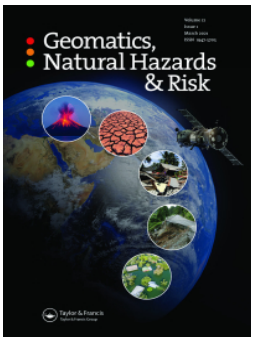

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Simulating the spatial impacts of a coastal barrier in Galveston Island, Texas: a three-dimensional urban modeling approach

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ABSTRACT

Due to its vulnerability to hurricanes, Galveston Island, TX, USA, is exploring the implementation of a coastal surge barrier (also referred to as the 'Ike Dike') for protection from severe flood events. This research evaluates the predicted effects that the coastal spine will have across four different storm scenarios, including a Hurricane Ike scenario and 10-year, 100-year, and 500-year storm events with and without a 2.4 ft. sea level rise (SLR). To achieve this, we develop a 1:1 ratio, 3-dimensional urban model and ran real-time flood projections using ADCIRC model data with and without the coastal barrier in place. Findings show that inundated area and property damages due to flooding will both significantly decrease if the coastal spine is implemented, with a 36% decrease in the inundated area and $4 billion less in property damage across all storm scenarios, on average. When including SLR, the amount of protection of the Ike Dike diminishes due to flooding from the bay side of the island. While the Ike Dike does appear to offer substantial protection from flooding in the short term, integrating the coastal barrier with other non-structural mechanisms would facilitate more long-term protection when considering SLR.

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Information modeling; digital twin; resilience; infrastructure; climate change

Introduction

Galveston Island, TX, has a long history of being vulnerable to hurricanes due to its flat topography and coastal adjacency. Apart from being a barrier island needing protection against storm surge (Johnson et al. 2020), the island also supports a dense population, viable economy, and several ecosystem services for the broader Houston-

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Galveston region (Merrell et al. 2011). Due to the negative impacts of Hurricane Ike in 2008, scholars proposed a coastal barrier paralleling the island, known as 'the Ike Dike' to increase inland social and environmental protection for less resilient residents and coastal ecosystem (Merrell et al. 2011). Existing studies show that, while the coastal barrier may offer protection from storm surge, potential negative impacts could include (1) a reduction in steam flow area resulting in a decrease in tidal prism and tidal range causing a redistribution of the sediment from marshes and flats to the channels, (2) increases in current stream flow velocities near the barriers and decreases in the main bay, (3) increases in the residence time of fresh water in Galveston Bay and decreases in salinity and (4) changes of the hydrodynamics, water quality, and morphology in the bay potentially resulting in the loss of habitat and disturbance of existing ecologies (Ladd et al. 2011).

To complete the Ike Dike, the City of Galveston also proposes elevating the existing coastal roadway nearly 17 ft above sea level (Dike 2022) while using the existing Galveston Seawall to help protect the eastern side of the island from storm surge (Davis 1951). The estimated cost of completing the Ike Dike is nearly $28.8 billion (Watkins 2021). Because the implementation and construction costs are high and may also incur annual increases due to maintenance costs, evaluations comparing the cost of the Ike Dike and its protective impacts are vital. However, such investigations have yet to be fully conducted. In addition, to evaluate the long-term protection offered by the Ike Dike, including sea level rise (SLR) in evaluation metrics merits investigation.

There are several existing online coastal resilience tools, toolkits, and models for predicting and assessing the probable impacts of SLR. A sample of popular tools include the Risk Finder Tool (https://riskfinder.climatecentral.org/), the Coastal Resilience Toolkit (https://coastalresilience.org/), and the National Storm Surge Hazard Maps (https://www.nhc.noaa.gov/nationalsurge/). These tools only show coastal areas and projected inundation in traditional plan views, rather than street-level, perspective views, or 3-dimensional (3D)/bird's eye views. Moreover, these tools, while valuable, primarily focus on estimating the impacts of flood events on the existing built environment, rather than evaluating the performance of additional flood prevention mechanisms such as coastal engineered structures or green infrastructure. Further, these tools do not always allow for the capability to evaluate flood effects across differing storm scenarios. The ability to show coastal areas and projected inundation in street-level or perspective views, in terms of disaster management, would add a myriad of advantages including capabilities for real time projections, ease of community input and dissemination of research to residents, and possibilities for dynamic monitorization of conditions of existing build environment sensors through digital twin sensors.

