CHARACTERIZING THE HYDRAULIC INTERACTIONS OF HURRICANE STORM SURGE AND RAINFALL-RUNOFF FOR THE HOUSTON-GALVESTON REGION

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ABSTRACT

Planning of traditional coastal flood risk management strategies are largely predicated on storm surge protection against extreme hurricanes, i.e. storm surge. However, (1) hurricane storm surge and (2) hurricane rainfall-runoff are not mutually exclusive flood hazards. Little research has emphasized the need for quantifying and characterizing the joint hydraulic processes between hurricane storm surge and rainfall-runoff during real events for enhancing effective flood risk mitigation. In this regard, an improved hydrological and hydrodynamic modeling framework has been developed for the Houston Ship Channel (HSC) and Galveston Bay to serve as a quantitative testbed for evaluating coupled hurricane storm surge and rainfall-runoff.

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Modularity within the modeling framework allows for landfall shifting of historical hurricane tracks, wind fields, and corresponding rainfall patterns to serve as numerical model inputs, as well as providing an expanded dataset of storm events. Distributed hydrologic and unsteady hydraulic analyses of upstream rainfall-runoff and storm surge are conducted for hurricanes Katrina (2005), Ike (2008), and Isaac (2012) under three synthetically shifted landfall locations near the HSC and Galveston Bay regions. For the modeled scenarios, results show that peak flows from storm surge easily dominate those of rainfall-runoff, but that rainfall-runoff can constitute more than half of the total flood volume draining towards the HSC. Most modeled scenarios reveal less than 24 hours of separation between peak surge and peak rainfall-runoff. In the same way that storm surge is sensitive to hurricane landfall location and angle of approach, so are spatial rainfall distributions and associated inland runoff processes, due to wide topological variations in coastal watershed boundaries. Analysis of coastal flood mitigation is extended with the dynamic modeling of a proposed storm surge barrier system at the HSC, with its performance quantified under the given hurricanes. The surge barrier system is demonstrated to be hydraulically feasible for all scenarios, with maximum water surface elevation reductions ranging between 0.63 m and 3.28 m. However, accurate storm surge and riverine flood forecasting methods will be critical for achieving optimal gate and barrier operations.

Keywords: Hurricane Rainfall-Runoff, Hurricane Storm Surge, Surge Barrier, Distributed Inland Hydrology, Unsteady Riverine Modeling, SWAN+ADCIRC

1. Introduction

For the United States (U.S.) and many countries, events of the last decade have exposed the general lack of effective coastal resilient measures necessary for communities to recover from severe flood hazards, as evidenced by extreme tropical cyclones such as Hurricanes Katrina (2005), Rita (2005), Ike (2008), Sandy (2012), Typhoon Haiyan (2013), and Cyclone Pam (2015). This has resulted in fatalities of catastrophic proportions and unprecedented flood related damages, for which many affected regions are still recovering today. Such events have prompted national institutions, professional societies, task force committees, independent expert review panels, and coastal municipalities to re-evaluate effective policy and strategies for managing and reducing coastal flood risks in the U.S. (City of New York, 2013; Reid, 2013; Aerts et al., 2014; National Research Council [NRC], 2014; Traver, 2014).

Implementing effective coastal flood risk management strategies requires a comprehensive understanding of the critical interactions between hydraulic forces that contribute to the overall flood risk, leading to an accurate “picture” of the coastal hydrologic landscape. For example, it has been observed that hurricane-induced flooding is driven by two sources, (1) hurricane storm surge and (2) rainfall-runoff, yet traditional coastal flood risk reduction strategies are typically biased towards surge only. Hurricanes can introduce massive volumes of storm surge, and unleash torrential quantities of rainfall as they move inland. For example, during Hurricane Ike, between September 13, 2008, 6:00a.m and September 14, 2008 6:00 a.m., the Harris County Flood Control District’s (HCFCD) Flood Warning System recorded approximately 33.6 cm of rainfall in 24 hours in northwest Houston near U.S. Highway 290 (HCFCD, 2014). For the Greater Houston region, such a precipitation-duration is equivalent to a rainfall event containing a 0.01 annual exceedance probability (100-year rainfall event) (HCFCD,

2009). Although, this rainfall was not uniformly distributed across the watershed, nearby areas experienced similarly intense downpours, causing localized inland flooding. Much of this rainfall-runoff drains into Galveston Bay, a semi-enclosed bay with a finite storage capacity; this can lead to inland backwater effects from high tailwater conditions along the Houston Ship Channel (HSC).

A notable interaction of hurricane rainfall and surge was observed during Hurricane Isaac, which made landfall just west of New Orleans, Louisiana in August 2012. Isaac was unique because of its significant rainfall, with its peak rainfall intensity having occurred at the time of maximum surge (Boyett, 2013a). Although the recently completed Hurricane and Storm Damage Risk Reduction System (HSDRRS) performed successfully during Isaac (Reid, 2013; Boyett, 2013b), persistent flooding for unprotected low-lying communities outside of New Orleans, just north of Lake Pontchartrain, was exacerbated when high rainfall totals produced high water levels in the lake, prolonging upstream drain time (Mueller, 2013).

