

Article

Retrospective Dynamic Inundation Mapping of Hurricane Harvey Flooding in the Houston Metropolitan Area Using High-Resolution Modeling and High-Performance Computing

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Abstract: Hurricane Harvey was one of the most extreme weather events to occur in Texas, USA; there was a huge amount of urban flooding in the city of Houston and the adjoining coastal areas. In this study, we reanalyze the spatiotemporal evolution of inundation during Hurricane Harvey using high-resolution two-dimensional urban flood modeling. This study's domain includes the bayou basins in and around the Houston metropolitan area. The flood model uses the dynamic wave method and terrain data of 10-m resolution. It is forced by radar-based quantitative precipitation estimates. To evaluate the simulated inundation, on-site photos and water level observations were used. The inundation extent and severity are estimated by combining the retrieved water depths, images collected from the impacted area, and high-resolution terrain data. The simulated maximum inundation extent, which is frequently found outside of the designated flood zones, points out the importance of capturing multi-scale hydrodynamics in the built environment under extreme rainfall for effective flood risk and emergency management.

Keywords: dynamic inundation mapping; Hurricane Harvey; high-resolution modeling

1. Introduction

Hurricane Harvey made landfall in southeast Texas on August 25, 2017, as a Category 4 hurricane. The storm then stalled, with its center around the Texas coast, dropping historic amounts of rainfall in the Houston metropolitan area from August 26 to 28. The three-day rainfall in parts of Houston and the storm's total rainfall were estimated to have return periods of over 9000 [1] and 2000 years [2], respectively. These rains caused unprecedented flooding and caused over 70 fatalities with \$125 billion US dollars in damages [3], making Harvey the second costliest hurricane in US history. A recent study found that most drowning deaths from Hurricane Harvey in the Houston area occurred outside of the flood zones identified as being at high risk of flooding by the Federal Emergency Management Agency (FEMA) [4,5]. A number of studies have also been undertaken to examine the meteorological impact [6] and the role of human-induced changes on Hurricane Harvey's extreme rainfall [7,8]. To date, however, the spatiotemporal evolution of the surface water inundation that occurred in Houston, the fourth-largest city in the US, has yet to be closely examined.

Although urban flooding is affected by various natural and man-made controls [9], mechanisms of inundation can be largely divided into two types: fluvial flooding (i.e., inundation of river flow) and

pluvial flooding (i.e., flash flooding on the surface). The flow spills out of rivers toward floodplains and leads to fluvial flooding, while pluvial flooding is induced by extreme rainfall. The two urban flooding mechanisms have different spatiotemporal scales: fluvial flooding has widespread influences on floodplains, lasting for several days or more, while pluvial flooding affects locally in shorter durations. Different modeling approaches are used to simulate different types of urban flooding. For fluvial flood modeling, the propagation of inundation from rivers to floodplain needs to be solved effectively at a large spatial scale with sophisticated treatment of dry/wet conditions, while the flow on the complicated urban geometry is represented with a reduced accuracy. On the other hand, accurate representation of flows around urban features (i.e., buildings and roads) in a relatively small domain is regarded as more important in pluvial flood modeling, since predefined flow paths no longer exist, and flow depth and direction are governed by local geometry. High-resolution urban modeling is therefore crucial to better understanding of pluvial urban flooding.

The last two decades have seen increasingly rapid advances in urban flood modeling especially in relation with high-resolution approaches [9–14]. Liang et al. [15] successfully applied a two-dimensional (2D) quadtree model on the River Thames in case the flood defenses were breached by the river at Thamesmead. Lewis et al. [16] applied the LISFLOOD-FP inundation model for the northern Bay of Bengal region to estimate flood risk from storm surges. Lee et al. [17] estimated the road network and effects of building configurations in urban areas under flooding. Wang et al. [18] developed the cellular automata scheme-based model, CADDIES, and showed that urban micro-features could significantly influence simulated inundation extent and depth.

One of the major challenges in Hurricane Harvey flood modeling is that both fluvial and pluvial flooding occurred at a city-wide scale due to the extreme amount and spatial extent of rainfall. In addition, Houston's unique geography, land use, and storm surge likely made a significant impact on the city's inundation during Hurricane Harvey. The conventional modeling approaches focus on a single dominant inundation mechanism, (e.g., high-resolution flash flood modeling at small scale or coarse-resolution river inundation modeling at large scale), and therefore have limitations in providing a complete picture of large-scale inundation induced by different urban flooding mechanisms. For assessment of the aforementioned factors, high-resolution inundation modeling at a city-wide scale is necessary, which cannot be easily addressed with typical urban models. H12, the hybrid code for 1D/2D urban flood modeling used in this study, can simulate pluvial urban flooding at a high resolution [17,19] with the capacity for large-scale modeling through hybrid parallelization [9].

The other challenge in the retrospective analysis is that the inundation around the Houston metropolitan area during Hurricane Harvey was not very well observed by satellite and airborne sensors due to clouds and strong winds. In addition, there remain technical hurdles in differentiating in satellite images between an inundated water surface and roads or buildings [20,21]. Though limited in spatial coverage, numerous images and video footage taken on-site by citizens and journalists do exist. They contain important hydraulic information, and hence can provide missing pieces in understanding the dynamic evolution of the flood.

In this study, we reanalyze the spatiotemporal evolution of inundation in the Houston metropolitan area during Hurricane Harvey using high-resolution modeling. The two-dimensional (2D) urban flood model used is based on dynamic wave approximation of surface flow at a 10-m resolution. It is forced by the radar-based precipitation estimates produced for operational forecasting by the National Weather Service (NWS). The resulting dynamic inundation map is evaluated using on-site photos and water depth measurements. The inundation extent and severity are estimated quantitatively by combining the retrieved water depths and images from a large area with high-resolution terrain data. The simulated maximum inundation extent, derived from the dynamic modeling, is compared with the 1-percent and 0.2-percent annual-chance FEMA flood maps for discrepancies between the flood zones designated based solely on fluvial flooding and the inundation areas from retrospective simulation based on both fluvial and pluvial flooding.

2. Materials and Methods

2.1. Study Domain

The model domain is approximately a 100 km $\times$ 65 km rectangle in the Houston metropolitan area that includes Buffalo, Brays, Greens, Hunting, Sims, and White Oak Bayous (see Figure 1). These bayous flow easterly to drain into Burnet Bay in the Gulf of Mexico, which was affected by storm surge during Hurricane Harvey. Upstream of Buffalo Bayou, there are two man-made reservoirs, Addicks and Barker, which were built in the 1930s for flood protection. They are dry in non-rainy periods, but rose to historic levels during Harvey, flooding thousands of homes in both up- and down-stream areas [22].

