%$) and decreased time-to-peak by 13.0 (± 8.72) h relative to the baseline conditions. The model results also demonstrate that the relative impact of climate change on peak discharge, volume and time-to-peak is greater for urbanized conditions than pre-development conditions or, in other words, the impact of climate change is exacerbated by urbanization. For example, when comparing the climate change scenario against the baseline model, we find that a uniform 15% increase in rainfall (i.e. the anthropogenic climate change signal) relative to the baseline conditions increases peak discharges by 20.2%; whereas a 15% increase in rainfall relative to the 2017 development conditions increases peak discharge by 30.0% on average.

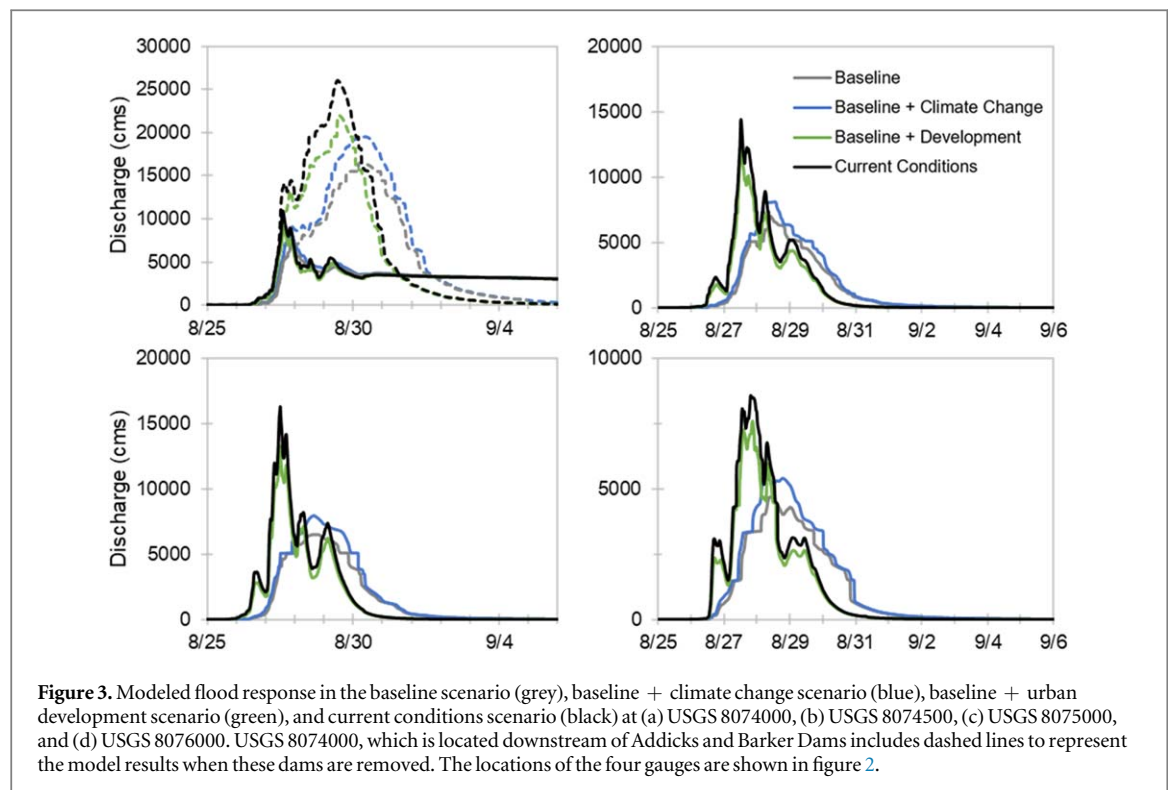


Figure 2 also demonstrates that the impact of urbanization on peak discharge is, in general, inversely related to catchment size—that is, smaller catchments tend to be more susceptible to increases in peak discharge as a result of increases in impervious surfaces—whereas, the influence of a 15% increase in rainfall leads to nearly uniform increases in peak discharge across all catchments. This makes sense since linear increases in rainfall across the catchment area should yield proportional increases in streamflow at the outlet, holding development constant. Less distinct relationships are observed between catchment size and runoff volume or difference in time-to-peak.