In regards to long-term hurricane rainfall trends, the Intergovernmental Panel on Climate Change (IPCC) (2013) projects increased levels of extreme precipitation from tropical cyclones for storms making landfall along the Gulf of Mexico and the western and eastern coasts of the U.S., Canada, and Mexico. Table 1 summarizes some of the most recent and notable Gulf of Mexico (“Gulf system”) hurricanes that have occurred in the last decade. It can be shown that real hurricane systems exhibit wide variability in peak surge and peak rainfall patterns, particularly throughout a storm’s synoptic lifetime. Table 1 seemingly reveals an inverse relationship between hurricanes of high maximum surge and little maximum rainfall (e.g. Katrina) and hurricanes of low maximum surge and high maximum rainfall (e.g. Isaac)

[Table 1 Inserted Here]

In either case, such meteorological complexities highlight the need for improved insights on the coupled hydraulic interactions of hurricane storm surge and associated rainfall-runoff for achieving effective coastal flood protection strategies. Resio and Westerink (2008) state that rainfall-runoff has traditionally been neglected in hurricane modeling, yet plays an integral part in coastal flood dynamics. These insights are particularly important for densely populated coastal regions in proximity to partially or fully sheltered bay systems.

The objective of this paper is to systematically investigate the relative hydraulic contributions and interactions of (1) hurricane storm surge and (2) rainfall-runoff downstream of the HSC. The proposed modeling framework extends the efforts of Christian et al. (2014) by including a larger suite of hurricanes that encompass a broader range of hydrological conditions. To accomplish this, historical hurricane tracks are shifted, while preserving spatial and temporal characteristics of their corresponding rainfall distributions and wind field patterns. Modeled hurricane hydrographs at the HSC are analyzed into component parts for investigating rainfall-surge contributions. Hydraulic insights are complemented with a performance analysis of a storm surge barrier, also introduced in Christian et al. (2014).

2. Background and Study Area

Fig. 1a illustrates the study area layout and regional hydrography. The HSC is located at the downstream end of the San Jacinto River Basin (SJR). The SJRB has an effective watershed area of approximately 11,655 km², containing all of Harris County and parts of Montgomery, Waller, Walker, Grimes, Liberty and San Jacinto counties, as well as a total of 18

contributing watersheds. The main stem of the San Jacinto River flows along the eastern side of Harris County and forms a confluence with the HSC prior to flowing into Galveston Bay along the southeastern edge of the county. Land use consists mostly of urbanized development in Harris County and forested areas in the far north. The HSC's geographic proximity to Galveston Bay makes it naturally vulnerable to extreme hurricane events. This vulnerability is compounded by the fact that the HSC hosts the second largest petrochemical complex in the world, with a port that ranks first in the U.S. in export tonnage and serves as the primary economic engine for the region (Port of Houston, 2013). Undisturbed HSC operations are critical to the economic growth of the region and the nation. Galveston Bay connects the SJRB with the Gulf of Mexico and is the seventh largest estuary in the U.S., with an area of 1,600km². Additionally, Galveston Bay inhabits significant biodiversity in both terrestrial and aquatic wildlife.

[Fig. 1 Inserted Here]

While Hurricane Ike (2008) demonstrated that major hurricanes can produce considerable storm surge and rainfall in Galveston Bay and near the HSC, the maximum surge height was located near Sabine Pass, approximately 90 km northeast of its official landfall at Bolivar Roads (Berg 2009). Had Hurricane Ike made landfall 40 km southwest, thousands of industrial facilities and petrochemical storage tanks along the HSC would have likely experienced widespread flooding from storm surge (Bedient 2012; Sebastian et al., 2014). It is estimated that flood related damages from extreme storm surge along the HSC could have exceeded \$140 billion in facility and infrastructure damage (Blackburn et al., 2014), as well as lost production

and operational downtime. Should the industrial facilities along the HSC become inundated from severe storm surge, the potential environmental repercussions from the spillage of hazardous materials would likely be significant. Approximately 4,000 HSC storage tanks contain hazardous materials or petroleum products that could be affected from a 7.6 m surge event (Blackburn et al., 2014). Such an event would likely lead to chemical and petrochemical spills into the HSC and Galveston Bay, impacting the health and welfare of the surrounding Galveston Bay ecosystems and fishing industries. Thus, providing proper protection from the effects of tropical cyclones to the HSC is essential and serves as the impetus for detailed evaluation of a proposed storm surge barrier system (Fig. 1b) under a wider range of extreme hydrologic conditions.

3. Modeling Framework

Fig. 2 illustrates the coupled modeling framework which consists of three major components, i.e. (1) inland watershed hydrology of the SJRB (Fig. 2a), (2) tidally influenced riverine hydraulics of the HSC (Fig. 2b), and (3) coastal hydrodynamics of Galveston Bay (Fig. 3c). In short, both the inland hydrology and coastal hydrodynamic models serve as numerical inputs to the riverine hydraulics model.

The distributed, physics-based hydrologic modeling approach is adopted for predicting rainfall-runoff response for the SJRB. This allows for spatial variability in watershed characteristics to be preserved for the entire watershed. With a distributed approach, conservation of mass, momentum, and energy for overland runoff are solved, as opposed to lumped hydrologic methods that spatially aggregate watershed characteristics with empirical parameters. Doubleday et al. (2013) and Christian et al. (2014) demonstrated the utility of using

a distributed hydrologic approach for predicting watershed response in Harris County watersheds and nearby regions. The distributed hydrologic model is developed using *Vflo*TM (Vieux and Vieux, 2002). The model domain is represented by a computational grid containing 50,000 grid cells, with a grid cell size of approximately 550 m x 550 m. Overland routing is accomplished using kinematic wave for transforming excess rainfall into runoff. The kinematic wave analogy used in *Vflo*TM follows the one-dimensional continuity for overland flow which takes the form:

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} = R - I \quad (1)$$

where R is rainfall rate; I is infiltration rate; u is overland flow velocity rate; and h is flow depth. The kinematic wave method assumes uniform flow in place of full momentum, such that the inertial terms in the full momentum equation are negligible and the overland bed slope is equivalent to the friction slope (or energy grade line). For shallow overland flow, the kinematic wave method assumes that backwater effects are negligible. Given such simplifications, the relationship between water depth h and velocity u can be elegantly represented using Manning's equation as follows:

$$u = \frac{S_o^{1/2}}{n} h^{2/3} \quad (2)$$

where S_o is the bed slope, and n is Manning's roughness. Backward finite difference numerical methods are then implemented by *Vflo*TM to simultaneously solve for flow and velocities at each grid cell.