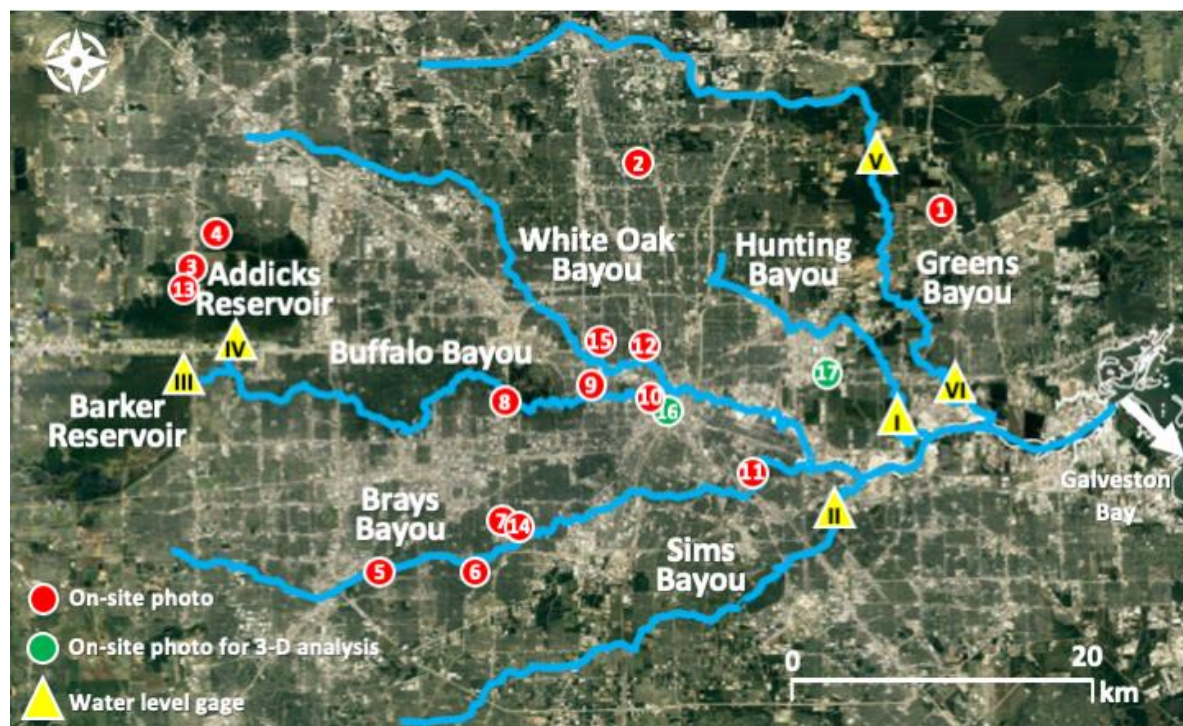


Figure 1. Study domain with locations of the on-site photo (red circle), photo for 3D analysis (green circle), and water level gage (yellow triangle).

2.2. Data Used

The radar-based operational multi-sensor precipitation estimator (MPE) [23,24] products from the West Gulf River Forecast Center (WGRFC) were used to force the urban flood model hourly at a 4-km resolution. As shown in Figure 2a, the seven-day precipitation from August 25 to 31 ranged from 800 mm to 1100 mm for most of the Houston metropolitan area, which is consistent with the estimates from previous studies [1,7]. For daily accumulation, the precipitation estimates for August 27 exceeded 300 mm in most areas and 500 mm for lower Brays Bayou (see Figure 3c). According to [1], the return period of 350 mm per day is about once in 800 years.

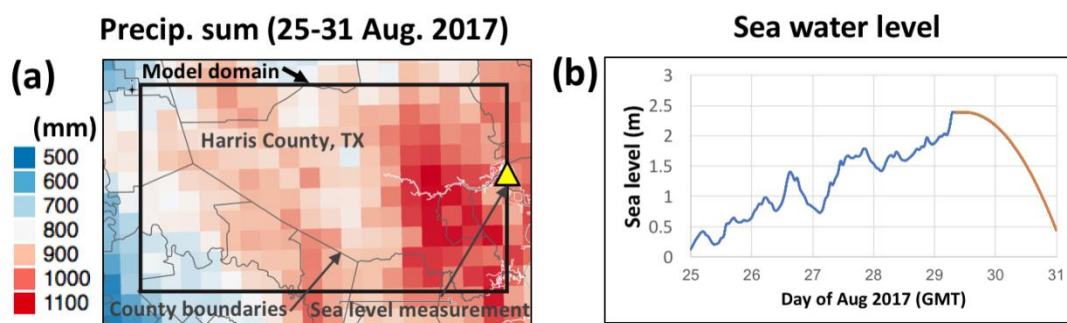


Figure 2. (a) The accumulated daily precipitation maps from 25 to 30 August 2017. A box in each sub plot represents the boundary of the study domain. The thin black line represents the lower Buffalo Bayou and the coastal line. A triangle in Figure 2a represents the location of the water level measuring gage on downstream Buffalo Bayou in Figure 2b. (b) The hourly mean water levels on downstream Buffalo Bayou (Lynchburg Landing, TX; datum: North American Vertical Datum of 1988; [18]). The orange line indicates the assumed sea level due to the lack of measurements.

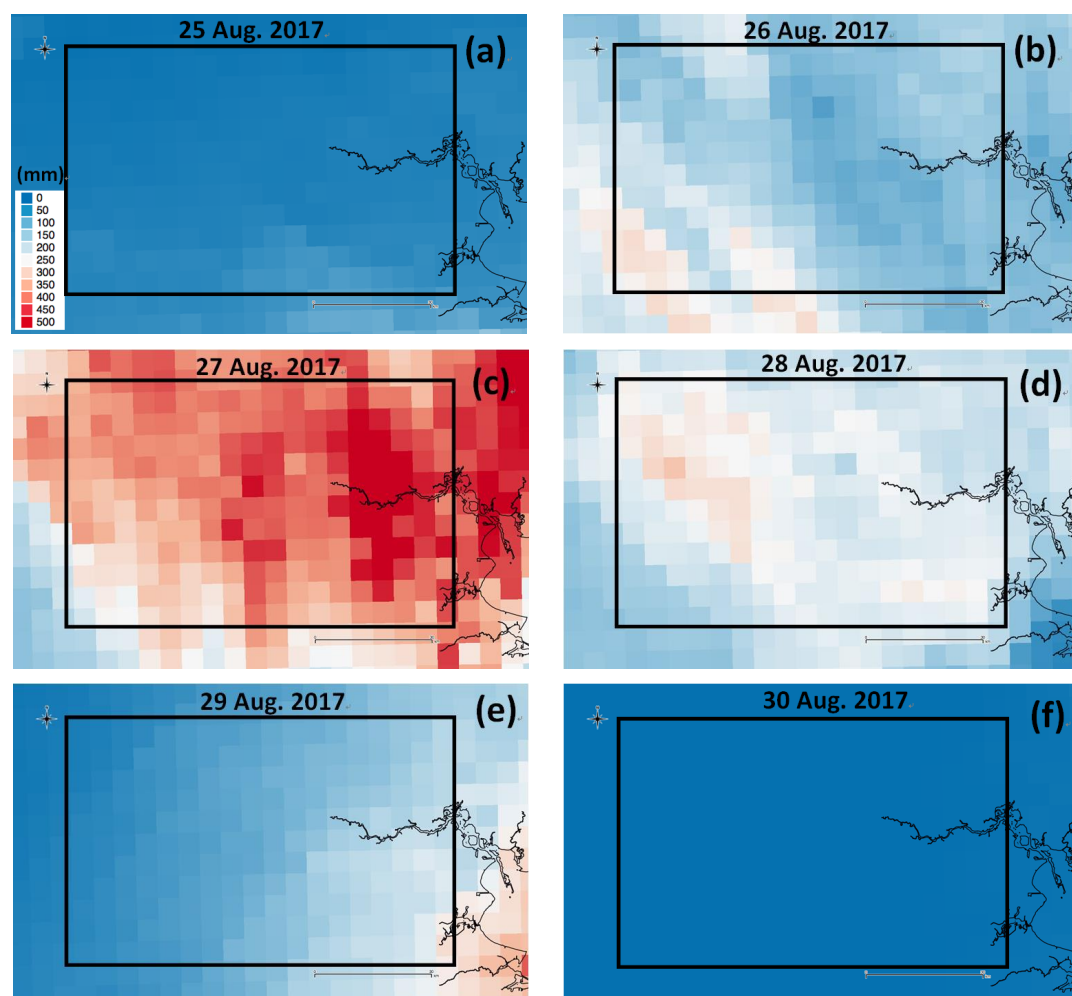


Figure 3. (a–e) The accumulated daily precipitation maps from 25 to 30 August 2017. A box in each sub plot represents the boundary of the study domain. The thin black line indicates the lower Buffalo Bayou and the coastal line.