Currently, surge models simulated by ADCIRC (Advanced CIRCulation) modeling can best afford the capabilities to not only inform researchers about storm impacts across different scales and including SLR, but also display the inundation depth of any land flooded within the study area (Chl 2012). ADCIRC modeling is a high-performance, cross-platform numerical ocean circulation model popular in simulating storm surge, tides, and coastal circulation problems. ADCIRC is a proven and highly utilized hydrodynamic modeling technology that conducts short- and long-term simulations of tide and storm surge elevations and velocities in deep-ocean, continental shelves, coastal seas, and small-scale estuarine systems (Pringle et al. 2021). While ADCIRC modelling has shown to be an accurate method for projecting future uncertainties in coastaline dynamics, improving the accuracy in the prediction of SLR requires more investigation due to complexities in hydrology, coastal dynamics, and limitations from remote sensing technologies (Blum and Roberts 2012; Cohen & Mangrove Dynamics in Southern Louisiana, 2021; Herdman et al. 2018; Sabatino et al. 2016). Apart from ADCIRC models, there are other exiting options that also examine nearshore wave patterns, offshore structural erosion, and can perform coastal flooding simulations. Specifically, for shallow water wave prediction based on bathymetry or underwater topography, SWAN (Simulating Waves Nearshore) and the SWAN DHH platform can be an optimal choice regardless how smooth or rugged the terrain is (Afzal and Kumar 2022). For local scour impacts on offshore structures examination, a three-dimensional numerical model known as REEF3D can provide detailed flow fields and sediment transport simulations with high agreement with lab measurements, meaning it is a proven reliable approach (Ahmad et al. 2015). For coastal flood forecasting integrated with risk assessment modeling, MIKE FLOOD (FLOOD, 2023) and Delft3D (Delft3D-WAVE 2023) are also proven tools which allow for the simulation of storm scenarios.

To help increase the functionality of the existing coastal resilience tools, we use Galveston Island, USA, as a case site, developing 3D urban models and projecting inundation scenarios across each model to simulate the potential impacts of the implementation of 'the Ike Dike', the proposed engineered coastal spine which could, conceptually, protect the island from hurricanes and storm surge events. In this research, we firstly review the traditional flood simulation technologies, previous urban 3D modeling workflows, and common flood impact evaluation metrics. We then introduce a novel 3-dimensional approach to examine how the proposed coastal spine will protect Galveston Island across different storm scenarios, considering circumstances with and without the SLR. Through this process, we describe the study area characteristics, data preparation techniques, and modeling processes utilized. We then evaluate the performance of the Ike Dike using 3D urban analytic-based modeling from a newly created digital twin of the site. We examine the effectiveness of the proposed Ike Dike in protecting Galveston Island through 10-year, 100-year, and 500-year storms as well a Hurricane Ike scenario. The primary research question is, how well will the coastal spine system protect Galveston Island across different storm scenarios under the current sea level and a 2.4 ft SLR?

Literature review

Socioeconomic variables

The Houston-Galveston area is more flood-vulnerable compared to other parts of Texas due to its geographic location and urban development patterns. It is a coastal area with dense industrial land uses that is experiencing intense urban development (Zahran et al. 2006). Adding to those vulnerabilities, the abundant amount of industrial land uses can cause chemical pollutant releases, should any of the facilities become damaged by flood events or storm surge (Burleson et al. 2015). In such cases, the chemical contaminants are carried away through surface runoff, washed through neighboring communities, and may be eventually released into the ocean (Atoba Kayode et al. 2018).

Some researchers have calculated the economic losses from flooding by coupling damage totals with residential and industrial land uses. Overall, most research shows that economic losses within the built environment are positively related to (1) the scale and magnitude of flooding and storm surge, (2) the amount of wetland alternation over time, and (3) the amount of precipitation during the flood event (Brody et al. 2011). However, economic losses during flood events have been shown to be negatively related to household income, development density, and the coastal protection mechanisms/policies in place;further, the research indicates that higher household income, development density changes, and increased coastal protection approaches can reduce potential economic losses caused by flooding (Zahran et al. 2008). The casualties suffered during flood events are positively related to social vulnerability conditions and increased population densities (Zahran et al. 2008).

Since development density is significant to flood vulnerability, scholars typically use changes in land cover, land use, and imperviousness as indicators for flood mitigation needs. Though highly populated areas are typically considered more vulnerable to flooding (through greater exposure), if appropriate flood mitigation systems are in place in densely developed areas, such mechanisms can better protect more people from flooding by maximizing their effectiveness. Simultaneously, scholars believe that the more strongly residents support flood mitigation policies, the more likely they will be protected from flooding disasters (Oguz et al. 2007). For example, non-structural flood mitigation strategies, such as green infrastructure, are positively related to organizational capacity (Brody et al. 2010), education level (Zahran et al. 2006), and hazard exposure frequency (Brody et al. 2010). Further, the use of nonstructural mitigation approaches coupled with increasing community organizational capacity has been shown to lead to increases in both disaster awareness and response. Therefore, flood protection efforts should aim both to reduce potential economic losses in residential and industrial areas and to increase public support for promoting mitigation policies. Moreover, increased coastal protection mechanisms and increases in community organizational capacity in highly developed areas result in less economic losses in residential and industrial areas (Shepherd et al. 2010).