For inland channel routing, modified Puls was implemented in $Vflo^{TM}$ to account for attenuation storage. Modified Puls routing is a simple extension to the standard continuity relationship, but leverages pre-defined storage-discharge relationships for wide channels that can be approximated as linear reservoirs, and coupled with an empirical representation of the momentum equation (Chow, 1964; Henderson, 1966). Under modified Puls channel routing, the continuity equation can be generalized using the following form:

$$(I_n + I_{n+1}) + \left(\frac{2S_n}{\Delta t} - Q_n \right) = \left(\frac{2S_{n+1}}{\Delta t} - Q_{n+1} \right) \quad (3)$$

where I is inflow, Q is outflow, and S is storage. The only unknowns in Eq. (3) are S_{n+1} and Q_{n+1} , allowing for a recursive solution at each time step for routing a flow hydrograph.

Finally, the Green and Ampt (Green and Ampt, 1911) method is implemented in $Vflo^{TM}$ for modeling soil infiltration loss. The Green and Ampt equation reads:

$$f = K \left[1 + \frac{(\phi - \theta_i)S_f}{F} \right] \quad (4)$$

where K is the hydraulic conductivity, ϕ is soil porosity, θ_i is the initial soil water content, S_f is the wetting front soil suction head, F is accumulated infiltration, and f is infiltration rate. The Green and Ampt method extends Darcy's Law for ponded infiltration by assuming rainfall over homogenous soils with a changing wetting front. Fig. 2a shows the required model inputs and typical outputs that were computed using the distributed hydrologic model.

[Fig. 2 Inserted Here]

The ADvancedCIRCulation (ADCIRC) and Simulating WAVes Nearshore (SWAN) models was implemented for modeling hurricane storm surge and wave setup within the Gulf of Mexico, Galveston Bay, and the HSC. ADCIRC is an integration of open source computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions (Luettich and Westerink, 2004). Spatial discretization of the model domain is represented with a flexible computational mesh of non-overlapping, unstructured triangular elements. ADCIRC then employs continuous, piecewise linear Galerkin finite element numerical schemes for approximating the depth-averaged shallow water equations, solving for momentum and continuity. ADCIRC has been used to validate storm surge for numerous historical hurricanes within the Gulf of Mexico including hurricanes Katrina (2005), Rita (2005) and Gustav (2008); see Westerink et al. (2008), Bunya et al (2010), Dietrich et al. (2011a), Dietrich et al. (2011b).

SWAN was developed by the Delft University of Technology (TU–Delft) to simulate gravity surface wind generated waves (TU–Delft, 2014). SWAN and ADCIRC are tightly coupled, as described in Dietrich et al. (2011b), and are executed on the same computational mesh. The resulting code is referred to as SWAN+ADCIRC; the performance of SWAN+ADCIRC on high performance computers is documented in Dietrich et al. (2012). Validation of SWAN+ADCIRC for Hurricane Ike (2008) is documented in Hope et al. (2013) and further applications of the model for Ike are described in Sebastian et al. (2014).

The computation mesh and other model inputs and outputs are illustrated in Fig. 2c. The computational resources at the Texas Advanced Computing Center (TACC) at the University of Texas at Austin were utilized for all hurricane simulations. SWAN+ADCIRC computations

were executed using the Lonestar Linux cluster, consisting of 1,888 compute nodes, 22,656 processing cores, 44 terabytes of memory, and a peak performance of nearly 302 teraflops.

Fig. 2b illustrates the 1-D hydraulic and unsteady riverine model of the HSC which serves as the interfacing hub for coupling upstream and lateral hydrological processes, computed using *Vflo*TM (Fig. 2a), with downstream hydrodynamic processes, computed using SWAN+ADCIRC (Fig. 2c). Upstream and lateral HSC inflows and downstream storm surge are numerically represented in the 1-D hydraulic model as time variant boundary conditions. The unsteady hydraulic model was developed using HEC-RAS version 4.1 for routing full flow and stage hydrographs from rainfall-runoff and storm surge events, as well as computing water surface profiles and floodplain maps (USACE, 2010). Such a framework is suitable because the highly incised geometry of the HSC lends itself to 1-D continuity and momentum assumptions. Previous research efforts have demonstrated the utility of using a 1-D approach for modeling tidally influenced and well incised coastal channels where effects of wave action are less dominant (Ray et al., 2011; Christian et al., 2014; Mashriqui et al., 2014). The topographies of the HSC and the lower reaches of the San Jacinto River are represented with approximately 153 cross sections based on 2008 Light Detection and Ranging (LIDAR) data and 2007 bathymetry data. Serving more than a coupling interface, the unsteady hydraulic model allows for the dynamic modeling of a proposed HSC storm surge barrier system located near the watershed outlet of the SJRB, just downstream of the Fred Hartman Bridge. An architectural rendering of the proposed HSC barrier system is provided in Fig. 1b.