For the boundary condition of the flood model at the outlet of Buffalo Bayou (the yellow triangle in Figure 2a), the mean water level at Lynchburg Landing, Texas, from the National Oceanic and Atmospheric Administration (NOAA) [25] was used. Due to lack of measurements, the sea level

past noon of August 29 was assumed to follow the patterns found at nearby measurement locations (Morgans Point, Barbour's Cut, Eagle Point, Galveston Bay, TX), as shown in the orange line in Figure 2b, while diurnal variations were not considered between noon on August 29 and 31.

For terrain modeling, the base digital elevation model (DEM) with a resolution of 1/3 arc second (about 10 m) was used. The DEM is referenced to North American Vertical Datum of 1988. It is extracted from the National Elevation Dataset (NED), produced by the US Geological Survey (USGS). The vertical accuracy (expressed as the root mean square error) of the NED is 1.55 m. We added to the base DEM solid urban features, such as houses and buildings that obstruct the flow of stormwater. For this, we used the building footprint GIS layer from an open-source database [26] and identified the positions of buildings and houses in the DEM by increasing the elevation of the pixels inside of the building footprint polygons. The base DEM, which was provided after a basic treatment for removing the elevated roads and bridges over relatively large streams, was adjusted additionally to remove erroneous structures over water bodies that unrealistically obstruct the flow of water (see Figure 4). The six land cover types used in the modeling include road, residential or commercial areas, vegetation, park or open spaces, bare ground, and bodies of water (see Figure 5), and are from the 2011 National Land Cover Database. For quantitative image analysis of on-site photos in Section 3.2, we used the LiDAR point-cloud data acquired from the Texas Natural Resources Information System (TNRIS) and processed to generate a 1-m resolution digital surface model (DSM).

2.3. Urban Flood Model and Validation Methods

The urban flood model, which was used to reanalyze the temporal evolution of the inundation, was based on 2D dynamic wave equations [19] as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = \alpha \cdot r_e \quad (1)$$

$$\frac{\partial M}{\partial t} + \frac{\partial(uM)}{\partial x} + \frac{\partial(vM)}{\partial y} = -gh \frac{\partial H}{\partial x} - \frac{gn^2 M \sqrt{u^2 + v^2}}{h^{4/3}} \quad (2)$$

$$\frac{\partial N}{\partial t} + \frac{\partial(uN)}{\partial x} + \frac{\partial(vN)}{\partial y} = -gh \frac{\partial H}{\partial y} - \frac{gn^2 N \sqrt{u^2 + v^2}}{h^{4/3}} \quad (3)$$

where h is the water depth, $M (= uh)$ and $N (= vh)$ are the x - and y -directional fluxes, u and v are the x - and y -directional velocities, respectively, r_e is the rainfall intensity and α is the runoff coefficient, g is the gravitational acceleration, H is the water level, and n is Manning's roughness coefficient. For solving these governing equations numerically, finite difference discretization was utilized with the leapfrog method. The details of the numerical scheme and stability conditions can be found in [19]. The values of α and n were set differently with respect to the types of land covers, as shown in Table 1.

To reduce time for high-resolution computations for the entire Houston metropolitan area, hybrid parallel computing was applied [9], which combines both the distributed memory parallelism (e.g., the message passing interface (MPI)) and shared memory parallelism (e.g., OpenMP) by separating the simulation domain into multiple, smaller sub-domains. The seven-day simulation period was from 25 to 31 August 2017.

In order to prescribe realistic initial conditions of water depths in the streams, the model was warmed up until the simulated water depths at multiple gauging stations reached a steady-state condition close to the observed area. Storm drains, infiltration, and evapotranspiration were not explicitly simulated, as they were not expected to have significant effects on the extreme flooding. Surface runoff was estimated by multiplying the rainfall estimates with the runoff coefficients assigned for different land cover types. Due to the large amount of computation necessary (e.g., a seven-day simulation requires about a 10-h computation on 384 CPU cores), model calibration was limited to making a small number of runs with different runoff coefficients and Manning's roughness and selecting the best-performing parameter settings (Table 1).



Figure 4. An example digital terrain model enlarged for the mid Brays Bayou.

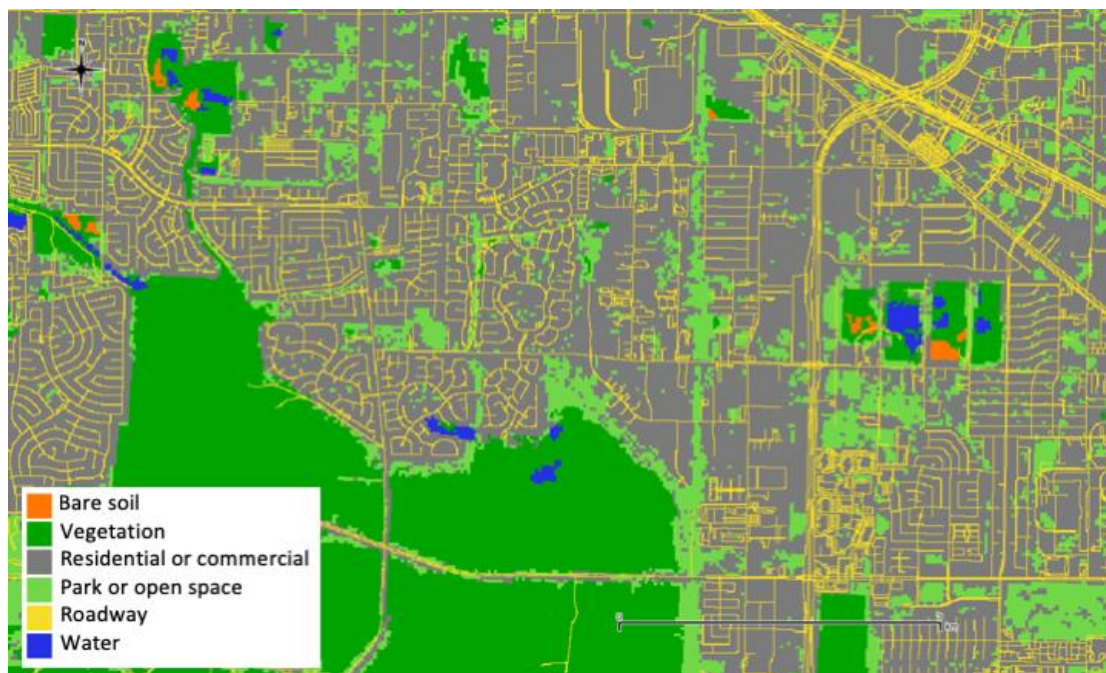


Figure 5. An example land cover map enlarged for upper part of the Addicks reservoir.

