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Impacts of urbanization, antecedent rainfall event, and cyclone tracks on extreme floods at Houston reservoirs during Hurricane Harvey

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Abstract

The objective of this study is to evaluate the effects of urbanization, an antecedent rainfall event (ARE), and varying cyclone tracks on the streamflow—and thus the subsequent reservoir status—during the floods caused by Hurricane Harvey in August–September 2017. Through a hydrological modeling approach, we examined how these factors influenced the inflows, peak pool elevations, and outflows of the two most important detention reservoirs in the Houston region, the Addicks and Barker Reservoirs. A high-resolution rainfall reanalysis dataset for extreme storm events, along with a suite of synthetic rainfall values from a variety of storm tracks, were adopted to represent both the truth and the maximum possible rainfall during the Hurricane Harvey period. The results showed the following: Urbanization only led to slight increases in peak inflows, not necessarily to an increase in peak pool elevations, and the ARE contributed to the peak inflow and pool elevation slightly. In contrast, if the cyclone had followed the most adverse track consistent with earlier forecasts (all else being equal), the total volumetric flow into the two reservoirs would have been significantly larger (37% and 49% respectively), thus increasing the peak pool elevations by 1.06 and 1.37 m respectively. These results suggest that large uncertainties exist for flood management at a watershed scale during hurricanes, because of the uncertainties in the cyclone track. This would remain true even if storm-relative precipitation rates could be predicted perfectly.

1. Introduction

Hurricane Harvey, a category 4 hurricane that struck Texas at the end of August 2017, claimed 106 lives and caused \$125 billion in losses (Blake and Zelinsky 2018, Wang *et al* 2018). After making landfall along the middle of the Texas coast on August 26, 2017, Hurricane Harvey advanced northward, stalled, and then moved back offshore at 0300 UTC on August 28 (Blake and Zelinsky 2018). The highest total storm rainfall set a new record value of 1539 mm near Nederland (Texas), while the total rainfall ranged from 635 to 1300 mm in the Houston metro area (Blake and Zelinsky 2018). This unprecedented precipitation resulted in extreme flooding in

the Houston watersheds, including a 1000-year flood event along the Buffalo Bayou (Nyaupane *et al* 2018). Although Houston did not receive the greatest precipitation from the storm (compared to other locations), it suffered the largest economic losses during this event.

Recent studies have assessed the probabilities of Harvey's rainfall, and the possible contributions of climate change to this extreme precipitation (Emanuel 2017, Risser and Wehner 2017, van Oldenborgh *et al* 2017, Kao *et al* 2019). However, fewer studies have investigated the streamflow and inundation areas caused by this precipitation (Zhang *et al* 2018a, Wing *et al* 2019, Sebastian *et al* 2019). Moreover, the effects of reservoirs on hydrological

processes warrant exploration with regard to flood management during hurricanes. For instance, while the two detention reservoirs (Addicks and Barker) are used for alleviating floods in downtown Houston, their flood waters inundated the upstream vicinity during Hurricane Harvey (Lindner and Fitzgerald 2018).

Reservoir inflows can also be affected by factors other than the accumulative precipitation brought on by a storm. Land use change has long been recognized as an important aspect impacting floods (Bronstert *et al* 2002, Defries and Eshleman 2004, Saghafian *et al* 2008; Zhang *et al* 2018b), especially the effects of urbanization, which have been extensively investigated (Hollis 1975, Hollis and Lockett 1976, Olivera and Defee 2007; Du *et al* 2012, Zhao *et al* 2016a). Urban expansion can amplify floods by increasing the precipitation amount from a hydrometeorological perspective (Guo *et al* 2006, Yang *et al* 2019, Yin *et al* 2020), but the most direct hydrological impact from urbanization is the increase of runoff and peak flow caused by the expansion of the impervious area (Olivera and Defee 2007, Jacobson 2011, Zhao *et al* 2016a, Hodgkins *et al* 2019).

Antecedent rainfall events (AREs) are another key factor affecting floods (Seeger *et al* 2004, Thomas *et al* 2016, Berghuijs *et al* 2016, Schoener and Stone 2019), especially for rapid runoff and flash flooding (Grillakis *et al* 2016). This justifies the importance of continuous simulations (vs. single event simulations) for obtaining reliable initial conditions in flood simulations (Berthet *et al* 2009, Pathiraja *et al* 2012). Grillakis *et al* (2016) suggested that the role of AREs depends more on the magnitudes of floods rather than the climate or region. Nonetheless, AREs before flooding events could influence streamflow regimes considerably by elevating the antecedent soil moisture (Woldemeskel and Sharma 2016). About three weeks before Hurricane Harvey, a severe storm event occurred between August 2nd and August 8th with an accumulative rainfall of 242 mm in the Addicks and Barker watersheds, which is about 28% of that from Harvey. Although the two reservoirs were already depleted before Hurricane Harvey, the high antecedent soil moisture conditions still could have elevated the runoff generation during Harvey.

In addition, from a spatial scale perspective, hurricanes typically cover areas much larger than individual watersheds, within which flood management activities are typically carried out. For any specific watershed, the flood severity can be worse or better if the storm center takes a different route. Therefore, the spatial distribution of the precipitation, which depends on the cyclone tracks over land (Lonfat *et al* 2004, Zawislak *et al* 2016), is crucial for watersheds of interest. Cyclone tracks are determined by many hydrometeorological conditions (Dacre and Gray 2009, Mukhopadhyay *et al* 2011), and there

are large uncertainties associated with such tracks (Franklin *et al* 2003).

Considering the factors discussed above, three questions about the Harvey floods were raised:

- (a) How much did the expansion of the impervious area impact the extreme flooding around the Addicks and Barker Reservoirs near Houston during Harvey?
- (b) To what extent did AREs make a difference in these extreme floods?
- (c) How would the flooding situation have been altered if Hurricane Harvey had followed a different track (assuming that the storm intensity, structure, and storm location-relative precipitation rates would have been unaffected)?

To address these questions, this study examined the hydrological impacts from multiple factors—urbanization, AREs, and cyclone tracks—on the floods during Hurricane Harvey via a hydrological modeling approach. Specifically, we evaluated the effects of these factors and their associated uncertainties by conducting a series of scenario-driven hydrological model simulations. To provide more new information for decision makers, some additional scenarios were tested to (1) evaluate the role of inter-watershed flow from the Cypress watershed; and (2) estimate the potential effects of changing reservoir operation rules on moderating the flooding around the reservoirs.