Flood simulation output

Galveston Island is surrounded by the Gulf of Mexico, making it highly vulnerable to storm surges and SLR. The island is also at increased risk of compound flooding due to accumulated wave heights from the sea and the excessive surface runoff caused by intensive rainfall coupled with high impervious surface ratios due to urban growth (Rego and Li 2010; Sebastian et al. 2014). To examine how this coastal area suffers from adverse flood conditions, simulated hydraulic modeling have been conducted. For example, ADCIRC (Advanced Circulation) and SWAN (Simulating WAves

Nearshore) modeling, based on historical records, have proven to be highly accurate methods of projecting storm events. Such models can simulate flood scenarios (1) at different storm surge/storm scales (Ray et al. 2011), (2) within different time periods (Warner and Tissot 2012) and (3) with or without existing or proposed protection devices (Davlasheridze et al. 2019). Moreover, the models can simulate flood scenarios at different scales and typologies of flood sources such as river tributaries, watersheds, or even regionally.

When using ADCIRC and SWAN models, water level is one of the easiest factors to observe; in coastal areas, it is measured by comparing water depths to tidal datums, including Mean Higher High water (MHHW), Mean High Water (MHW) and Mean Sea Level (MSL) (Warner and Tissot 2012). And the output of predicted water level from two models are in raster datasets or other types of 2D plan view.

Apart from the traditional 2-dimenional simulation approaches of projecting floods, a select few of scholars have attempted to apply 3Dmethods to visualize flooded areas using Light Detection and Ranging (LiDAR) as a data source. For this approach, the team processed LiDAR data is processed in a BlenderGIS module to obtain 3D flood layer. (Presa-Reyes and Chen 2017). Compared to 2-dimentiaonal flooding simulations, the 3-dimensional visualization approaches display hazard risk more vividly, especially when linked with capabilities to measure potential impacts (Wang et al. 2019).

Urban 3-dimensional models

Estimating damage costs due to flood events can be challenging, and property and improvement values are often utilized to tally overall damage estimates (Atoba Kayode et al. 2018). Building footprint data is oftentimes difficult to obtain. Further, the modeling process of buildings, including detailed facades, can be quite time consuming, depending on the required standards of detail and accuracy (Kim and Wilson 2015). When using CityEngine, issues related to building modeling efficiency can be resolved by obtaining building footprint data from Open Street Map and using Computer-Generated Architecture (CGA) grammar to generate buildings and detailed facades three-dimensionally (Shojaei et al. 2013). Inputs for this approach can include building height, roof type, roof height, and façades in multiple style types. Though downloading building footprint data from Open Street Map is convenient, the latest versions of such data for most countries is over a decade old, which can limit accuracy. Therefore, missing or updated structures must be drawn manually and imported into CityEngine; these data also require the attachment of attributes for building height, and roof height/type manually before CGA rules can be applied to them (Ribeiro et al. 2014).

Overall, there are three knowledge gaps in the current literature that this research fills. First, not much research has assessed the potential effects of the Ike Dike from socioeconomic perspectives or with SLR, with most studies examining only inundated area. Second, little research has used 3-dimensional modeling to visualize the study areas and evaluate inundation scenarios during flood events. Lastly, there is a lack of accurate and detailed 3D urban flood models of study areas. Therefore, we both

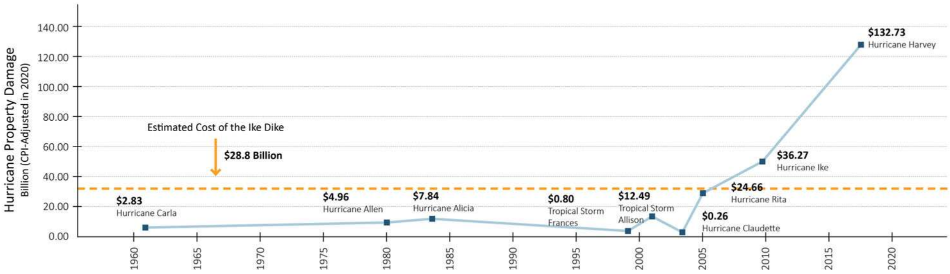

Figure 1. Historical damages from flood events in Galveston County from 1960–2020.

extract and visualize 3D urban elements of Galveston Island and examine physical, land use-related, and socioeconomic metrics across different storm scenarios.