Table 1. The land cover types, runoff, and Manning's roughness coefficients.

Land Cover	Bare Ground	Vegetation	Residential or Commercial	Parking Lot or Open Space	Road	Water Body
Runoff coeff.	0.6	0.5	0.9	0.9	0.9	1.0
Manning's roughness	0.035	0.13	0.015	0.015	0.015	0.03

The simulated inundation conditions were validated with on-site photos from the news sources and social media and with water level measurements collected by the Harris County Flood Warning System [27]. We also reconstructed the scenes in 3D with Google Earth using the estimated flood water level and compared with the photo images to conduct qualitative assessment that the estimated water level agreed with the on-site photos.

3. Results and Discussion

This section describes the spatiotemporal evolution of inundation and compares the simulated maximum extent of inundation with the FEMA flood maps [5].

3.1. Spatiotemporal Evolution of Inundation

An example simulated inundation map is illustrated in Figure 6a for the middle part of Brays Bayou at 11:00 GMT August 27, 2017. The maps of the same area 24 h before and after this date are shown for comparison (Figure 6b,c). For contrast, only the water depth exceeding 0.1 m is displayed. Comparison of the three figures shows how the inundation developed and propagated during Harvey. On August 26 (Figure 6b), streets started to flood, while most of the residential areas remained dry. On August 27 (Figure 6a), most of the roads and the residential areas were inundated. On August 28 (Figure 6c), the areas near the middle of Brays Bayou remained inundated, whereas the water depth decreased in areas of relatively higher elevation. It is also apparent that the inundation depths significantly varied within the inundation area, which partly demonstrates the value of high-resolution modeling.

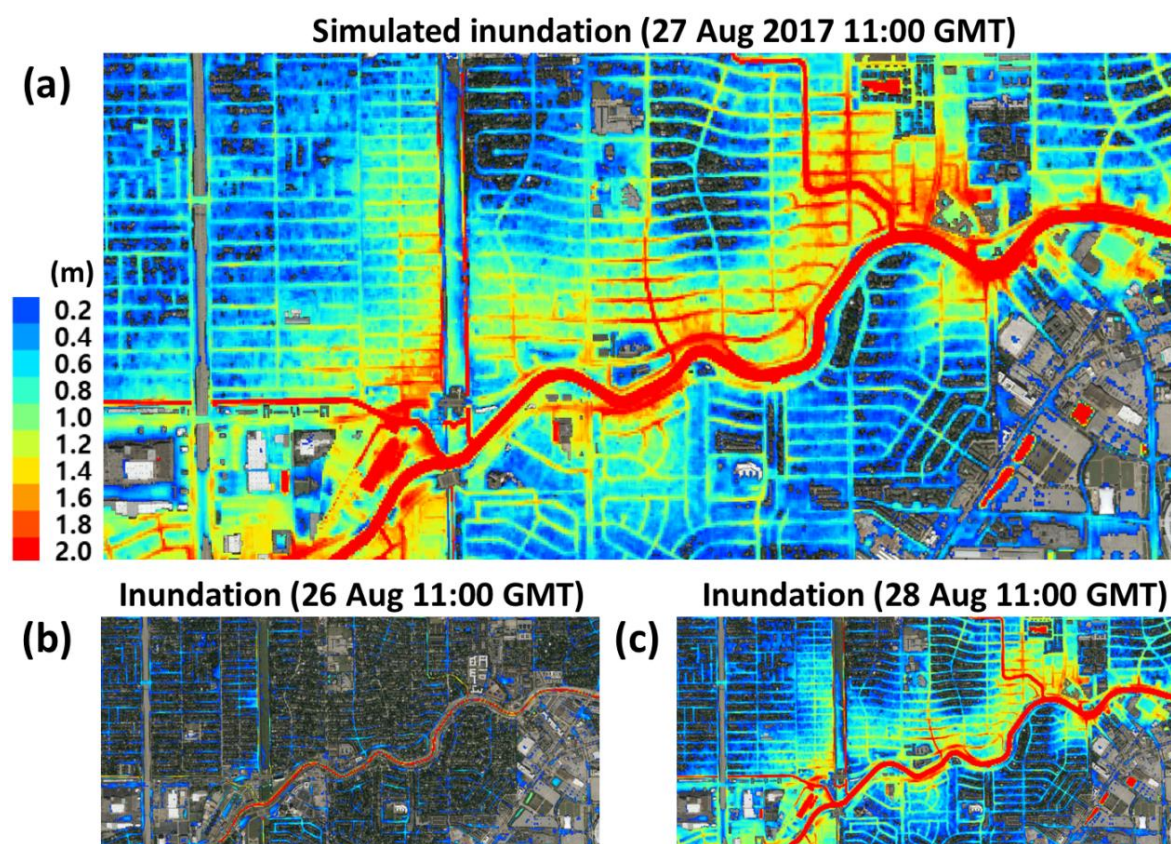


Figure 6. (a) The simulated inundation at 11:00 GMT August 27 around the middle of Brays Bayou. (b) The simulated inundation at 11:00 GMT August 26. (c) The simulated inundation at 11:00 GMT August 28.

The simulated inundation was evaluated using multiple on-site photos (Figures 7 and 8). The water depth was estimated at the point where the reference object (e.g., human, car, direction sign, etc.) in a photo was located. In Figures 7 and 8, the simulated inundation depth exceeding 0.1 m is shown on the satellite-based map. In the inset of each panel (Figure 7), an on-site photo taken at the numbered location (Figure 1) is compared. In Figure 8, the simulated inundation at the numbered location is displayed. The photos are not shown due to copyright limitations, but their web addresses are available in Section References. In Figures 7 and 8, it was found that the inundation captured in on-site photos were reproduced well in the simulation, demonstrating the street-resolving capability of the high-resolution model. As seen in Table 2, the mean of root mean square error (RMSE) was 0.26 m and the percentage error ranged from -150% to 100% , which were within an acceptable range given that urban flooding unfolded dynamically in time and space. It was also observed that the development and propagation of the inundation occurred concurrently in both the streams and the interior areas, while most of the roadways in relatively low elevations were flooded and thus functioned as ephemeral streams. The reanalysis figures help explain why the majority of the fatalities occurred from drowning in and around vehicles, whereas a relatively small number of fatalities (11%) were found in buildings [4]. It is noteworthy that, despite inherent uncertainties in on-site photos (e.g., length of reference object, resolution, angle), information from the photos is critical to being able to verify the occurrence of inundation at specific times and locations and to demonstrate the adequacy of simulated inundation for assessing severity. In future research, binary (e.g., flooding/non-flooding) or categorical (e.g., low/middle/high risks) estimation of inundation from on-site photos is recommended for model validation or data assimilation [28].

Interestingly, the on-site photos with higher water depths (>1 m; e.g., locations 4, 6, 9, and 12) were mostly taken at the edges of the simulated inundation, presumably due to the photographers' accessibility. On the contrary, the photos with lower water depths (<0.6 m; e.g., locations 2, 5, 7, and 14) were taken even in the middle of the simulated inundation. This may be because the shallow water depth and the low velocity gave a sense of security to the photographer, even in the midst of flooding.

Table 2. A comparison of simulated and measured inundation depths using on-site photos.