2. Study area and methods

2.1. Study area

The Addicks and Barker Reservoirs, along with their upstream drainage areas, were chosen as the study areas in this research (figure 1(a)). Such detention reservoirs are commonly used for flood control in urban areas worldwide (Ngo *et al* 2016, 2018). Due to the region's flat terrain, flood waters from the Cypress watershed can cross the boundary line between the two watersheds and enter the Addicks watershed when the rainfall magnitude is large (figure 1(a)). Therefore, the inflow into the Addicks Reservoir may consist of both local flood water and the inter-watershed flow from the Cypress. However, it is difficult to measure or evaluate the amount of the inter-watershed flow accurately (TWDB 2015, Lindner and Fitzgerald 2018).

These three watersheds have experienced dramatic urbanization during past several decades. Many homes constructed during this period are distributed near and even within the reservoirs, albeit above the originally-estimated 100 year reservoir flood pool levels. Although there had been almost no urban area in these watersheds in the 1940s, by 2016, the urban area covered about 48%, 43%, and 12% of

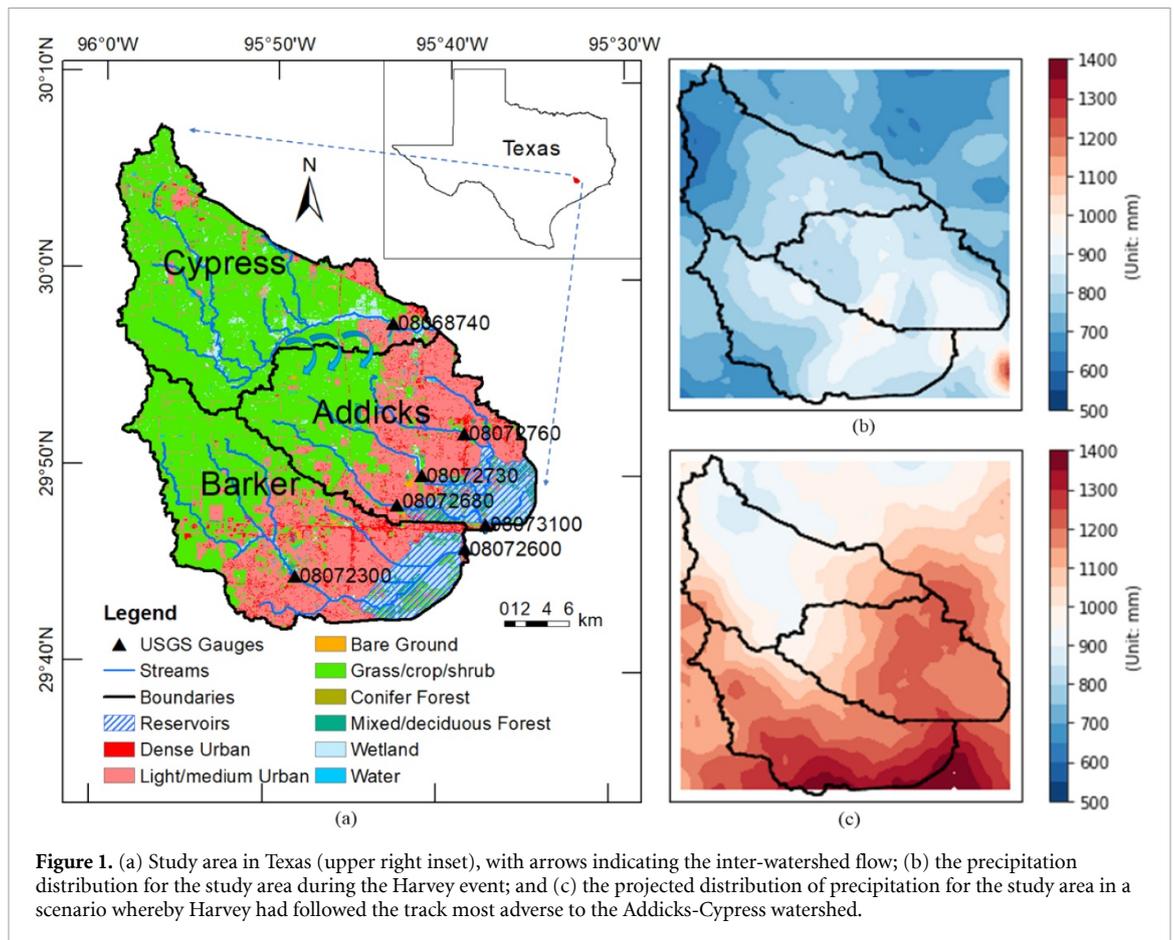


Figure 1. (a) Study area in Texas (upper right inset), with arrows indicating the inter-watershed flow; (b) the precipitation distribution for the study area during the Harvey event; and (c) the projected distribution of precipitation for the study area in a scenario whereby Harvey had followed the track most adverse to the Addicks-Cypress watershed.

the Addicks, Barker, and Cypress watersheds, respectively. During Hurricane Harvey, the water reached unprecedented levels in the reservoirs and inundated many homes (GHFMC 2017). However, to what degree urbanization exacerbated the magnitude of the flooding caused by Harvey has not been quantified.

2.2. DHSVM modeling

2.2.1. DHSVM

The Distributed Hydrology Soil Vegetation Model (DHSVM, Wigmosta *et al* 1994) was used for the hydrological simulations. DHSVM is a physics-based distributed hydrological model with high spatial and temporal resolutions. The model has been updated to enable the simulation of hydrological processes with urban land cover (Cuo *et al* 2008; see supplementary material S.1.1 (available online at stacks.iop.org/ERL/15/124012/mmedia)) and reservoir regulation (Zhao *et al* 2016b). Furthermore, the reservoir release scheme was modified to better simulate the reservoir release processes of detention reservoirs (see supplementary material S.1.2). Additionally, the DHSVM codes were modified to use an eight direction (D8) flow model produced by ArcGIS. This allows the routing module to perform better on flat terrain.

2.2.2. Model inputs and forcing data

In this study, DHSVM was set up at a 30 m spatial resolution and an hourly time step. The main geospatial inputs include digital elevation models (DEM), soil texture, land cover (see supplementary material S.1.3), and meteorological forcings.