Methods

Study area

Galveston Island is located in the western Gulf of Mexico and is nearly 211.7 square miles in size, with only a 7 ft elevation, on average. Due to its geographic location, Galveston Island has been threatened by hurricanes, storms, and flooding for centuries. From the historical records, hurricane frequency has been increasing since 2000 and property damage has also exponentially increased. For example, the larger Galveston County area saw an increase in flood damages from 36.37 billion to 125 billion dollars from Hurricane Ike in 2008 to Hurricane Harvey in 2017 (Witt O'Brien's 2017) (Figure 1).

As a result, Galveston Island has implemented an 18 ft tall, 3-mile long seawall to protect the eastern side of the island against storm surge from the Gulf of Mexico (Davis 1951). However, this small portion of seawall cannot adequately protect the entire island from hurricanes. Therefore, the Ike Dike has been proposed as a coastal spine system to protect the Houston-Galveston Area from such events. The total length of the coastal spine system is 58.5 miles, consisting of 56 miles of proposed linear dune and 2.5 miles of storm surge barriers included within two proposed floodgates (Jonkman et al. 2015) (Figure 2)

In this research, we examine the study area with and without the proposed Ike Dike across four storm scenarios (a 10-year storm, a Hurricane Ike scenario, a 100-year storm, and a 500-year storm) as well as the same four storm storms with a 2.4 ft SLR, which is based on patterns from the Galveston shoreline retreat rate after year 1930 (*Historical Shoreline Changes in Trinity et al.* 1986).

Data preparation

To examine socioeconomic patterns, we used year 2020 census tract data from the H-GAC Regional Data Hub as well as year 2021 parcel data and year 2019 street centerline data from the City of Galveston's Official GIS data website. The census track data includes the number of people and housing units; the parcel data includes information on land use, improvement value, land value, and building built year; the street

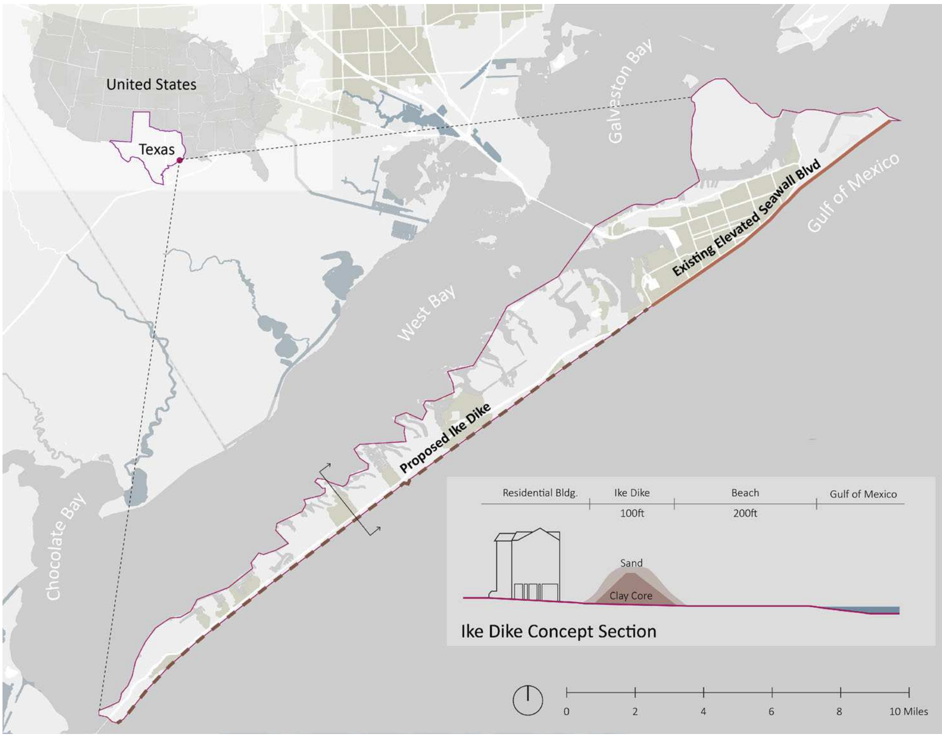

Figure 2. Proposed Galveston coastal spine system referred to as the Ike Dike.

centerline data includes the geographic locations of streets and their length. To build the 3D urban model, we extracted topography, buildings, and vegetation from the year 2018 LiDAR point cloud data from Texas Natural Resources Information System. The accuracy of this data, according to the American Society for Photogrammerty and Remote Sensing is: 1) class 10 cm, 19.6 cm at a 95% confidence interval (System and T. N. R. I 2013); and 2) the margin of error for the 2.4 ft SLR projection is 13.7% or 26.8% at a 95% confidence interval (Johnson et al. 2020). It should be noted that we utilized the roadway data from year 2019 Open Street Map. For water level and inundated area per storm scenario, we obtained ADCIRC inundation raster files from the Rice University SSPEED center (Atoba Kayode et al. 2018; Davlasheridze et al. 2019) (Table 1).