Site No. [Reference of Photo]	Water Depth from Photos (m, A)	Simulated Water Depth (m, B)	Error Range		Time (GMT)	Location	
			Depth (m, A – B)	Percentage (A – B)/B × 100		Latitude	Longitude
1 [27]	0.5–0.7	0.5	0–0.2	0.0–40.0	August 28 18:00	29.8532465	–95.1923113
2 [29]	0.4–0.6	0.3–0.7	–0.3–0.3	–100.0–100.0	August 28 22:00	29.8793650	–95.3733786
3 [30]	0.3–0.5	0.4	–0.1–0.1	–25.0–25.0	August 28 20:00	29.8319180	–95.6456570
4 [31]	1.0–1.2	1.0	0.0–0.2	0–20	August 28 12:00	29.8513660	–95.6306056
5 [32]	0.1–0.2	0.2–0.4	–0.3–0.0	–150.0–0.0	August 27 22:00	29.6714014	–95.5283436
6 [33]	1.5–2.0	1.6–2.0	–0.5–0.4	–31.3–25.0	August 27 10:00	29.6756906	–95.4799078
7 [34]	0.4–0.6	0.6–0.8	–0.4–0.0	–66.7–0.0	August 27 14:00	29.6846520	–95.4588430
8 [35]	3.0–4.0	3.6–5.0	–2.0–0.4	–55.6–11.1	August 27 23:00	29.7612616	–95.4596318
9 [36]	0.8–1.1	1.1–1.6	–0.8–0.0	–72.7–0	August 27 23:00	29.7618828	–95.3919220
10 [36]	0.5–1.0	1.5–1.7	–1.2 to –0.5	–80 to –29.4	August 28 17:00	29.7643435	–95.3605748
11 [37]	2.5–3.0	3.0–3.2	–0.7–0.0	–23.3–0.0	August 28 17:00	29.7098815	–95.2547888
12 [38]	0.9–1.1	1.0–1.2	–0.3–0.1	–30.0–10.0	August 27 17:00	29.7822252	–95.3766821
13 [39]	0.4–0.6	0.4–0.6	–0.2–0.2	–50.0–50.0	August 29 12:00	29.8394170	–95.6454320
14 [40]	0.5–0.6	0.6–0.8	–0.3–0.0	–50.0–0.0	August 27 13:00	29.6865858	–95.4588247
15 [41]	0.6–0.7	1.0–1.4	–0.8 to –0.3	–80.0 to –21.4	August 28 19:00	29.8055937	–95.4280031

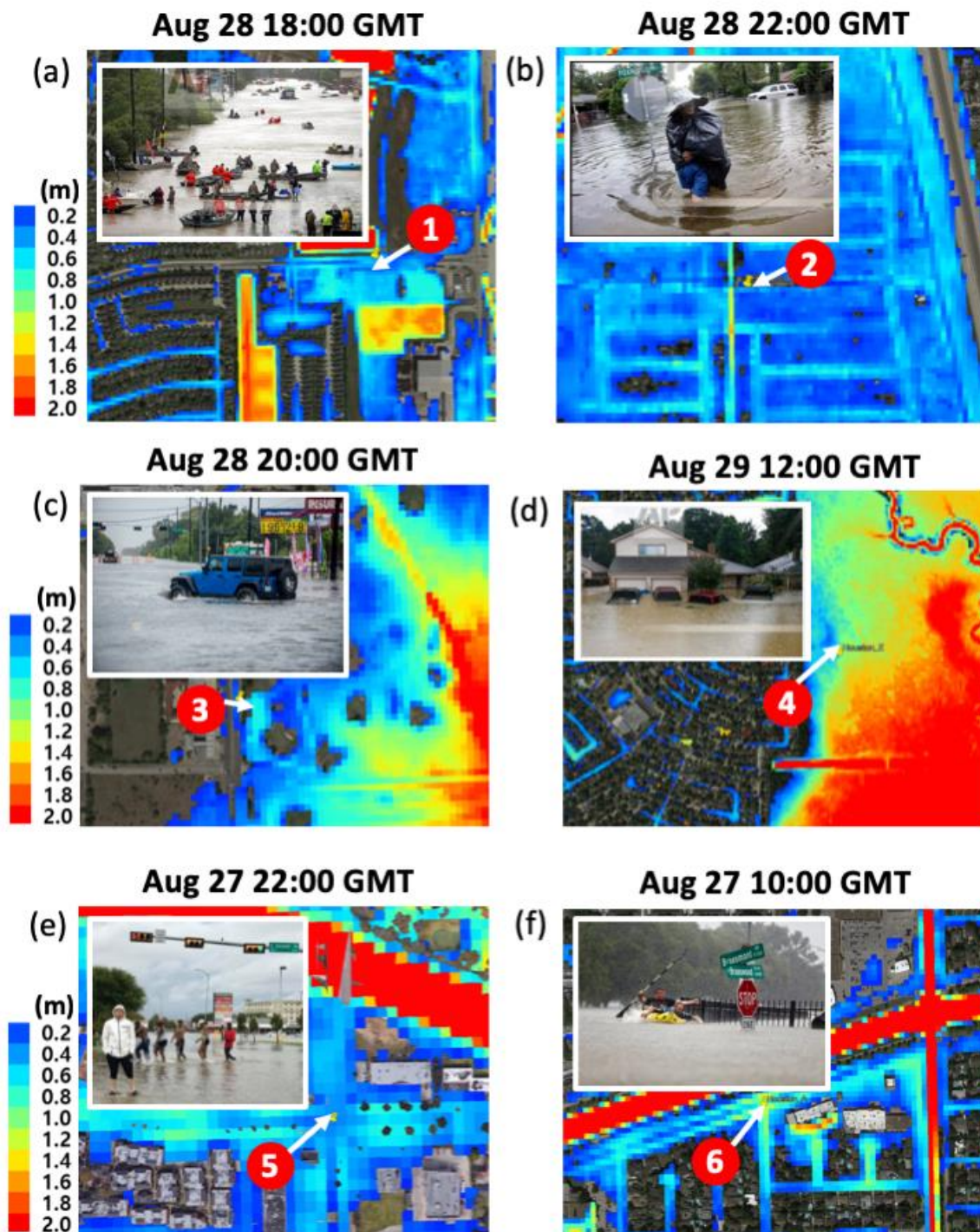


Figure 7. A comparison of simulated and measured inundation depths using on-site photos. On-site photos were provided courtesy of (a) AP Photo/David J. Phillip [27], (b) AP Photo/Elizabeth Conley [29], (c) Shawn Hamilton [30], (d) AP Photo/Michael Ciaglo [31], (e) DJ Willy B [32], (f) AP Photo/Mark Mulligan [33].