The meteorological forcings include precipitation, temperature, wind speed, relative humidity and downward shortwave and longwave radiation. First, we used daily maximum and minimum temperature, wind speed and precipitation values from the U.S. National Oceanic and Atmospheric Administration (NOAA) gauges to drive the Mountain Microclimate Simulation-Model (MTCLIM, Hungerford 1989), which is widely used as a pre-processor for hydrologic modeling (Bohn *et al* 2013). This step served two purposes: to generate additional forcing terms needed by DHSVM (e.g. relative humidity and radiation) and to downscale daily data to hourly to match the DHSVM time step. As detailed in supplementary material S.6.2, the uncertainties associated with these disaggregated forcings (note: precipitation is not from the MTCLIM) are negligible. To accurately represent the high spatial and temporal varying rainfall, VIC downscaled precipitation was not used as a DHSVM input. Instead, MetStorm analyses (Parzybok *et al* 2015) were adopted to represent the

rainfall ground truth during the Hurricane Harvey period, and radar data were used for the other times (when MetStorm data are unavailable). By integrating data collected from the precipitation gauges, dual-polarimetric radar, and satellites, the MetStorm rainfall reanalysis is designed to provide high-resolution, reliable rainfall data during extreme storm events. For the remainder of the simulation period (2005–2017), National Weather Service Stage IV Radar precipitation data were used (Lin 2011).

In addition, a suite of synthetic rainfall scenarios was produced based on alternative tracks that Hurricane Harvey could have followed according to the official National Hurricane Center (NHC) forecasts made in real time (see supplementary material S.2 for details). Different values of parameter A correspond to different possible tracks within the forecast envelope; positive A corresponds to slower than observed storm motion consistent with the NHC forecasts. The hourly gridded precipitation fields were displaced along with the storm to estimate the time-evolving precipitation under the possible track scenarios. Slower storm motion tends to increase the maximum storm-total precipitation while also changing the location where that maximum occurs.

2.2.3. Model calibration, validation, and inter-watershed flow estimation

Model calibration and validation for streamflow simulation are described in supplementary material S.3.1, and more discussions about the parameterization uncertainty are provided in supplementary material S.6.1. The inter-watershed flow was estimated after the models for the Addicks and Cypress watersheds were calibrated jointly. Inter-watershed flows were expected to account for some of the differences between the simulated flows and the observed flows at the Cypress mainstream gauge (gauge 08068740, figure 1(a)), which is located downstream of the area where inter-watershed flows occur. A simulated flow rate of $1.00 \times 10^5 \text{ m}^3 \text{ h}^{-1}$ at this gauge was selected as the threshold for determining whether there was inter-watershed flow (above which there were observable discrepancies between the simulated and observed flows). This magnitude was close to the peak discharge at a 20% exceedance probability, $1.13 \times 10^5 \text{ m}^3 \text{ h}^{-1}$, above which considerable inter-watershed flows have occurred in the past (TWDB Texas Water Development Board (TWDB) 2015). Next, a scatter plot was obtained to show the relationship between the inter-watershed flows from Cypress and the simulated flows at the gauge. Finally, a linear regression was fitted between these two variables, in order to estimate the inter-watershed flows based on the simulated flows at gauge 08068740's location. This regression model was evaluated by comparing the simulated flow at gauge 08068740—with the estimated inter-watershed flow removed—against the

observed flow. The results suggest that this method is adequate to account for the inter-watershed flow from Cypress to Addicks (see supplementary material figure S.3.2).

For the reservoir module, the Elevation-Storage relationships were adopted originally from the US Army Corps of Engineers (USACE 2008a, 2008b), and the parameters related to the release flow were calibrated against the observed outflows at the closest downstream gauge locations. For validation, the simulated pool elevations and releases during flood events were compared to their counterpart USGS observations (figure 2). The simulated peak pool elevation at the Addicks and Barker Reservoirs during Harvey (33.21 m and 30.90 m) are close to the observed records (33.23 m and 30.96 m).

2.3. Designed scenarios

DHSVM model scenarios were designed to examine the impacts from urbanization, AREs, and cyclone tracks. To evaluate the urbanization effects, the modeled results using LC2016 as a baseline (to represent the land cover during Hurricane Harvey) were compared with the results from four different historical land covers (LC1940, LC1970, LC1991, and LC2001), each of which was at a lower urbanization level compared to the baseline. To quantify the impacts from the ARE, five scenarios were tested, with a focus on the streamflow uncertainties associated with the timing of the ARE. In the first scenario, the ARE during early August was removed. In the other four scenarios, the ARE was shifted by ± 10 or ± 5 d compared to the real occurrence dates. For the impacts from the cyclone tracks, Scenario P_Max, which represents the largest total precipitation over the area of interest (figure 1(c)), was tested to investigate the worst possible floods in the watersheds within the range of hypothetical tracks. To better understand the impacts from the uncertain cyclone trajectories, intermediate scenarios—D020, D040, D060, and D080, with the values of A set to 0.2, 0.4, 0.6 and 0.8 respectively—were also examined.

3. Results

The DHSVM model results under the designed scenarios were compared with those from the baseline to evaluate the impacts from different factors (table 1). Specifically, the analyses focused on the maximum hourly inflow ($Q_{in, max}$), peak reservoir pool elevation (H_{max}), total inflow volume (V_{in} , i.e. the sum of the inflows from August 25 to September 16), and maximum hourly release ($Q_{out, max}$).

3.1. Urbanization impacts

For the Addicks Reservoir, the $Q_{in, max}$ values from the scenarios using earlier land cover maps are slightly smaller than those from the baseline (LC2016). For