Figures 3(a)–(d) shows modeled hydrographs at four representative gauges in the watershed. The model results show that urbanization significantly alters the shape of the hydrograph, presenting a much steeper rising limb and higher peak, whereas climate change increases the peak but does not significantly alter the rising limb or shape of the hydrograph. Moreover, the urbanized scenarios generate several additional peaks, indicating that under urbanized conditions, the watershed was more sensitive to rainfall timing and intensity in 2017 than in 1900. Hydrograph results at USGS 8074000 (figure 4(a)), which is located along the main stem of Buffalo Bayou and downstream of Addicks and Barker Dams, shows that the presence of the reservoirs decreases peak discharge by 91% and volume by 84%.

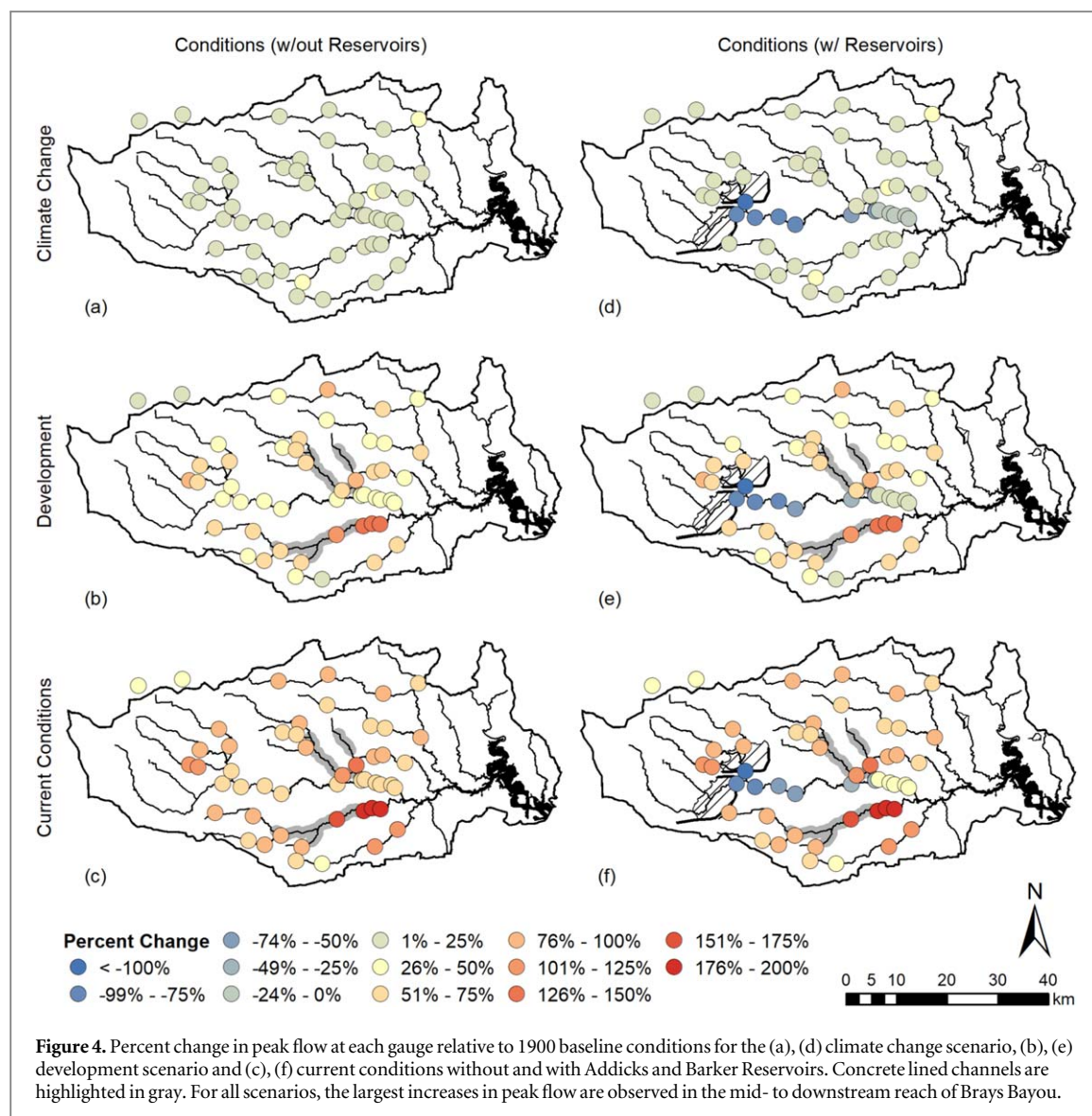
3.1. Influence of the reservoirs on peak flows