The capability of shifting hurricanes is one of the key advantages of this modeling framework. Because extreme hurricanes are low probability, high consequence events, ample availability of paired datasets containing time series hurricane rainfall and windfields are limited,

particularly for specific areas where the need to study and evaluate performances of coastal flood risk mitigation strategies under a full rainfall-surge spectrum is paramount. Fig. 3 provides an embellished concept of the hurricane track shifting approach. This concept is illustrated for Hurricane Katrina to convey how a shifted hurricane's rain bands (Fig. 3b) and windfield (Fig. 3c) are held spatially and temporally consistent from its original landfall location to a shifted landfall location. In short, the latitude and longitude coordinates for a hurricane's original landfall location are translated to a new point of interest, ensuring that spatial and temporal rainfall distribution and windfield patterns remain consistent. This was necessary to maintain a hurricane's synoptic spatial and temporal integrity (in both rainfall distribution and windfield) so as not to introduce unintended meteorological biases in the hurricane development process, a complex phenomenon far beyond the scope of this paper. Customized Fortran-based scripting methods were used to appropriately shift hurricane windfiles for ADCIRC, while HEC-MetVue (USACE, 2012) was utilized to assist in transposing radar-based multisensor precipitation estimates (MPE). MPE is a product of the U.S. National Weather Service (NWS) River Forecasting Centers and is routinely used to perform regional flood forecasting. HEC-MetVue is a toolkit provided by the U.S. Army Corps of Engineers (USACE), and was only used in this study to transpose historical MPE rainfall at hourly increments.

The shifted hurricanes in this paper are limited to those having occurred in the Gulf of Mexico, more specifically those crossing the Louisiana-Texas shelf, to avoid inclusion of hurricanes with improbable characteristics for this region.

[Fig. 3 Inserted Here]

4. Model Calibration

One of the major advantages of implementing a distributed hydrologic modeling approach is owed to greater flexibility in the calibration process for a study watershed of this size, i.e. 11,655 km². Bulk selection of grid cells allows for more efficient fine tuning of watershed characteristics. The SJRB hydrologic model was calibrated to three major rainfall events, (1) Hurricane Ike, (2) July 2012 rainfall event, and (3) April 2009 rainfall event. Parameters such as Manning's roughness, hydraulic conductivity, and soil depth were calibrated to match observed subwatershed streamflows. Major watershed model calibrations were made for Hurricane Ike's rainfall, with minor adjustments for the July 2012 and April 2009 rainfall events. Multiple storms were also needed to ensure adequate rainfall coverage necessary for calibration. In addition, the SJRB watershed contains 3 major reservoirs, i.e. Lake Conroe, Lake Houston, and Barker Reservoir. Of these, Lake Conroe and Barker Reservoir provide flood storage capacity. To simplify complexities of modeling reservoir operations, maximum outflow discharges from the last ten years were collected from historical U.S. Geological Survey (USGS) streamflow records immediately downstream of Lake Conroe, while Barker Reservoir outflows were regulated according to USACE (2009). Thus, under high modeled flow conditions, assumed maximum allowable outflows of approximately 57 m³/s and 142 m³/s were applied to Barker Reservoir and Lake Conroe, respectively, for all analyses. Results of the calibration process are illustrated in Fig. 4. Fig. 4a–f shows full hydrograph comparisons between observed and modeled streamflows for Brays and Hunting Bayous, two of the major tributaries draining into the HSC. It can be seen that streamflow magnitude, timing, and volumes show good agreement for all three rainfall events. The July 2012 event was particularly challenging due to multiple peaks in rainfall intensity. Fig. 4g–i compares observed and modeled peak flow for all

subwatersheds draining into the HSC. The coefficient of determination (R^2) values for the Ike, July 2012, and April 2009 rainfall events are 0.947, 0.782, and 0.908, respectively. This was considered acceptable for a watershed of this size.

[Fig. 4 Inserted Here]

A comprehensive hindcast validation of Hurricane Ike for the SWAN+ADCIRC computation mesh was carried out by Hope et al. (2013). Such efforts were necessary to account for Ike's unique storm surge forerunner that forced an early rise in water levels well before the hurricane made landfall. This exacerbated the surge flooding at Galveston during Hurricane Ike. The same validated computational mesh was adopted in this study. For the HEC-RAS model, acceptable stage comparisons between modeled and observed locations for Hurricane Ike were provided in Christian et al. (2014), and the same validated channel reaches and cross-sectional geometries were also applied in this study.

5. Analysis and Results

5.1. Hurricane Modeling Scenarios

Of the hurricanes provided in Table 1, Hurricanes Ike, Katrina, and Isaac were selected for critical analyses. These hurricanes are selected as suitable representations of Gulf system hurricanes producing high maximum surge and low maximum rainfall (i.e. Katrina), and hurricanes of low maximum surge and high maximum rainfall (i.e. Isaac). Each hurricane is analyzed under three different landfall tracks, as illustrated in Fig. 5. It can also be seen that the selected hurricanes provide useful variability in angles of landfall approach. The various