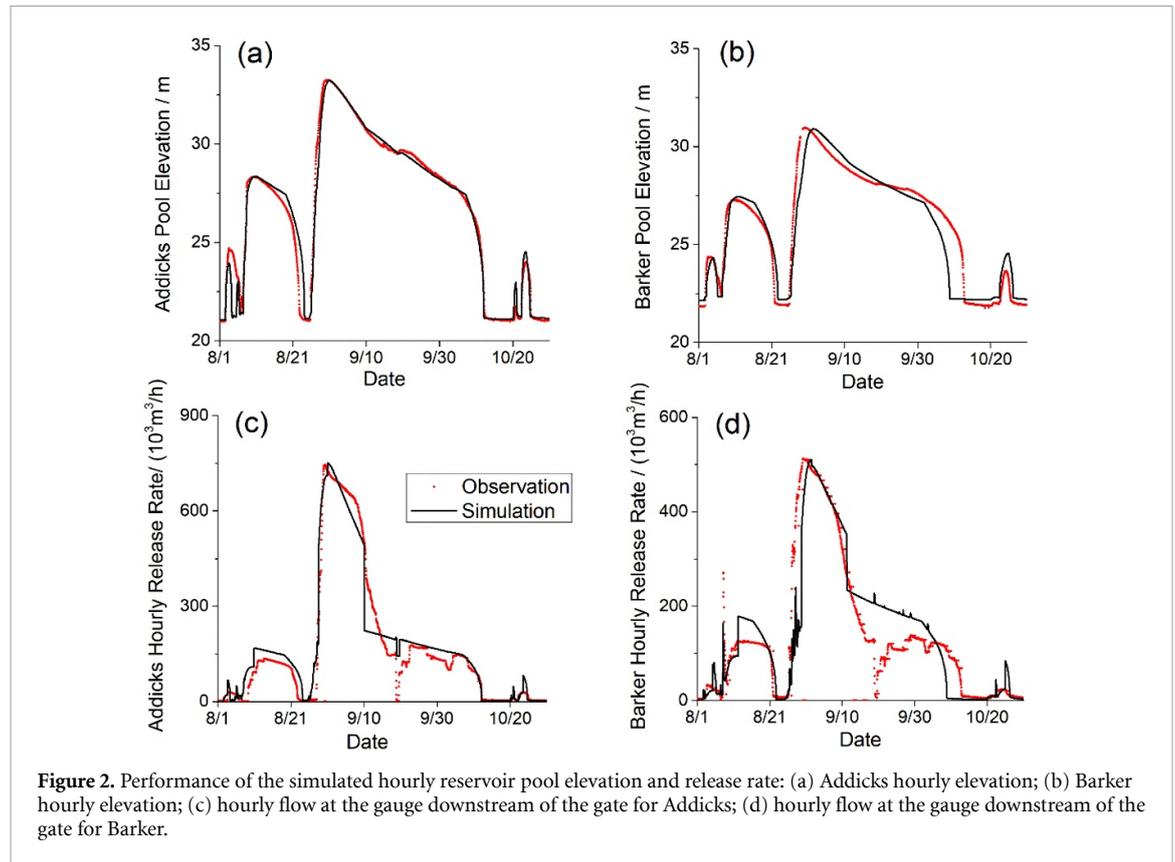


Table 1. Simulation results under the designed scenarios (results in scenarios other than the Baseline Scenario are shown as the change values compared to those under the Baseline Scenario).

Scenarios	Maximum Hourly Inflow Rate ($Q_{in,max}$) / ($10^6 mc h^{-1}$)		Peak Reservoir Pool Elevations (H_{max}) / m		Total Inflow Volume (V_{in}) / $10^8 m^3$		Maximum hourly Release Rate ($Q_{out,max}$) / ($10^5 mc h^{-1}$)		
	Addicks	Barker	Addicks	Barker	Addicks	Barker	Addicks	Barker	
Baseline	5.30	3.12	33.21	30.90	3.32	2.62	7.50	5.08	
Urbanization ^a	LC1940	-6.17%	-2.94%	0.14	-0.10	1.87%	-4.80%	2.20%	-1.79%
	LC1970	-6.27%	-3.08%	0.13	-0.10	1.86%	-4.67%	2.09%	-3.25%
	LC1992	-7.24%	-9.00%	0.06	-0.19	0.69%	-6.19%	0.89%	-4.70%
	LC2001	-4.40%	-3.46%	0.04	-0.09	0.43%	-3.32%	0.55%	-3.04%
Antecedent	No_ ARE	-6.40%	-6.75%	-0.25	-0.22	-6.28%	-6.10%	-3.84%	-5.02%
	10b	-1.47%	-1.53%	-0.06	-0.05	-1.55%	-1.54%	-0.98%	-0.97%
Rainfall Event (ARE) ^b	5b	-0.81%	-0.68%	-0.04	-0.03	-0.93%	-0.78%	-0.59%	-2.00%
	5 a	1.16%	1.48%	0.08	0.06	1.48%	1.57%	1.23%	0.00%
	10 a	2.32%	2.97%	0.32	0.30	3.49%	3.43%	4.99%	3.69%
Cyclone Track ^c	D020	-10.96%	-1.11%	-0.26	0.01	-5.73%	0.82%	-4.06%	-1.43%
	D040	0.35%	-9.40%	0.11	0.15	6.83%	7.07%	1.70%	0.64%
	D060	-0.59%	3.71%	0.71	0.87	25.88%	31.06%	6.00%	12.31%
	D080	-15.94%	5.49%	0.99	1.35	34.95%	48.62%	6.00%	20.28%
	P_Max	-16.26%	-0.42%	1.06	1.37	37.00%	48.70%	6.00%	20.56%

^aLC1940, LC1970, LC1992, and LC2001 represents the land cover in 1940, 1970, 1992, and 2001, respectively.

^bNo_ ARE³ indicates that the ARE was removed from the precipitation data; 10b, 5b, 5 a and 10 a indicate that the ARE was moved to 10 or 5 d before and 5 or 10 d after, respectively.

^cD020 means that the precipitation under the cyclone track with A being 0.20; a similar notation is used for the other Cyclone Track scenarios. P_Max means the possible maximum precipitation over the reservoir drainage areas: For the Addicks Reservoir, P_Max represents the precipitation under the cyclone track with A being 0.81 (D081); for Barker Reservoir, P_Max represents the precipitation under the cyclone track with A being 0.86 (D086).

example, the $Q_{in,max}$ has increased by 7% from 1940 to 2016, after 48% of the land in the Addicks watershed had been urbanized (from grass/crop/shrub land). The differences in V_{in} , H_{max} , and $Q_{out,max}$ among these urbanization scenarios are less pronounced. For example, the H_{max} decreased from 33.35 m under the LC1940 scenario to 33.21 m under LC2016 (i.e. by 0.14 m). Similar results were found for the Barker Reservoir. The $Q_{in,max}$ increased from $3.03 \times 10^6 \text{ m}^3 \text{ h}^{-1}$ under LC 1940– $3.12 \times 10^6 \text{ m}^3 \text{ h}^{-1}$ under LC 2016 (by 3%). The H_{max} increased by 0.10 m under the Baseline Scenario (LC2016) compared to that under LC1940.