Data processing

In general, ArcGIS Pro and CityEngine are the two software packages used to produce the 3D Galveston Island and inundation scenarios visualization and analysis. In ArcGIS Pro, we used two other commands, known as ‘solutions’, in the program, to process the LiDAR and inundation level datasets: the 3D Base maps solution and the Flood Impact Analysis solution are both applied, respectively. In CityEngine, we primarily used four types of Computer-Generated Architecture (CGA) rules to generate the final models (Figure 3).

Table 1. Overview of data examined and description of datasets.

Objective	Name	Information	Source	Year
Examine the socioeconomic change	Census Tract	Number of people and house units	H-GAC Regional Data Hub	2020
	Parcels Data	Land use, improvement value, land value, and building built year	Galveston Central Appraisal District	2021
	Street Centerline	Street geographic locations and length in miles	City of Galveston's Official GIS website	2019
Build 3-Dimensional Urban Model	LiDAR Point Cloud	DEM, DTM, bldg. height, bldg. base elevation, roof type, vegetation species and vegetation height	Texas Natural Resources Information System	2018
	Road	Street geographic locations and street width	Open Street Map	2019
	Inundation Level	Geographic location and water depth	SSPEED Center, Rice University	2021

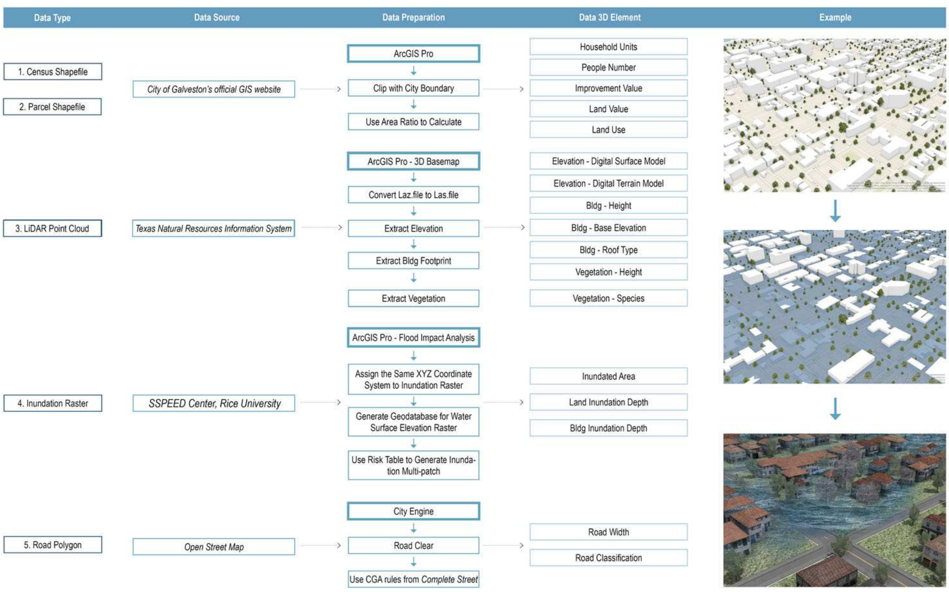

Figure 3. Urban 3D modeling workflow.

To extract urban elements from the LiDAR data, we applied the ArcGIS Pro solution, 3DBasemaps (source: https://doc.arcgis.com/en/arcgis-solutions/latest/reference/introduction-to-3d-basemaps.htm) to process the data. This solution can extract building footprint and vegetation information based on LiDAR class codes through three steps. Before launching the solution for Galveston Island, we downloaded 12 LiDAR point cloud grids (Figure 4), and, for each grid we went through three steps. In Step 1, Elevation Extraction, we input the LiDAR point cloud data in the Laser (LAS) format and created three types of elevation files: 1) Digital Surface Model (DSM), 2) Digital Terrain Model (DTM) and 3) Normalized Digital Surface Model (NDSM). In Step 2, Building Footprint Extraction, we input the processed LAS dataset to create 3D building footprint shapefiles and then linked the 3D building attributes by inputting all the elevation files with the building footprint shapefiles. In