hurricane tracks are identified as landfall points A, B, and C. Landfall point A is located at the San Luis Pass bay inlet, near the southwestern end of Galveston Island. Landfall point B is located at the Bolivar Roads bay inlet. Landfall point C landfall is located near the Rollover Pass bay inlet, in the northeast portion of Bolivar Peninsula. These three landfall locations are a subset of a larger and carefully developed suite of landfall points, described in further detail by Sebastian et al. (2014). Their work entailed a systematically derived set of landfall points and associated sensitivity analyses on resulting storm surge. More specifically, Sebastian et al. (2014) analyzed approximately 10 landfall locations and three constantly scaled maximum wind speed intensities for Hurricane Ike. They showed that spatially subtle changes in hurricane landfall locations along the upper Texas Coast can have the ability to generate unique storm surge responses within the semi-enclosed Galveston Bay, particularly for landfall locations of points A, B, and C of this manuscript (Sebastian et al., 2014). This phenomenon corroborates the need for analyzing the three selected hurricane landfall locations illustrated in Fig. 5 and the associated storm surge responses at the HSC. Table 2 summarizes the hurricane scenarios analyzed. This includes three hurricanes, three landfall locations, and scenarios of “with” and “without” an HSC surge barrier, for a total of 18 modeled scenarios. Referring to Table 2 and Fig. 5, it is worth noting that Hurricane Ike at landfall point B represents the only original landfall location, while all other scenarios represent a synthetic shifting of Hurricanes Ike, Katrina, and Isaac.

[Fig. 5 Inserted Here]

[Table 2 Inserted Here]

5.2. Hydraulic Interactions of Hurricane Storm Surge and Rainfall-Runoff

Fig. 6 provides the SWAN+ADCIRC computed maximum storm surge elevations for all nine combinations of hurricane/landfall scenarios. All elevations are in reference to the North American Vertical Datum of 1988 (NAVD 88). Fig. 6a identifies the HSC location for spatial reference. For all scenarios, it is seen that maximum storm surge at the HSC is sensitive to hurricane landfall location and angle of approach. For Hurricane Ike, at landfall points A, B, and C, maximum storm surge downstream of the HSC is computed to be 5.28 m, 3.74 m, and 2.49 m, respectively. Similarly, for Hurricane Katrina, maximum storm surge for the HSC is computed at landfall points A, B, and C, to be 5.23 m, 4.74 m, and 2.90 m. Finally, for Hurricane Isaac, landfall points A, B, and C have computed maximum surges of 4.06 m, 3.24 m, and 2.12 m. The overall trend is that landfall at point A results in higher surge values for all scenarios. This makes sense, since hurricane storm surge is typically highest on the right-hand side of the storm relative to its direction of motion (Aguado and Burt 2004), and the landfall point A location tends to maximize this phenomenon with the higher likelihood of placing Galveston Bay and the HSC within a direct path to a hurricane's radius to maximum winds. The same reasoning supporting the severity of storm surge from a landfall point A location was also corroborated in further detail by Sebastian et al. (2014).

It is worth noting that Hurricane Katrina, when shifted to Galveston Bay, did not generate as high magnitudes of storm surge as it originally did in Louisiana and Mississippi. At its original landfall, Katrina generated storm surges ranging from 7.3 m to 8.5 m. In the Galveston Bay region, Katrina generates storm surges ranging from 5.5 m to 6.7 m, depending on landfall location. These differences arise not only from changes in angle of approach, as a result of the landfall shifting, but may come as a result from changes in bathymetry and differences in the characteristics of the continental shelf. This is because, in simplest expression, storm surge is

proportional to shelf width and wind stress and inversely proportional to water depth and bathymetry. Therefore, large and shallow continental shelves have the propensity to produce larger surges than steeply sloped shelves (Resio and Westerink, 2008). To place in context, Katrina would have been more devastating than Ike in terms of maximum surge at the HSC for all landfall locations except the landfall at point A, where they are roughly similar. Hurricane Isaac, a relatively weak Category 1 storm at landfall, generated a maximum surge of 3.4 m at Shell Beach, Louisiana. However, when shifted to a landfall point A location, Isaac produces a maximum storm surge at the HSC of 3.8 m, approximately 0.3 m higher than the maximum storm surge for the original landfall for Hurricane Ike (landfall point B).

[Fig. 6 Inserted Here]

In regards to hurricane rainfall, Figs. 7a–c illustrate the modeled spatial variability of accumulated rainfall in the SJRB for the landfall point B location from Hurricanes Ike, Katrina, and Isaac, respectively. Fig. 7a identifies the HSC location for spatial reference within the dotted box. For example, Fig. 7a shows that a large portion of Ike’s total rainfall is contained and spatially centered within the SJRB watershed boundaries. Recall that the landfall point B location represents the original landfall location for Hurricane Ike. Thus, Fig. 7a supports recorded observations that much of Ike’s heavier rainfall (39 cm to 52 cm) resulted in urbanized flooding across northwest Houston near U.S. Highway 290. Hurricane Katrina’s accumulated rainfall for a landfall point B location is represented in Fig. 7b. For Katrina, this resulted in total rainfalls ranging from 20 to 30 cm in the lower portion of the SJRB. Fig. 7c shows Hurricane Isaac’s accumulated rainfall, with much of the west and eastern portions of the SJRB receiving

11 to 22 cm and 27 to 40 cm, respectively. Although not shown in Fig. 7, total rainfalls for Ike, Katrina, and Isaac for landfall points A and C resulted in corresponding shifts of rainfall accumulations southwest (point A) and northeast (point C) of the SJRB.

It is worth clarifying that simulated maximum rainfall totals within the SJRB hydrologic model and for shifted hurricanes may not coincide with observed values because of the spatial non-uniformity in watershed areas and locations for the watershed of interest. When shifted, the maximum rainfall bands for Hurricane Isaac are located just beyond the SJRB watershed and model domain, in the northeast portions of Liberty County. This highlights an important observation of hurricane rainfall. Similar to storm surge, hurricane landfall location and angle of approach can greatly influence maximum observed hurricane rainfall for a given watershed, as well as associated runoff and streamflow processes that influence combined flood risks.