To further understand the performance of the reservoirs under changing land use and climate conditions,

we explored the results of the modeled scenarios with and without the reservoirs. The results shown in figure 4 demonstrate that even with the reservoirs, peak discharges at gauges downstream of the dams have increased over the previous century due to climate change (26.8%) and urbanization (42.3%), and that the percent reduction in peak discharge, i.e. the benefit of the reservoirs, is attenuated as one moves downstream (figures 4(d)–(f)). For example, at gauges below the confluence of Buffalo Bayou with White Oak Bayou, there is still an overall increase in peak discharge (+15.1%) due to urbanization relative to 1900 conditions despite the presence of the reservoirs.

4. Discussion

The results demonstrate that the combined effects of urbanization and climate change over the course of a century can significantly alter the hydrologic response of watersheds in ways that increase flood risk. More specifically, for the Buffalo Bayou watershed, we find that increases in impervious surfaces and rainfall as a result of climate change from 1900 to 2017 nearly doubled peak discharge, shortened the time to peak by almost 14 h on average, and increased the total runoff volume observed during Hurricane Harvey. However, we also found that there was a significant amount of variability in response to precipitation trends within the study area, which highlighted a key finding: there is a nonlinear relationship between increasing development and watershed response as rainfall amounts and intensity increase.



In a study of over 1000 stream flow gauges across the US, Hodgkins *et al* (2019) similarly found that although urbanization was associated with increasing peak flows, the magnitude of impacts were highly non-linear. In short, as watersheds become less pervious, they lose their capacity to absorb and slow runoff processes, making them more vulnerable to the increasing trends in the magnitude and severity of precipitation events as a result of climate change.

This loss in adaptive capacity makes sense since as development increases in the watershed, natural landscapes that would have infiltrated rainwater and slowed down the flood response are lost. Consequently, a larger portion of the rainfall resulting from climate change is directed into the surface drainage system contributing to greater peak flows and volumes during extreme events. A trend identified in this study was that smaller watersheds experienced greater increases in peak flows; however, the largest increases in peak discharge occurred in communities characterized by the following: increased overland flow due to increased impervious surface area and the concrete

lining of channels. At these locations, the impacts of anthropogenic climate change and urbanization more than doubled peak discharge relative to 1900 conditions for Hurricane Harvey. Many previous studies have also found links between development metrics and increasing peak flows (Olivera and DeFee 2007, Ogden *et al* 2011, Du *et al* 2012, Mogollón *et al* 2016, Rosburg *et al* 2017), with some studies suggesting that a threshold level of development exists after which large increases in peak flow can be observed (Hollis 1975). Moreover, previous studies have also found that the combined effect of both land cover changes and climate change are greater than either in isolation (Kaspersen *et al* 2015). However, the impact of increasing development is not homogenous on basin adaptive capacity, since incorporation of open space configurations and inclusion of well-distributed drainage networks can offset losses due to increased impervious surface (Doubleday *et al* 2013, Hopkins *et al* 2015).

Finally, the findings also indicate the presence of reservoirs have significantly offset both the impact of

upstream development and climate change on flooding immediately downstream of their outlets. The only gauges experiencing decreases in peak flow under current conditions with the reservoirs compared to 1900 conditions are located immediately downstream of the dams; however, the benefits associated with the reservoirs decrease as one moves further downstream. At the confluence of Buffalo and White Oak Bayous peak flows begin to increase relative to 1900 conditions (largely due to urbanization in the contributing tributaries). It is important to point out that additional growth is projected to occur upstream of the reservoirs, particularly in Addicks and in Cypress Creek Watersheds. This development is projected to increase overflows from Cypress (Gori *et al* 2018) and can be expected to further reduce the capacity of these dams, increasing risk downstream. While the dams have been shown to reduce peak discharge and volumes, the risk downstream will continue to increase due to non-stationarity in both climate change and urbanization.