3.2. Impacts from ARE

Without the ARE in early August, the $Q_{in,max}$, V_{in} , H_{max} , and $Q_{out,max}$ at the Addicks Reservoir would have decreased by $3.39 \times 10^5 \text{ m}^3 \text{ h}^{-1}$ (6%), $2.08 \times 10^7 \text{ m}^3$ (6%), 0.25 m, and $2.88 \times 10^3 \text{ m}^3 \text{ h}^{-1}$ (4%) respectively. As expected, the $Q_{in,max}$, V_{in} and $Q_{out,max}$ would have decreased slightly if the ARE had occurred 5 d or 10 d earlier (and would have shown the opposite trends if later). The H_{max} would have decreased slightly if the ARE had occurred earlier—by 0.06 m and 0.04 m under Scenario 10b and Scenario 5b, respectively. However, the range of the increment would be slightly larger—0.08 m and 0.32 m—if the ARE had occurred 5 d and 10 d later, respectively. The changes in $Q_{out,max}$ due to the timing of the ARE range from –1% to 5%. Similar results were found at the Barker Reservoir due to the timing changes of the ARE.

3.3. Impacts from different cyclone tracks

Under the most adverse cyclone tracks (Scenario P_Max), the V_{in} into the Addicks and Barker Reservoirs would have increased by $1.23 \times 10^8 \text{ m}^3$ (37%) and $1.23 \times 10^8 \text{ m}^3$ (49%), causing the H_{max} to surge by 1.06 m and 1.37 m, respectively. In addition, this possible maximum rainfall would push the $Q_{out,max}$ at Addicks to its release capacity of $7.95 \times 10^5 \text{ m}^3 \text{ h}^{-1}$ (USACE 2012)—which is about 6% higher than the $Q_{out,max}$ under the baseline. At Barker, $Q_{out,max}$ would be $6.13 \times 10^5 \text{ m}^3 \text{ h}^{-1}$ (an increment of 21%).

Under Scenarios D020 and D040, the increment of H_{max} is no more than 0.15 m at the Addicks and Barker Reservoirs compared to that under the Baseline Scenario. However, under D060, the H_{max} would have increased by 0.71 m and 0.87 m for Addicks and Barker, respectively. Then, the H_{max} would have continued to increase until the value of A reached 0.81 and 0.86 for these two reservoirs. Although the chance for the cyclone to exactly follow the most adverse track is small, there is still a broad range of tracks that would have led to substantial increases in total inflows. Also, other possible storm characteristics, such as different landfall locations and different intensities, might lead to even greater inflows.

4. Discussion

The results from the most representative urbanization, ARE, and cyclone track scenarios for the Barker Reservoir were used to compare the impacts of these three factors (figure 3). The differences between the results under scenario LC1940 and the baseline (LC2016) indicate that urbanization accelerated the process of the reservoir reaching its peak elevation, with a steeper rising limb in the hydrograph under LC2016 (figure 3(a)). This is also the same for the Addicks Reservoir (see supplementary material figure S4). Although the overall trend of these results is consistent with previous studies on the effects of urbanizations on flood peak flows (Jacobson 2011, Zhao *et al* 2016a, Shao *et al* 2020), the percentage increases of $Q_{in,max}$ (7% for Addicks and 3% for Barker) during Hurricane Harvey are much smaller than those in previous studies. Indeed, the urbanization induced increases of $Q_{in,max}$ during the flood produced by the ARE in early August were 59% and 215% for Addicks and Barker, respectively. Although the $Q_{in,max}$ in flood events with smaller magnitudes is sensitive to some of the urban parameters, it is barely affected by such parameters under extreme events like Harvey (see supplementary material S.6.1). This is because the total rainfall from Hurricane Harvey was so large (843 mm over the Barker watershed and 851 mm over the Addicks watershed) that any soil would have become mostly saturated shortly after the hurricane rainfall started in the region. As a result, the peak runoff generated from different land covers would become more similar.

Without the ARE, the V_{in} would not change noticeably compared to the baseline, except that $Q_{in,max}$ (figure 3(a)) and H_{max} (figure 3(c)) would be slightly lower. This agrees with the finding that floods with large magnitudes tend to be less sensitive to initial soil moisture (Grillakis *et al* 2016). In addition, the impacts of ARE on peak inflow and peak elevation tend to be more significant if the ARE occurs closer to the storm event.

Under the most adverse cyclone tracks (Scenario P_Max), there would be double peaks of the inflow during the flood event (figure 3(a)). This is because the cyclone under these tracks would produce two rainfall peaks at the watersheds—one occurring while the cyclone stalled, and the other occurring when it made landfall a second time. Although these two $Q_{in,max}$ values would be lower than the one under the Baseline Scenario, the accumulative inflow volume would exceed that of the Baseline Scenario after August 31 (figure 3(b)), thus leading to a continuous increase of H_{max} until September 3 (figure 3(c)). The $Q_{out,max}$ varies with the H_{max} under the different scenarios.

Under the Scenario P_Max, H_{max} would have increased by 1.06 m and by 1.37 m for the Addicks and Barker Reservoirs, respectively. This would