[Fig. 7 Inserted Here]

Times series results (stage and flow hydrographs) of storm surge and rainfall-runoff at the HSC are computed for all scenarios outlined in Table 2. In the interest of space, only representative hydrographs are provided in Fig. 8. A full and concise summary of modeled hydraulic results downstream of the HSC, near Fred Hartman Bridge, are provided in Table 3. Fig. 8 provides flow hydrograph decompositions of rainfall-runoff and storm surge downstream of the HSC for Ike at landfall point A, Isaac at landfall point B, and Katrina at landfall point C. The fine dotted lines represent the flow hydrograph contributions from hurricane rainfall-runoff. The darker hatched lines represent the flow contributions from hurricane storm surge. The dark solid line represents the combined hydrographs. Negative flows in Fig. 8 imply reverse flow

direction due to storm surge entering the HSC. It can be seen at all landfall locations that storm surge dominates peak flow contributions and intensity for the first 24 to 48 hours.

Referring to Fig. 8a (Ike, landfall point A), the surge hydrograph is very clear, since the HSC is in the direct path of the stronger right-hand side of Hurricane Ike's windfield. Absolute values of peak surge flow and peak rainfall-runoff were computed to be $14,177 \text{ m}^3/\text{s}$ and $1,861 \text{ m}^3/\text{s}$, respectively. Much of the rainfall-runoff arrives just after the storm surge hydrograph begins to recede, with the peak runoff arriving nearly 20 hours after peak surge.

Referring to Fig. 8b (Isaac, landfall point B), absolute values of peak surge flow and peak rainfall-runoff are computed to be $4,665 \text{ m}^3/\text{s}$ and $1,155 \text{ m}^3/\text{s}$, respectively. For the first 60 to 100 hours the HSC is weakly driven by surge, with a peak surge of $4,665 \text{ m}^3/\text{s}$. At about 240 hours (10 days), the rainfall-runoff contributions arrive. This timing separation was somewhat surprising, considering Isaac resulted in a "peak-on-peak" (simultaneous arrival of peak surge and peak rainfall-runoff) scenario when it originally made landfall in Louisiana. However, it was noted that much of Isaac's heavier rainfall occurred just inside of the eyewall and on the right side of its spiral bands. A simple shift in Isaac's track from its original Louisiana landfall location to landfall point B near Galveston Bay was enough to place its maximum rainfall just outside of the SJRB watershed during the earlier hours of the model simulation. As simulation time progressed, more of Isaac's rainfall fell within the drainage boundaries of the SJRB, but in the upper portions of the watershed. Although conceptually simple in hindsight, this highlights the nonlinear trends and behaviors of hurricane rainfall-runoff due to variable topologies of coastal watershed boundaries. It is for these reasons, that Isaac's timing separation between peak surge and peak rainfall-runoff "jumps" approximately 200 hours (8.5 days) from landfall point A to point B locations (shown in Table 3). This is because landfall points B and C place much of

Isaac's heavier rainfall at the northern portion of the SJRB, where the hydraulic lag time and "time of concentration" is much longer. The time of concentration is a hydrologic term used to describe the relative time it takes for a watershed's area to fully contribute to rainfall-runoff. Simply stated, hurricane landfall location and angle of approach can greatly influence hurricane rainfall-runoff just as it can for storm surge.

Fig. 8c (Katrina, landfall point C), conveys a similar message to Fig. 8b, except in this case, peak rainfall-runoff and peak surge at the HSC occur at nearly the same time. The overall magnitudes of Katrina's peak surge and rainfall-runoff, 5,039 m³/s and 1,410 m³/s, are relatively low when compared to Ike for the same landfall location. This is owed to Katrina's angle of approach for the landfall point C location. For both Fig. 8b and 8c (landfall points B and C), Hurricanes Isaac and Katrina generate more seiche effects within Galveston Bay, given their angles of approach, causing peculiarities in modeled hydrograph shapes.

[Fig.8 Inserted Here]

[Table 3 Inserted Here]

Fig. 9 shows the overall contributions in storage volumes from hurricane storm surge and rainfall-runoff for the HSC without storm surge protection. For all modeled hurricanes, the distributed hydrologic model was executed with a model duration of 14 days to ensure that time of concentrations for the SJRB watershed were reached. The same duration was applied to the riverine model. It is consistently shown that landfall point A locations contribute to more severe cases of overall flood volumes among the hurricanes analyzed. Stated differently, landfall point

A appears to serve as the more severe landfall for generating maximum storm surge, while simultaneously capturing significant hurricane rainfall. The exception is Ike at landfall point B. Ike at landfall point B simply delivers much of the heavier rainfall within the confines of the SJRB watershed, with the heavier rainfalls occurring in northwest Houston, as previously mentioned. A summary of hurricane storm surge and rainfall-runoff storage volumes measured downstream of the HSC and the Fred Hartman Bridge are provided in Table 3.

In addition, it is consistently shown that volumes from hurricane rainfall-runoff contribute more to the overall storage volume budget than storm surge, with more than 50% of the volume share, as shown in Fig. 9. The exception is Isaac at landfall point C where the rainfall completely misses the SJRB watershed. However, percent contributions of total storage volume should not be confused with increases in flooding potential. In most cases, storm surge will drive the flood wave hydraulics at the HSC, due to its higher magnitude and shorter time duration. However, overtime a hurricane's rainfall-runoff over the SJRB can contribute to comparable flood volumes at the watershed outlet. It is seen that the longer lag times of rainfall-runoff in the SJRB minimizes the likelihood of peak-on-peak phenomenon from occurring.