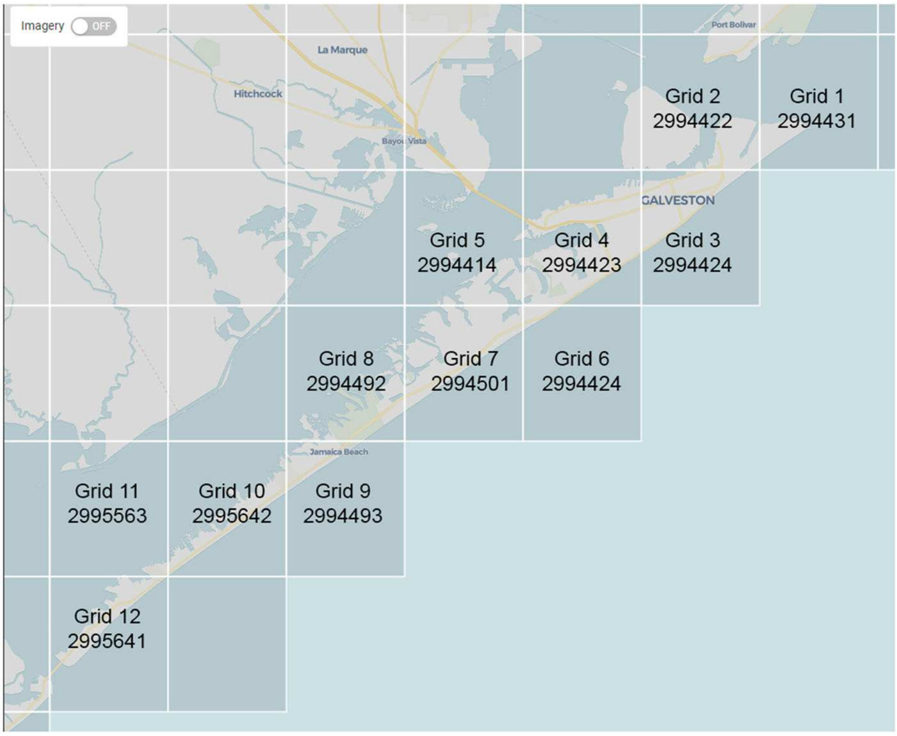

Figure 4. Galveston Island LiDAR grids.

Step3, Vegetation Extraction, we input result from previous two steps, and generate accurate vegetation location, species, and height *via* LiDAR class codes. As a result, the model is complete with comprehensive 3D building information including building heights, building base elevations, roof forms, and the number of floors per building.

To visualize the flood water level 3-dimentionally for each scenario, we adopted another ArcGIS Pro solution, the Flood Impact Analysis (source: https://doc.arcgis.com/en/arcgis-solutions/latest/reference/introduction-to-flood-impact-analysis.htm). This solution is more customized than 3DBasemaps since input values can be adjusted by risk type. This solution allows the ability to define risk types and change inundation values based on the statistical information from the ADCIRC data. Also, this approach allows the capability to assess impact on buildings, bridges, and roadways. During the processing, the most important thing is to keep all coordinate systems the same including the vertical coordinate system for all raster files. For Galveston Island, the x-y coordinate system is NAD_1983_2011_UTM_Zone_15N and the vertical coordinate system is NAVD88 height.

After obtaining all the urban elements and 3D inundation layers, we imported them into CityEngine 2019.0 as shapefiles to generate a Digital Twin model. A digital twin is a digital representation of a real-world entity or system; the implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object, process, organization, person or other abstraction (VanDerHorn and Mahadevan 2021). Specifically, we downloaded street network and parcels from Open

Street Map, then applied complete street CGA rules (source: https://www.arcgis.com/home/item.html?id=863f4e7139314101a5cee1d7cde079d9) and formal parks for the parcels (source: https://www.arcgis.com/home/item.html?id=a7b7ee6da9954be2a5bac0-becf9e773e) from ESRI CityEngine for street and parcel texture visualization respectively, and self-created extrusion rules for the water level, see 3D model in CityEngine (see Figure 5). Using self-created extrusion rules, we included the adjustable attributes of the SLR layer, the range of water depth, and the transparency of this layer in a 3D model using the code below:

```
version '2019'
@Range(min = 0, max = 5)
attr height = 0.27
@Order@Range(min = 0, max = 1)
attr opacityvalue = 0.5
Lot →
extrude (height)
color ('#1F618D')
set (material.opacity, opacityvalue)
```

To assess the socioeconomic effectives of the Ike Dike in protecting Galveston Island across 16 storm surge scenarios, we categorized the variables into three categories, physio-economics (inundated area/property damage, and by depth), built-environment (inundated street/household units/industrial land use, and inundation affect people number), and building impact (total inundated building number/acreage/historical building/improvement value, and by depth). To improve the accuracy of the CityEngine-based model, we used the list of 3D cadastral visualization requirements as a guideline. This requirement synthesizes information about the case-study through

Figure 5. Rendered 3D model in CityEngine.