4.1. Policy implications

The results of the study provide support for a precautionary approach to flood risk management that considers future conditions rather than historical trends. In other words, decision makers should consider how specific flood mitigation techniques will perform over relatively long time horizons. Traditionally, natural hazard planning has relied on assessing the impacts of flood events post hoc and then selecting strategies that would best alleviate those impacts (Milly *et al* 2008). The problem with this approach is that it neglects non-stationarity of the background drivers of risk such as increasing extreme rainfall trends and changes in overland flow due to urbanization. Instead, changing land use and climatic conditions should be integrated into present day cost-benefit calculations to more comprehensively assess the viability of specific mitigation projects. The outcome of this process would lead to more proactive flood risk reduction measures that increase the adaptive capacity of communities and watersheds and discourage development in areas that may become flood prone.

5. Conclusions

In this paper, we present the first analysis to date that attributes the relative impacts of anthropogenic change on flood flows. While previous studies have focused on attributing Harvey's rainfall to climate change (Emanuel 2017, Risser and Wehner 2017, Van Oldenborgh *et al* 2017, Kossin 2018, Trenberth *et al* 2018, Wang *et al* 2018) and urban development (Zhang *et al* 2018) in Houston and Southeast Texas, we focus on their individual and combined impact on catchment response. Our results demonstrate that the increasing presence of development in the form of impervious surfaces magnifies the impact of climate

change on flood flows, nearly doubling peak flows ($84\% \pm 35\%$) observed in Houston during Hurricane Harvey. Through this analysis, we also demonstrate that urban development has led to a loss in adaptive capacity in the watershed, decreasing the ability of the region's watersheds to accommodate increases in extreme rainfall due to climate change, and that even with reservoirs and channel modifications intended to provide regional flood reductions, climate change and urbanization have led to net increases in peak flows. These results provide justification for looking at future conditions when planning today's infrastructure, noting that the design conditions are non-stationary and that their impacts should not be analyzed in isolation. When designing infrastructure (residential, commercial, as well as bridges), attention should be paid as to where development might be expected to occur and the combined effects of both development and climate change should be analyzed. Steps to ensure that land uses upstream are set aside or preserved (e.g. through land banking) in areas where future development is projected to occur could help to avoid the future exposure of millions of dollars in assets to flooding downstream. Considering the findings presented in this study, future research will focus on analyzing the cost-benefits of recent policy initiatives and mitigation alternatives under projected urban development and future climate conditions in the Houston region.

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Data availability statement

The Vflo[®] Software used for this analysis is available from Vieux and Associates, Inc. Unless otherwise noted in the methods, the data that support the findings of this study are publicly available as follows: (i) the US Geological Survey (USGS) 3D Elevation Program (3DEP) National Elevation Dataset (NED) (<https://viewer.nationalmap.gov/basic/>) was used to map the topography and generate a flow direction network; (ii) USGS Texas topographic surveys from the Perry-Castañeda Map Collection at the University of Texas Libraries (<https://legacy.lib.utexas.edu/maps/texas.html>) were used to generate raster grids representing historical overland roughness and impervious cover; (iii) Multi-Resolution Land Characteristics (MRLC) Consortium's National Land Cover

Database (NLCD) 2011 (<https://mrlc.gov/>) was used to generate raster grids representing present-day over-land roughness and impervious cover; (iv) US Department of Agriculture (USDA) Gridded Soil Survey (gSSURGO) (<https://gdg.sc.egov.usda.gov/>) was used to derive modeled infiltration parameters; (v) Iowa State Repository of National Severe Storms Laboratory (NSSL) Multi-Radar/Multi-Sensor System (MRMS) sensor data (<http://mtarchive.geol.iastate.edu/>) was used to obtain gauge bias corrected, 1-hr precipitation accumulation for historical storms for model calibration and validation; and (vi) USGS discharge data (<https://waterdata.usgs.gov/>) was used to calibrate and validate the distributed hydrologic model.

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