[Fig.9 Inserted Here]

5.3. Hydraulic Performance of Proposed Storm Surge Barrier at the HSC

In the case of storm surge protection, the issue of rainfall-runoff and timing becomes more critical. This is particularly true for studying gate operation reliability. An unforeseen scenario may occur that prevents the surge gate from re-opening. Most of the modeled hurricane scenarios in Table 3 (i.e. Ike and Katrina) show that there is less than 24 hours separating peak

surge from peak rainfall-runoff. Therefore, barrier operators and technicians would have between 12 to 24 hours to contend with any mechanical issues before the arrival of peak rainfall-runoff. This arrival of rainfall-runoff under a fully closed barrier could lead to adverse flooding on the protected side through overtopping of the HSC banks and the surge barrier system. This highlights the need for accurate hurricane rainfall and storm surge forecasting to inform barrier system operations and procedures.

Christian et al. (2014) provided the proof-of-concept for the proposed storm surge barrier system. This paper extends that effort by re-evaluating the surge barrier performance for all nine hurricane/landfall scenarios. The surge barrier is represented as a combined levee and gate system 4.8 km in length and set to an elevation of 8.2 m above NAVD 88, connecting topographic ridges on both sides of the barrier. Crossing the HSC is a moveable gate 488 m wide and 7.6 m high, located just downstream of the Fred Hartman Bridge. The surge gate is represented with 16 binary (open/close) gates that commence an inward closure sequence staggered in 15 minute increments when the downstream water surface elevation (WSEL) rises 1 m above mean sea level. The modeled representation of the barrier system is illustrated in Fig. 1c. The gates are modeled in this way to emulate the gradual closure of radial sector gates, similar to the Maeslantkering, in the Netherlands, or the Lake Borgne Surge Gate, in New Orleans. The gates re-open in reverse order once a hydrostatic equilibrium is reached on the upstream and downstream faces of the barrier.

Table 3 includes a summary of the storm surge barrier performance. It is shown that the proposed barrier system provides significantly reduced flood levels for the modeled hurricane scenarios. Maximum WSEL reductions on the protected side of the HSC barrier range from 3.28 m for Ike at landfall point A to 0.63 m for Ike at landfall point C. Hurricanes Katrina and Isaac

at landfall point A yielded WSEL reductions of 2.61 m and 2.98 m, respectively, for the same area of protection. HEC-GeoRAS (USACE, 2005) was used to generate floodplain maps showing “with” and “without” the surge barrier under all three hurricane scenarios for the landfall point A location, as illustrated in Fig. 10. For each of the modeled hurricanes, the floodplain reductions along the protected side of the HSC as a result of including the proposed barrier system are easily distinguishable.

[Fig.10 Inserted Here]

6. Conclusions and Future Work

This manuscript investigates the relative hydraulic contributions and interactions of hurricane (1) storm surge and (2) rainfall-runoff at the HSC under various hydrologic conditions. The proposed modeling framework extends the efforts of Christian et al. (2014) by including a suite of hurricanes that encompass a broader range of hurricane characteristics. A hurricane shifting modeling framework is implemented that preserves the spatial and temporal characteristics of hurricane rainfall and wind fields. It is consistently shown that storm surge can dominate the flooding potential at the HSC, but that hurricane rainfall-runoff volume contributes to more than 50% of the volume share in regards to the overall storage budget. Moreover, the shifting of hurricane rainfall revealed nonlinear trends and behaviors of rainfall-runoff due to variable topologies of coastal watershed boundaries. In other words, and similarly to storm surge, hurricane landfall location and angle of approach can greatly influence hurricane rainfall-runoff. Such meteorological complexities highlight the need for improved insights on the

coupled hydraulic interactions of hurricane storm surge and associated rainfall-runoff processes for achieving effective coastal flood protection strategies.

Therefore, future work will aim to build a “library” of shifted hurricane datasets for hydrologic research applications. It is also worth noting the efforts of this paper investigated a single proposed barrier system at the HSC. Future work will investigate a more comprehensive approach to managing coastal flood risks within Galveston Bay that go beyond structural-based solutions. This may include nature-based protection, such as the use of oyster reefs, beneficial reuse of dredged soils, and wetland restoration and restored buffers. Such an effort will also incorporate comprehensive uncertainty analyses of model inputs, as well as the inclusion of barrier system performance under long-term scenarios of sea level rise.

Although this paper focuses on the Houston-Galveston region, insights provided may serve to benefit other bay and estuarine systems along the Gulf coastline. For example, the Texas coast is lined with a network of similarly shallow and semi-enclosed bay systems for which the proposed modeling approach can be extended. For example, these additional bay systems include: Sabine Lake, Matagorda Bay, San Antonio Bay, and Corpus Christi Bay. It is hoped the numerical modeling approaches established in this paper may motivate expanded studies on these similar bay and estuarine systems.