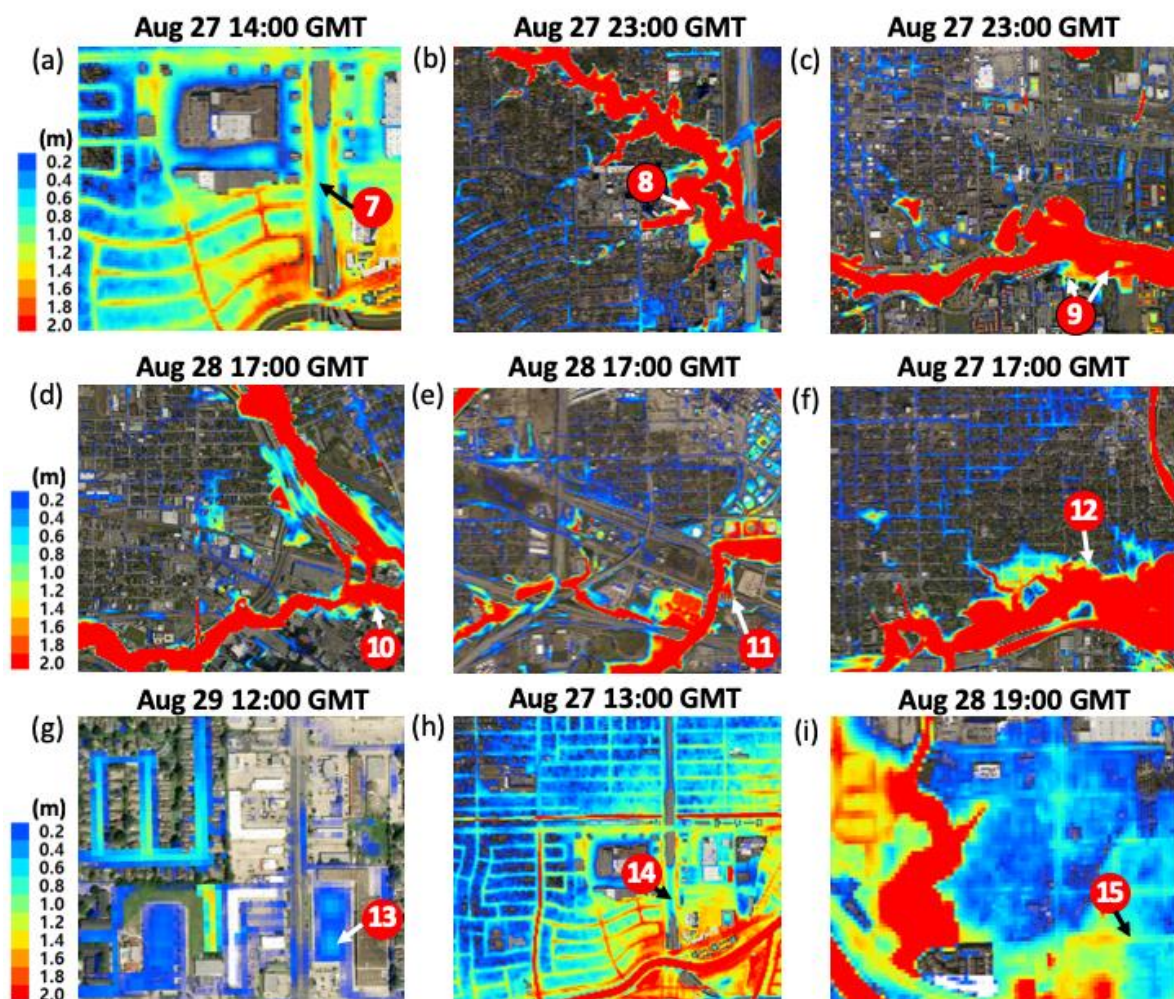


Figure 8. (a–i) Simulated inundation compared to the inundation estimated from on-site photos. The on-site photos for sites 7–15 can be found in references [33–40].

In addition to the validation of inundation outside of rivers using on-site photos, temporal variations of the simulated (blue) and observed (black) water levels were compared at the six gaging stations (Figure 9; see Figure 1 for locations). Note that the validation using water level observations was limited to the downstream locations, as 10-m grids might not reflect river bathymetry at the upstream locations. The average values of RMSE and the Nash Sutcliffe efficiency (NSE) for the plotted period (from 25 to 30 August 2017) at the six locations were about 1.25 m and 0.84, respectively (Table 3). Overall, the simulated stage hydrographs show good agreement with the observed, indicating that the high-resolution urban flood model was capable of simulating channel flow. Whereas the simulation captured the flood peaks and timing very well, there were periods of under- or over-simulation during the evolution (e.g., underestimation in the falling limb (Figure 9a) and overestimation in the falling limb between two flood peaks (Figure 9e)). A number of factors, such as simplified hydrologic processes and parameterization in the model, may have contributed to these discrepancies. For their attribution, additional research is needed. For variations of water depths at Barker and Addicks Reservoirs (Figure 9c,d), the significant difference in the initial stage may be due to the elevation differences around the local hydraulic structures, such as the reservoir gates, which the model may not have captured. Once the reservoirs started to fill up, the temporal evolution of water depths matched very well with the observed.

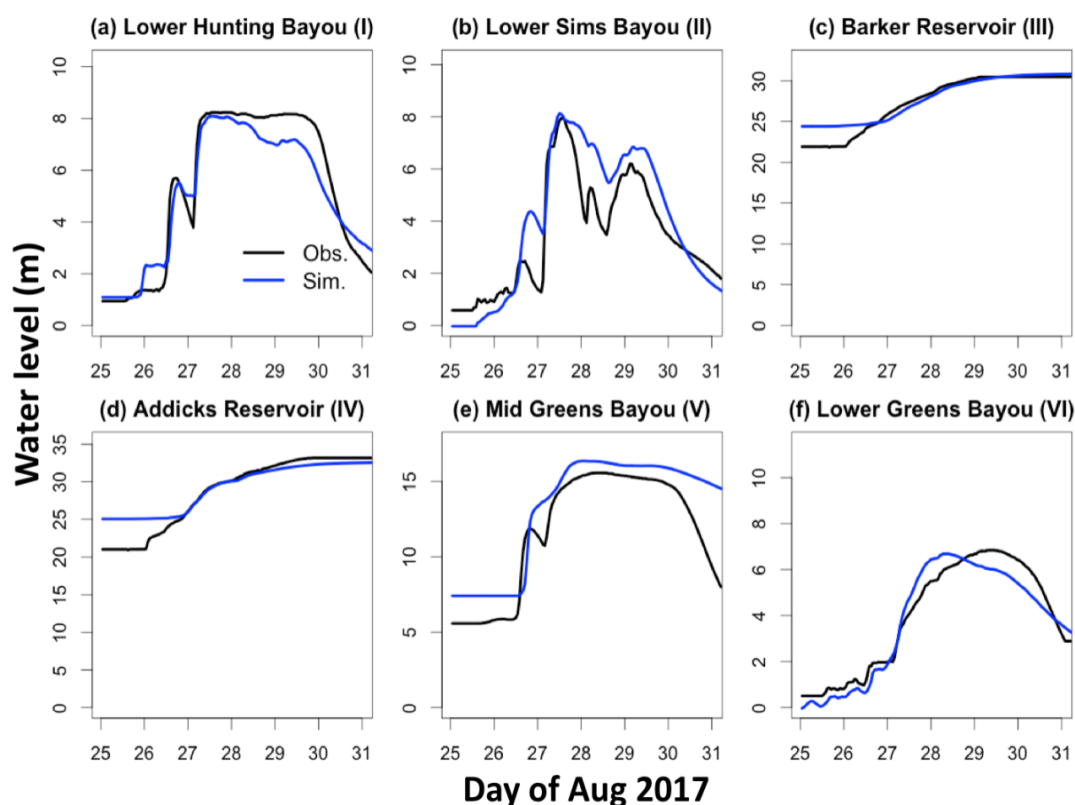


Figure 9. (a–f) A comparison of simulated and measured flow depths at six gaging locations.

Table 3. The root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE) for simulated and measured flow depths at six gaging locations.