3D model visualization, showing what types of data can improve user understanding of the spatial environment (Shojaei et al. 2013). These requirements suggest the inclusion of three major features for the model, cadastral (handling massive data), visualization (interactivity and non-functional features), and web-based 3D operations (Ribeiro et al. 2014). Finally, our research converts the ADCIRC inundation raster into a 3D inundation layer with transparency and visualize water level to display how Galveston Island will experience inundation across different storm scenarios. Instead of using building footprints from Open Street Map, we used 2018 LiDAR Point Cloud Data to generate urban three-dimensional models. These data include information on 1) buildings with more accurate geospatial information, such as building height, roof type/height/direction, and base elevation, 2) vegetation height and species type, and 3) data from a Digital Elevation Model (DEM) for elevation. After finishing the full model in CityEngine, we imported it into CityEngine Web Viewer for online users.

Results

Physio-economic impact comparison

To consider the physio-economic impacts of the Ike Dike, we examine inundated area percentage, inundation depth (below 3 ft, 3 ft-6ft, 6 ft-9ft and above 9 ft) https://noaa.maps.arcgis.com/apps/MapSeries/index.html?appid=d9ed7904dbec441a9c4dd7b277935fad&entry=1), and property damage amounts.

As shown in Figure 6, Galveston Island is extremely vulnerable to storm events; even a 10-year storm can inundate one-third of the entire island and this amount doubles with a 2.4 ft SLR (see Table 2 for full outputs). On average, the Ike Dike will protect 53.0% of the area normally inundated during a given storm without the Ike Dike in place across all four storm scenarios (10-year, Hurricane Ike, 100-year, and 500-year). Overall protection from the Ike Dike continues but decreases to only 29.1% across all storm scenarios with a 2.4 ft SLR. For example, if a storm similar to Hurricane Ike were to hit Galveston Island again, the Ike Dike would protect 77.5% (current) and 33.9% (with SLR) of the area from inundation, thereby reducing the inundated area by 20,776.37 acres (currently, approximately equal to ∼2/3 of the entire area of Galveston Island) and 9,316.45 acres (with SLR, or ∼1/3 of Galveston Island) compared to scenarios without the Ike Dike.

When assessing inundation depth from individual storm events, there will be more land with deeper inundation as storm scale increases, especially if no Ike Dike is put in place. However, the Ike Dike appears to be quite effective in the reducing area inundated by flooding above 9 ft in depth. It projects to reduce the 9 ft inundation depth area by 86.8% in the current situation and by 90.2% with SLR. This is important in that most of the residences built on stilts are currently around the 9 ft height so flooding over that height would damage them.

When compiling all storm events (10-year, Hurricane Ike, 100-year, and 500-year), the property damage would total near $33.96 billion (current) and $40.14 billion (with SLR, outweighing the cost of the implementing the Ike Dike ($28.8 billion). However, across all storms and storms with SLR scenarios, the Ike Dike would