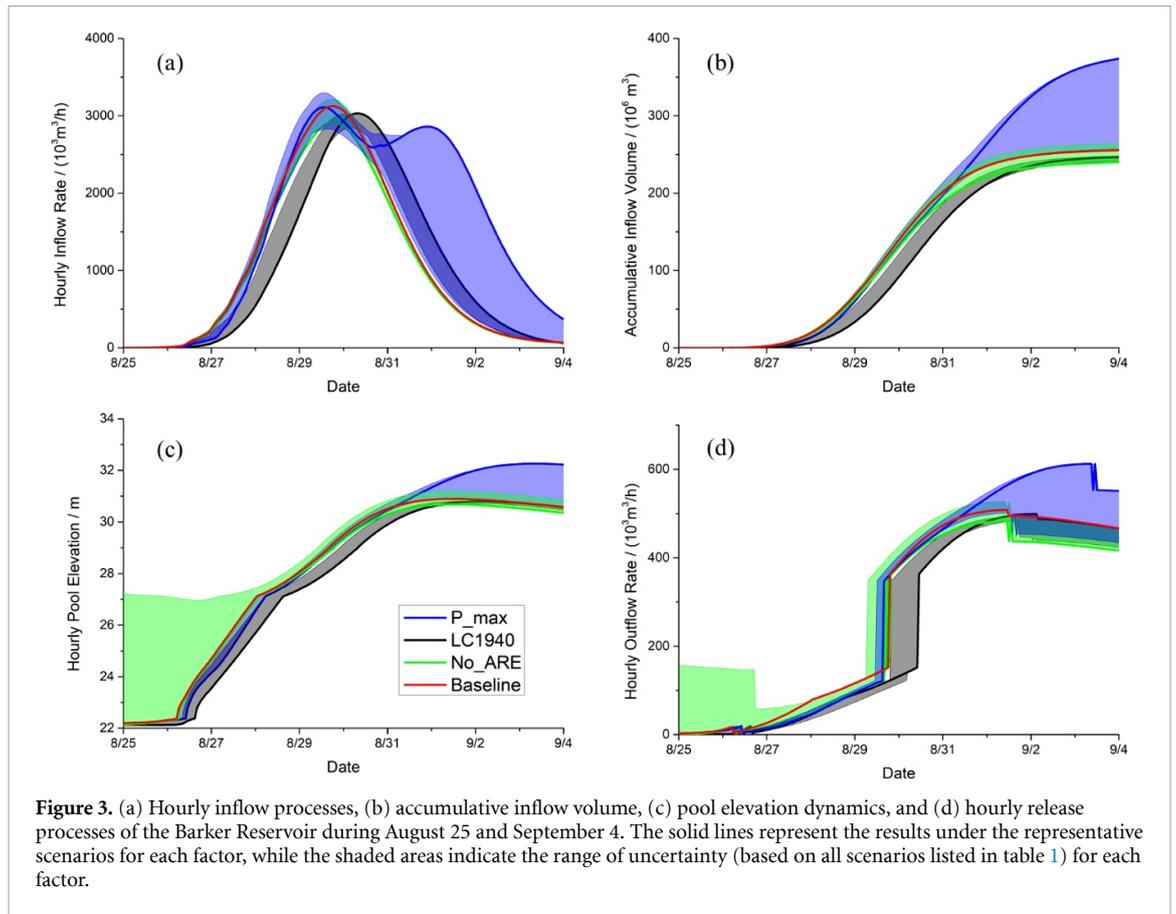


Figure 3. (a) Hourly inflow processes, (b) accumulative inflow volume, (c) pool elevation dynamics, and (d) hourly release processes of the Barker Reservoir during August 25 and September 4. The solid lines represent the results under the representative scenarios for each factor, while the shaded areas indicate the range of uncertainty (based on all scenarios listed in table 1) for each factor.

have led to much larger inundated areas. According to a rough estimation based on the DEM, the inundated areas would increase by 19% and 18% at Addicks and Barker. These increased percentages are 23% and 27%, respectively, when the inundated areas are estimated using the height-volume curves from USACE. Most of the additional inundation would affect urbanized land rather than open space. Another consequence of higher H_{\max} is a higher risk of dam failure. During Harvey, a peak reservoir storage of $268.41 \times 10^6 \text{ m}^3$ in Addicks was recorded by a USGS gauge—which exceeded its maximum storage capacity ($252.25 \times 10^6 \text{ m}^3$, www.twdb.texas.gov/surfacewater/rivers/reservoirs/addicks/index.asp). Under Scenario P_Max, the reservoir storage in Barker would also exceed its maximum storage capacity ($255.33 \times 10^6 \text{ m}^3$, www.twdb.texas.gov/surfacewater/rivers/reservoirs/barker/index.asp), peaking at $296.52 \times 10^6 \text{ m}^3$. Meanwhile, the H_{\max} (34.41 m in Addicks and 32.35 m in Barker) would approach or even exceed the level at the top of the spillways (34.14–35.05 m for Addicks and 32.31 m for Barker, GHFMC Greater Houston Flood Mitigation Consortium (GHFMC) 2017). Even under the D60 scenario, the reservoir storage in Barker would also have exceeded its storage capacity (with a peak value of $260.10 \times 10^6 \text{ m}^3$).

We conducted additional simulations to evaluate the role of the inter-watershed flow from the Cypress watershed and potential effects of changing reservoir operations on reducing the H_{\max} . Clear decreases in $Q_{\text{in}, \text{max}}$ (−20%), V_{in} (−26%), H_{\max} (−1.11 m), and $Q_{\text{out}, \text{max}}$ (−17%) were found at the Addicks Reservoir when there was no inter-watershed flow. Induced surcharge regulation is an operation option under which stored flood water is discharged at high release rates to control rising pool elevations, which is initiated only when the pool elevations reach designated thresholds (USACE 2012). Given the inflow, the existing reservoir storage capacity, and the discharge capacity, there are two options to reduce H_{\max} : (1) lowering the thresholds to initiate the induced surcharge regulation, and (2) increasing the release rate during the induced surcharge regulation. However, the results under both options suggest that the effects of changing the reservoir operations to moderate the floods around the reservoirs during Hurricane Harvey would be very limited (see supplementary material S.5). Therefore, additional measures—such as new reservoirs and diversions (Castro and Rifai 2019, Weber 2019)—are essential for lowering the risks of such extreme floods, which are projected to occur more frequently in the future as the climate changes (Emanuel 2017).

This study used a hydrological modeling approach to explore the impacts from the three aforementioned factors on extreme floods at two Houston reservoirs during Hurricane Harvey. Although a number of studies have investigated the impacts of urbanization and ARE on streamflow during floods (Jacobson 2011, Hodgkins *et al* 2019, Schoener and Stone 2019), few have focused on the extreme floods caused by hurricanes (Zhang *et al* 2018a; Sebastian *et al* 2019). Although these two reservoirs were the center of attention during Harvey (HCFCD 2017, Lindner and Fitzgerald 2018), the peak elevations and the release rates of reservoirs during flooding events were not evaluated in previous research. Furthermore, to our best knowledge, this is the first study addressing the impacts of the cyclone track on the flooding caused by a hurricane at the watershed scale. Additionally, we developed a practical approach for estimating the time series of inter-watershed flow by combining hydrologic modeling and gauge observations. This offers a universal approach applicable to regions with low topographic gradients, where inter-watershed flows readily occur in extreme floods (Wang *et al* 2010).

Despite of their uncertainties, the calibrated parameters are able to replicate the surface runoff processes and reservoir pool elevation dynamics. Further, the simulation uncertainties associated with the meteorological forcings (other than precipitation) were insignificant (see supplementary material S.6). It is worth noting that some water overflowed from the northern edge of the Addicks dam during Harvey, which was not considered in the simulations. Therefore, this model limitation might have led to a slight overestimation of H_{max} for the Addicks Reservoir under the scenarios with higher peak pool elevations (compared to the baseline). Since this study focused on the one-way impacts from these factors on the streamflow, the potential influences of urbanization and soil moisture conditions on the amount of hurricane precipitation (Nair *et al* 2019) were not considered.