Site No.	Gaging Location	RMSE (m)	NSE
Average	-	1.25	0.84
I	Lower Hunting Bayou	0.78	0.93
II	Lower Sims Bayou	1.21	0.68
III	Barker Reservoir	1.18	0.88
IV	Addicks Reservoir	1.86	0.84
V	Mid Greens Bayou	0.64	0.92
VI	Low Greens Bayou	1.79	0.79

3.2. 3D image Analysis Using On-Site Photos with LiDAR-Driven Surface Model

An on-site photo taken from a higher angle contains hydraulic information over an area, not limited to a point where a reference object is located. In this section, we combined the retrieved water depths, images collected from the impacted area, and high-resolution terrain data to validate the simulated inundation for a wider range of areas. We searched for on-site photos taken from a higher angle containing three key attributes: location, time, and water level. From the raw image of the downtown area taken from a tall building in the Houston City Center (Location 16 in Figure 1) in Figure 10a, we estimated the flood water level by inspecting the photo contents; the flooded area extended past the specific intersection from which the inundated elevation was inferred to be about 11 m, based on the elevation of the location extracted. In Figure 10b, the flood water extent in the image acquired from a traffic monitoring camera operated by Houston TranStar (Location 17 in Figure 1), was used for analysis. The time and location were extracted from the time stamp label in the image and the meta-data from the website, respectively. This image was useful because it showed the flood water reaching near the bottom of the light pole and submerging two-thirds of the highway sign. From the elevations of the bottom of the light pole and the highway sign, we estimated the flood level to be about

9 m at 7:15 pm on 27 August 2017. The flood water levels estimated from the reconstructed scenes (Figure 10c,d) were 9 and 11 m, respectively. Then, the simulated inundation maps were depicted on Google Maps (Figure 10e,f). Note that the inundation extent associated with the respective water levels agreed well with the on-site photo images. Although some differences were found at the reference locations, presumably due to the difference in the DEM resolution (10 m for flood modeling vs. 1 m for image analysis) and modeling uncertainty, the spatial delineation of inundation showed a good agreement between the simulated and the estimated. This approach can be applied to quantitative reconstruction of inundation for wider areas using any image sources taken from a higher angle (e.g., by a manned or unmanned aerial vehicle or from a tall building). Future research is recommended to develop correction methods to minimize multiple sources of errors in the estimation or extrapolation procedure due to a higher angle or a low resolution.

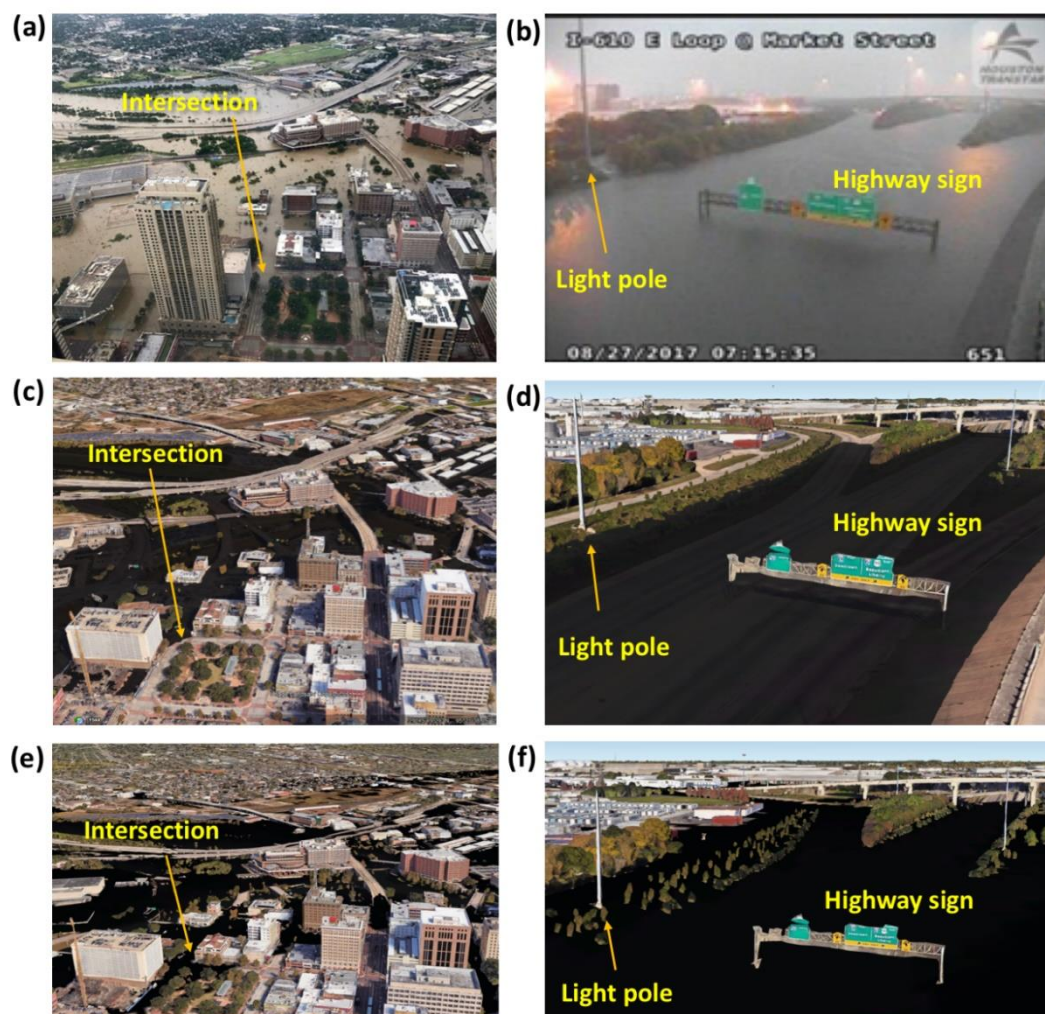


Figure 10. Example 3D reanalysis of on-site photos compared to the simulated inundation on the Google Maps. (a,b): On-site photos at the locations 16 and 17 in Figure 1, respectively. (c,d): The reconstructed inundation using photos and high-resolution elevation data. (e,f): The simulated inundation displayed on Google Maps. The water surface is shown in black from Figure 9c–f. On-site photos are provided courtesy of (a) Christian Tycksen [42] and (b) Houston TranStar [43].

3.3. Comparison of the Simulated Maximum Inundation Extent with Flood Maps

The simulated maximum inundation extent was compared with the FEMA flood maps to assess the magnitude and characteristics of flooding from Hurricane Harvey (Figure 11). The FEMA-produced 1-percent and 0.2-percent annual-chance flood maps [5] are the most widely used information to assess

flood risks in a specific area and to determine whether flood insurance is required for structures. The 1-percent annual-chance flood, also referred to as the 100-year flood, is defined as a flood having a 1-percent chance of being equaled or exceeded in any given year under the assumptions of stationarity and independence. To get the simulated maximum inundation extent from the high-resolution model output, a grid point is classified as inundated if the maximum water depth during the simulation period exceeded 0.3 m. In Figure 11a, the resulting simulated maximum inundation extent during Harvey, the 100-yr map, and the 500-yr map are illustrated in red, dark blue, and light blue, respectively. The enlarged view of the rectangular area in Figure 11a is shown in Figure 11b. The comparison shows considerable differences between the maximum inundation extent and the 1- and 0.2-percent flood maps.