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Table 1 –Notable Gulf System Hurricanes*

Hurricane	Year	Date of Landfall	Time of Landfall (UTC)	Landfall Location	Saffir-Simpson Category	Min. Central Pressure (mb)	Max. Sustained Winds (kph)	Max. Storm Tide (meters above NAVD 88)	Location of Max. Storm Tide	Max. Total Rainfall (cm)	Location of Max. Total Rainfall
Katrina ^a	2005	Aug, 29	1110	Lousiana	3	920	204	8.5	Pass Christian, LA	38	Big Branch, LA
Rita ^b	2005	Sept, 24	0740	Texas	3	930	185	4.6	Cameron, LA	41	Bunkie, LA
Ivan ^c	2004	Sept, 16	0650	Alabama/Florida	3	943	194	3.0 to 4.6	Mobile Bay, AL	43	Cruso, NC
Ike ^d	2008	Sept, 13	0700	Texas	2	951	175	3.9	Sabine Pass North, TX	48	Spring Creek @ FM 2979, TX
Gustav ^e	2008	Sept, 1	1500	Lousiana	2	953	167	3.7 to 4.0	Mississippi Delta, LA	53	Larto Lake, LA
Isaac ^f	2012	Aug, 29	0000	Lousiana	1	965	130	3.4	Shell Beach, LA	68	Pascagoula, MS

* Note: All figures are reported at time of U.S. landfall along major coastlines

^a Knabb et al. (2011b)

^b Knabb et al. (2011a)

^c Stewart (2005)

^d Berg (2009)

^e Beven II and Kimberlain (2009)

^f Berg (2013)

Table 2 – Modeled Hurricane Scenarios*

No.	Hurricane	Landfall Location
1	Ike	Pt. A
2	Ike	Pt. B (original track)
3	Ike	Pt. C
4	Katrina	Pt. A
5	Katrina	Pt. B
6	Katrina	Pt. C
7	Isaac	Pt. A
8	Isaac	Pt. B
9	Isaac	Pt. C

* Note: All scenarios are analyzed under "with" and "without" a storm surge barrier located downstream of the HSC, for a total of 18 scenarios.

Table 3 – Hydraulic Summary of Results Downstream of the HSC and Fred Hartman Bridge for Modeled Hurricanes

Hurricane	Landfall	Peak Flows		Peak Flow Timings			Maximum Storage Volumes		HSC Barrier Performance		
		Hurricane Storm Surge (m ³ /s)	Hurricane Rainfall-Runoff (m ³ /s)	Hurricane Storm Surge (hrs into simulation)	Hurricane Rainfall-Runoff (hrs into simulation)	Temporal Separation (hrs)	Storm Surge Volume (x10 ⁸ m ³)	Rainfall-Runoff Vol. (x10 ⁸ m ³)	Max. WSEL without Barrier (m)	Max. WSEL with Barrier (m)	Percent WSEL Reduction (%)
Ike	Pt. A	14,176.8	1,860.50	27.8	47.5	19.8	6.23	6.99	5.31	2.03	62%
	Pt. B	7,106.7	3,243.08	28.8	44.8	16.0	4.46	9.23	3.75	2.26	40%
	Pt. C	6,392.3	2,801.91	31.8	44.8	13.0	3.37	9.08	2.55	1.92	25%
Katrina	Pt. A	12,525.0	1,871.45	37.8	56.0	18.3	6.15	8.45	5.31	2.70	49%
	Pt. B	10,829.3	1,621.05	36.8	50.8	14.0	5.57	6.40	4.80	2.65	45%
	Pt. C	5,039.4	1,410.26	34.0	47.5	13.5	3.71	4.24	2.92	2.07	29%
Isaac	Pt. A	5,257.4	1,741.42	48.3	82.0	33.8	4.81	10.20	4.06	1.08	73%
	Pt. B	4,665.1	1,155.06	51.8	289.8	238.0	3.98	9.01	3.24	1.13	65%
	Pt. C	3,928.1	321.20	54.0	220.5	166.5	3.09	2.06	2.12	1.05	51%

Fig. 1. Study area showing San Jacinto River Basin (a) hydrography (b) architectural rendering and (c) hydraulically modeled representation of the proposed HSC storm surge barrier system.

Fig. 2. Modeling framework showing (a) distributed hydrology, (b) unsteady riverine hydraulics and surge gate representation, and (c) coastal hydrodynamics.

Fig. 3. Shifting hurricanes: (a) conceptual schematic, shifted (b) radar-rainfall and (c) wind fields for Hurricane Katrina.

Fig. 4. Calibrated rainfall-runoff hydrographs for (a) Hurricane Ike, (b) July 2012 event, (c) April 2009 event at Brays Bayou, (d) Hurricane Ike, (e) July 2012 event, (f) April 2009 event at Hunting Bayou, and observed versus modeled peak flows by watershed for (g) Hurricane Ike, (h) July 2012, and (i) April 2009 rainfall events.

Fig. 5. Shifted hurricane tracks and landfall locations for Hurricanes (a) Ike, (b) Katrina, and (c) Isaac .

Fig. 6. Maximum storm surge elevations (m) for Hurricanes Ike at landfall points (a) A, (b) B, (c) C; Katrina at landfall points (d) A, (e) B, (f) C; and Isaac at landfall points (g) A, (h) B, (i) C.

Fig. 7. Spatial distribution of total rainfalls (cm) in the San Jacinto River Basin for Hurricane Ike at landfall points (a) A, (b) B, (c), C; Katrina at landfall points (d) A, (e) B, (f) C; and Isaac at landfall points (g) A, (h) B, (i) C.

Fig. 8. Hurricane hydrograph decomposition downstream of HSC, near Morgan's Point, for Hurricanes (a) Ike at landfall point A., (b) Isaac at landfall point B, and (c) Katrina at landfall point C.

Fig. 9. Total volume contributions at the HSC from hurricane storm surge and rainfall-runoff landfall scenarios.

Fig. 10. Floodplain area reductions comparing “with” and “without” a surge barrier under hurricane conditions (a) Ike, (b) Katrina, and (c) Isaac at landfall point A locations.