5. Conclusions

This study adopted a modeling approach to evaluate the effects of urbanization, AREs, and the varying cyclone tracks on the floods over the Addicks and Barker Reservoirs during Hurricane Harvey, as well as their associated uncertainties. Both urbanization and the ARE exacerbated the peak inflows, although not to a significant extent. Urbanization shortened the flood peak time, which would make decision-making more challenging. Moreover, the results from the suite of modified cyclone tracks suggest that the peak inflows are very sensitive to storm trajectories and that the flooding at the two reservoirs from Hurricane Harvey easily could have been considerably more severe. An important message conveyed by this study is that large

uncertainties exist for flood management at a watershed scale during hurricanes due to the uncertainties in the cyclone track, even if storm-relative precipitation rates could be predicted perfectly.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

- Berghuijs W R, Woods R A, Hutton C J and Sivapalan M 2016 Dominant flood generating mechanisms across the United States *Geophys. Res. Lett.* **43** 4382–90
- Berthet L, Andreassian V, Perrin C and Javelle P 2009 How crucial is it to account for the antecedent moisture conditions in flood forecasting? Comparison of event-based and continuous approaches on 178 catchments *Hydrol. Earth Syst. Sci.* **13** 819–31
- Blake E S and Zelinsky D A 2018 National Hurricane center tropical cyclone report: Hurricane Harvey (AL092017) *National Hurricane Center* (available at: www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf)
- Bohn T J, Livneh B, Oyler J W, Running S W, Nijssen B and Lettenmaier D P 2013 Global evaluation of MTCLIM and related algorithms for forcing of ecological and hydrological models *Agr. Forest Meteorol.* **176** 38–49
- Bronstert A, Niehoff D and Burger G 2002 Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities *Hydrol. Process.* **16** 509–29
- Castro C V and Rifai H S 2019 Hydrological, societal, and environmental impacts of flood control reservoir releases on downstream communities using remote sensing and modeling during Hurricane Harvey *AGU2019*, GH13C–1062
- Cuo L, Lettenmaier D P, Mattheussen B V, Storck P and Wiley M 2008 Hydrologic prediction for urban watersheds with the distributed hydrology-soil-vegetation model *Hydrol. Process.* **22** 4205–13
- Dacre H F and Gray S L 2009 The spatial distribution and evolution characteristics of North Atlantic cyclones *Mon. Weather. Rev.* **137** 99–115

- Defries R and Eshleman N K 2004 Land-use change and hydrologic processes: a major focus for the future *Hydrol. Process.* **18** 2183–6
- Du J K, Qian L, Rui H Y, Zuo T H, Zheng D P, Xu Y P and Xu C Y 2012 Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhua River basin, China *J. Hydrol.* **464** 127–39
- Emanuel K 2017 Assessing the present and future probability of Hurricane Harvey's rainfall *P. Natl Acad. Sci. USA* **114** 12681–4
- Franklin J L, Mcadie C J and Lawrence M B 2003 Trends in track forecasting for tropical cyclones threatening the United States, 1970–2001 *B. Am. Meteorol. Soc.* **84** 1197
- GHFMC Greater Houston Flood Mitigation Consortium (GHFMC) 2017 How do addicks and barker reservoirs work? (available at: <https://capitol.texas.gov/tlodocs/85R/handouts/C2102018020609151/ae8f145c-a2d8-4766-921f-1f8d86fb3cc9.PDF>)
- Grillakis M G, Koutroulis A G, Komma J, Tsanis I K, Wagner W and Bloschl G 2016 Initial soil moisture effects on flash flood generation - A comparison between basins of contrasting hydro-climatic conditions *J. Hydrol.* **541** 206–17
- Guo X L, Fu D H and Wang J 2006 Mesoscale convective precipitation system modified by urbanization in Beijing *City Atmos. Res.* **82** 112–26
- HCFCD Harris County Flood Control District (HCFCD) 2017 Stormwater Rising into Neighborhoods near Addicks, Barker Reservoirs in West Harris County (available at: www.hcfdc.org/About/Press-Room/post/stormwater-rising-into-neighborhoods-near-addicks-barker-reservoirs-in-west-harris-county)
- Hodgkins G A, Dudley R W, Archfield S A and Renard B 2019 Effects of climate, regulation, and urbanization on historical flood trends in the United States *J. Hydrol.* **573** 697–709
- Hollis G E 1975 The effect of urbanization on floods of different recurrence interval *Water Resour. Res.* **11** 431–5
- Hollis G E and Luckett J K 1976 The response of natural river channels to urbanization: two case studies from southeast England *J. Hydro.* **30** 351–63
- Hungerford R D, Nemani R R, Running S W and Coughlan J C 1989 MTCLIM - a mountain microclimate simulation-model *Usda Serv. Int. R* 1–52 (available at: https://www.fs.fed.us/rm/pubs_int/int_rp414.pdf)
- Jacobson C R 2011 Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review *J. Environ. Manage.* **92** 1438–48
- Kao S C, Deneale S T and Watson D B 2019 Hurricane Harvey highlights: need to assess the adequacy of probable maximum precipitation estimation methods *J. Hydrol. Eng.* **24** 05019005
- Lin Y 2011 GCIP/EOP surface: precipitation NCEP/EMC 4KM gridded data (GRIB) stage IV data Version 1.0. UCAR/NCAR – Earth Observing Laboratory (<https://doi.org/10.5065/D6PG1QDD>)
- Lindner J and Fitzgerald S 2018 Immediate report—final hurricane harvey-storm and flood information Received by HCFCD Flood Watch/Partners, 4. (available at: <https://reduceflooding.com/wp-content/uploads/2018/06/Final-HCFCD-Harvey-Report.pdf>)
- Lonfat M, Marks F D and Chen S Y S 2004 Precipitation distribution in tropical cyclones using the tropical rainfall measuring mission (TRMM) microwave imager: A global perspective *Mon. Weather. Rev.* **132** 1645–60
- Mukhopadhyay P, Taraphdar S and Goswami B N 2011 Influence of moist processes on track and intensity forecast of cyclones over the north Indian Ocean *J. Geophys. Res.-Atmos* **116** D05116
- Nair U S et al 2019 Influence of Land cover and soil moisture based brown ocean effect on an extreme rainfall event from a Louisiana Gulf Coast tropical system *Sci. Rep.* **9** 17136
- Ngo T T, Yoo D G and Kim J H 2018 Decentralization-based optimization of detention reservoir systems for flood reduction in urban drainage areas *Urban Water J.* **15** 445–52
- Ngo T T, Yoo D G, Lee Y S and Kim J H 2016 Optimization of upstream detention reservoir facilities for downstream flood mitigation in urban areas *Water* **8** 290
- Nyaupane N, Bhandari S, Rahaman M M, Wagner K, Kalra A, Ahmad S and Gupta R 2018 Flood frequency analysis using generalized extreme value distribution and floodplain mapping for hurricane harvey in Buffalo Bayou *World Environmental and Water Resources Congress 2018: Watershed Management, Irrigation and Drainage, and Water Resources Planning and Management* pp 364–75
- Olivera F and Defee B B 2007 Urbanization and its effect on runoff in the Whiteoak Bayou watershed, Texas *J. Am. Water Resour. Assoc.* **43** 170–82
- Parzybok T, Lock N A, Porter C W, Laro K, Hendricks A S and Mokry W Jr. 2015 MetStorm:® near real-time storm precipitation analytics using dual-pol radar data *37th Conf. on Radar Meteorology*, (Norman, OK) (September 13–18, 2015)
- Pathiraja S, Westra S and Sharma A 2012 Why continuous simulation? The role of antecedent moisture in design flood estimation *Water Resour. Res.* **48** W06534
- Risser M D and Wehner M F 2017 Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey *Geophys. Res. Lett.* **44** 12457–64
- Saghafian B, Farazjoo H, Bozorgy B and Yazdandoost F 2008 Flood intensification due to changes in land use *Water Resour. Manag.* **22** 1051–67
- Schoener G and Stone M C 2019 Impact of antecedent soil moisture on runoff from a semiarid catchment *J. Hydrol.* **569** 627–36
- Sebastian A, Gori A, Blessing R B, van der Wiel K and Bass B 2019 Disentangling the impacts of human and environmental change on catchment response during Hurricane Harvey *Environ. Res. Lett.* **14** 124023
- Seeger M, Errea M P, Begueria S, Arnaez J, Marti C and Garcia-Ruiz J M 2004 Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish pyrenees *J. Hydrol.* **288** 299–311
- Shao M Q, Zhao G, Kao S C, Cuo L, Ranklin C and Gao H L 2020 Quantifying the effects of urbanization on floods in a changing environment to promote water security — a case study of two adjacent basins in Texas *J. Hydrol.* **589** 125–54
- Thomas N W, Amado A A, Schilling K E and Weber L J 2016 Evaluating the efficacy of distributed detention structures to reduce downstream flooding under variable rainfall, antecedent soil, and structural storage conditions *Adv. Water. Resour.* **96** 74–87
- TWDB Texas Water Development Board (TWDB) 2015 Cypress creek overflow management plan Contract Report Number: 1248321466 (available at: www.twdb.texas.gov/publications/reports/contracted_reports/doc/1248321466_HCFCD.pdf)
- USACE US Army Corps of Engineers (USACE) 2008a Rating curve data for Addicks (available at: www.waterdatafortexas.org/reservoirs/individual/addicks/rating-curve/usace/2008-10-01)
- USACE 2008b Rating curve data for Barker (available at: www.waterdatafortexas.org/reservoirs/individual/barker/rating-curve/usace/2008-10-01)
- USACE 2012 Water control manual, addicks and barker reservoirs, Buffalo Bayou and tributaries, San Jacinto River Basin, TX (available at: www.svg.usace.army.mil/Portals/26/docs/water%20control%20manual/2012%20water%20control%20manual.pdf)
- van Oldenborgh G J, van der Wiel K, Sebastian A, Singh R, Arrighi J, Otto F, Haustein K, Li S H, Vecchi G and Cullen H 2017 Attribution of extreme rainfall from Hurricane Harvey, August 2017 *Environ. Res. Lett.* **12** 124009
- Wang S S, Zhao L, Yoon J H, Klotzbach P and Gillies R R 2018 Quantitative attribution of climate effects on Hurricane