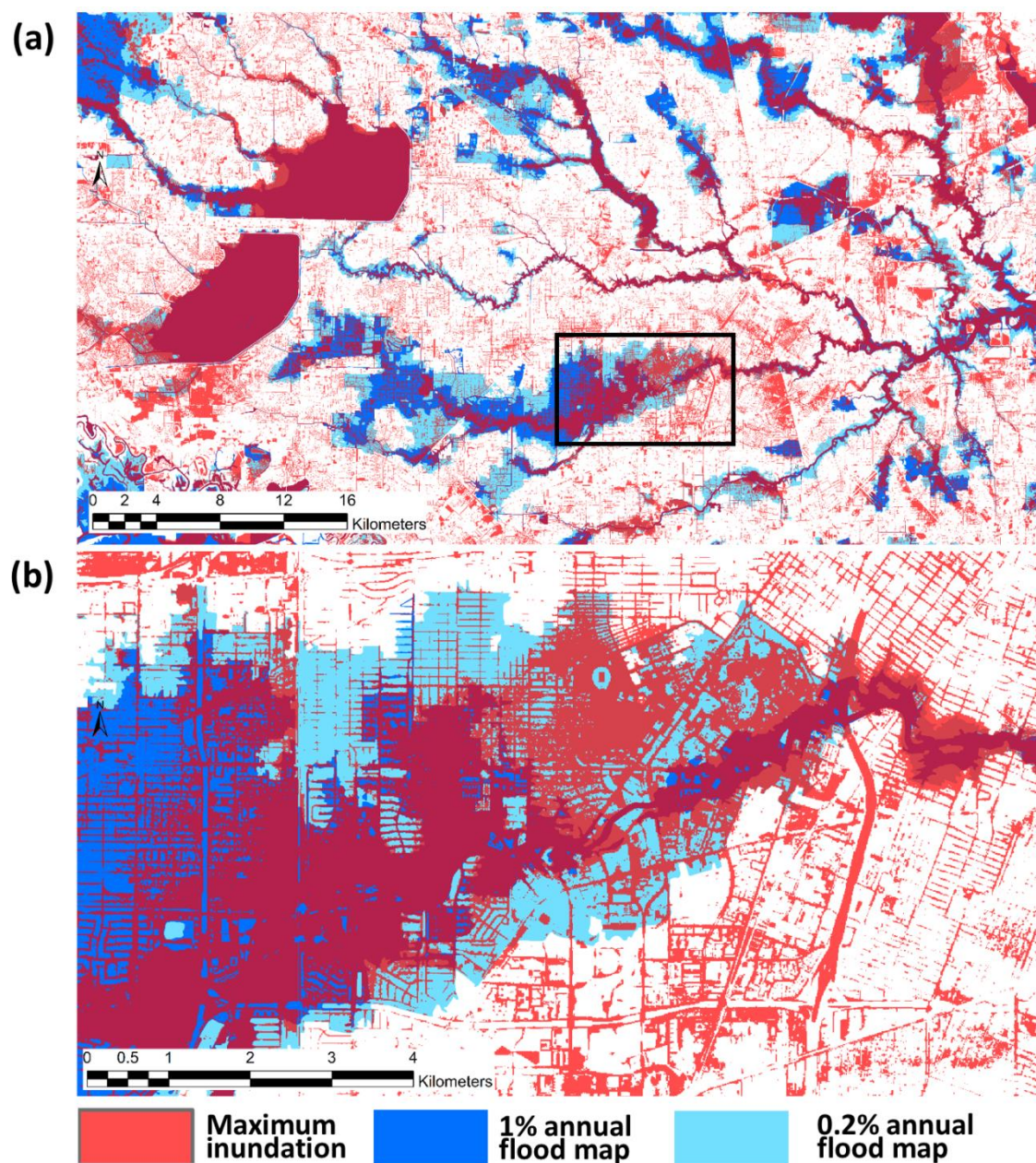


Figure 11. A comparison between the simulated maximum inundation extent (red) and the 1-percent (dark blue)/0.2-percent (light blue) annual-chance flood maps. (a) The entire domain. (b) The enlarged domain marked in (a).

The areas of the simulated maximum inundation extent were compared with FEMA flood maps in Table 4. The comparative analysis was performed within the catchments of six bayous shown in Figure 1. More than a half of the simulated inundation extent (55%) was found outside of the FEMA flood maps, while 70% of FEMA flood maps (637 km² out of 915 km²) was identified to be inundated during the Hurricane Harvey flooding. Given that the FEMA flood maps are not based on the precipitation from Hurricane Harvey and that they are generally considered a poor predictor of the location of damaging flooding in previous studies [4,44,45], some differences may be justifiable. The widespread discrepancies outside of the flood zones, however, do raise questions as to whether the conventional flood mapping approaches, which focus on fluvial flooding [46], are appropriate, particularly for urban areas where large risks exist also from pluvial flooding, as shown in this work. That many areas of the simulated inundation extent lie outside of the FEMA flood zones is in line with the fact that the majority of the fatalities [4] and high-water rescue calls [47] occurred outside of the flood zones. In addition, the spatial extent of flood zones in the FEMA flood maps was mostly larger than the severely inundated areas depicted by the high-resolution model. For better analysis of the impact of pluvial flooding, tracking sources and residence time of inundation is recommended as a future research topic.

Table 4. The areas of the simulated maximum inundation extent compared with Federal Emergency Management Agency (FEMA) flood maps.

Simulated Maximum Inundation Extent (km ²)			FEMA Flood Maps (km ²)	
Total	Inundation within FEMA Maps	Inundation Outside of FEMA Maps	0.2% Flood Map	1% Flood Map
1404.6 (100%)	636.6 (45%)	768.0 (55%)	915.0	594.1

4. Conclusions

Inundation in the Houston metropolitan area during Hurricane Harvey was retrospectively modeled using high-resolution two-dimensional urban flood modeling, on-site photo images, and water level observations. The flood model is based on dynamic wave approximation and 10 m-resolution terrain data, and is forced by the radar-based quantitative precipitation estimates. The study domain includes Buffalo, Brays, Greens, Hunting, Sims, and White Oak Bayous. Also proposed is a new method for retrieving inundation extent and severity by combining on-site photo images with high-resolution terrain data. The main findings are as follows:

- High-resolution hydrodynamical modeling can provide street-resolving inundation mapping in the Houston metropolitan area with reasonable accuracy during extreme events such as Hurricane Harvey.
- The conventional flood mapping method, which assumes that inundation occurs from the overflow of rivers (i.e., fluvial flooding), is not able to capture interior inundation (i.e., pluvial flooding) caused by extreme rainfall.
- More than a half of the simulated maximum inundation extent (55%) was found outside of the conventional flood maps, only 70% of which indicated inundation during the Hurricane Harvey flooding.
- High-resolution hydrodynamic modeling can capture multi-scale inundation, ranging from site-specific flooding in residential areas to inundation by backwater from man-made reservoirs, and to inundation from overflowing rivers.
- The combination of 3D image reanalysis and LiDAR-driven ground surface modeling makes possible quantitative reconstruction of inundation extent and depth when no stage or streamflow observations exist.

Recent studies suggest that anthropogenic warming may be attributable to a 10-percent decrease in tropical-cyclone translation speed from 1949 to 2016 [48] to the rainfall extremes on the Gulf Coast during Hurricane Harvey [1,2]. High-resolution inundation modeling and image analysis described herein provides a powerful method for developing street-resolving flood maps for all areas under current conditions, as well as for impact assessment of changes in land cover, and rainfall and storm surge potential of future hurricanes.

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