- Harvey's extreme rainfall in Texas *Environ. Res. Lett.* **13** 054014
- Wang X X, Liu T X, Shang S Y, Yang D W and Melesse A M 2010 Estimation of design discharge for an ungauged overflow-receiving watershed using one-dimensional hydrodynamic model *Int. J. River Basin Manage.* **8** 79–92
- Weber A 2019 Buffalo bayou and tributaries resiliency study update *Spring Partnering Forum* (available at: www.houstontx.gov/council/g/Buffer-Bayou-Study-20190327.pdf)
- Wigmosta M S, Vail L W and Lettenmaier D P 1994 A distributed hydrology-vegetation model for complex terrain *Water Resour. Res.* **30** 1665–79
- Wing O E, Sampson C C, Bates P D, Quinn N, Smith A M and Neal J C 2019 A flood inundation forecast of Hurricane Harvey using a continental-scale 2D hydrodynamic model *J. Hydrol. X* **4** 100039
- Woldemeskel F and Sharma A 2016 Should flood regimes change in a warming climate? The role of antecedent moisture conditions *Geophys. Res. Lett.* **43** 7556–63
- Yang L, Smith J and Niyogi D 2019 Urban impacts on extreme monsoon rainfall and flooding in complex terrain *Geophys. Res. Lett.* **46** 5918–27
- Yin J F, Zhang D L, Luo Y L and Ma R Y 2020 On the extreme rainfall event of 7 May 2017 over the coastal city of Guangzhou. Part I: impacts of urbanization and orography *Mon. Weather Rev.* **148** 955–79
- Zawislak J, Jiang H, Alvey G R, Zipser E J, Rogers R F, Zhang J A and Stevenson S N 2016 Observations of the structure and evolution of Hurricane Edouard (2014) during intensity change. Part I: relationship between the thermodynamic structure and precipitation *Mon. Weather. Rev.* **144** 3333–54
- Zhang W, Villarini G, Vecchi G A and Smith J A 2018a Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston *Nature* **563** 384
- Zhang X P et al 2018b Understanding land use and cover change impacts on run-off and sediment load at flood events on the Loess Plateau, China *Hydrol. Process.* **32** 576–89
- Zhao G, Gao H L and Cuo L 2016a Effects of urbanization and climate change on peak flows over the San Antonio river Basin, Texas *J. Hydrometeorol.* **17** 2371–89
- Zhao G, Gao H L, Naz B S, Kao S C and Voisin N 2016b Integrating a reservoir regulation scheme into a spatially distributed hydrological model *Adv. Water Resour.* **98** 16–31