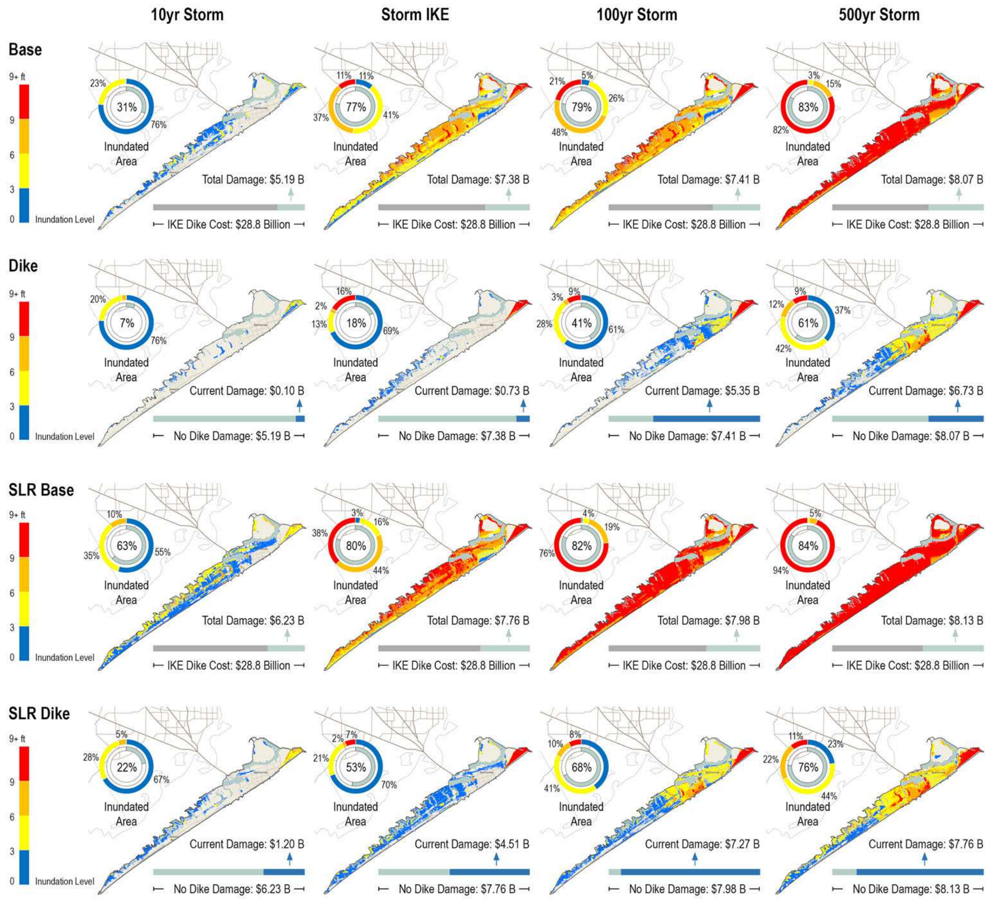

Figure 6. Galveston Island property damage across all scenarios.

protect $15.58 billion (45.9%) and $11.46 billion (28.6%) of property value from inundation, respectively. Overall, the Ike Dike would protect more property value in small to intermediate-scale storms (10-year and Hurricane Ike) rather than of large-scale ones.

Built environment impact comparison

We also examined the Ike Dike performance using four built-environment measures including transportation (inundated streets), housing (inundated household units), population (inundated people), and land use (inundated industrial area). In general, the Ike Dike will be more effective in protecting transportation (inundated streets) and land use (inundated industrial area), and is expected to protect more streets, household units, and people across all storm scenarios. Specifically, in all storm scenarios and plus each storm including a 2.4 ft SLR, the Ike Dike can protect 50.7% (current) and 31.1% (with SLR) more streets from flood inundation, 35.8% (current) and 27.6% (with SLR) household units, 33.8% (current) and 29.4% (with SLR) people, and 65.7% (current) and 58.9% (with SLR) industrial lands, respectively (See Table 3 for

Table 2. Physio-economic Impact Comparison across all Scenarios.

	10-Year Storm		Hurricane Ike		100-Year Storm		500-Year Storm		Protected in Total	Protected in Avg.
	Baseline	Dike	Baseline	Dike	Baseline	Dike	Baseline	Dike		
1a. Inundated Area (Acres)	10488.61 (21513.15 SLR)	2491.20 (7667.93 SLR)	26791.24 (27478.56 SLR)	6014.87 (18162.11 SLR)	26737.18 (28084.53 SLR)	14128.79 (23161.99 SLR)	28410.73 (28883.01 SLR)	20799.33 (26151.87 SLR)	48993.57 (30815.35 SLR)	**53.0% (29.1% SLR)**
Inundated Percentage	31% (63% SLR)	7% (22% SLR)	77% (80% SLR)	18% (53% SLR)	79% (82% SLR)	41% (68% SLR)	83% (84% SLR)	61% (76% SLR)		
Dike Protected Percentage	**76.2% (64.4% SLR)**		**77.5% (33.9% SLR)**		**47.2% (17.5% SLR)**		**26.8% (9.5% SLR)**			
Percentage of Dike Protected Area to Galveston Island Area	23.3% (40.4% SLR)		60.6% (27.2% SLR)		36.8% (14.4% SLR)		22.2% (8.0% SLR)			
1b. Inundated Area by Inundation Depth (Acres)										
Less than 3 ft	7997.89 (11829.70 SLR)	1898.61 (5126.07 SLR)	2888.78 (798.56 SLR)	4127.54 (12624.14 SLR)	1400.26 (251.67 SLR)	8563.23 (9405.48 SLR)	184.12 (41.93 SLR)	7708.63 (6004.08 SLR)	−9826.96 (−20237.91 SLR)	
3–6 ft	2458.43 (7435.24 SLR)	523.02 (2161.49 SLR)	10763.50 (4376.24 SLR)	754.23 (3977.66 SLR)	6914.40 (1114.10 SLR)	3911.90 (9566.79 SLR)	836.05 (314.98 SLR)	8641.30 (11572.56 SLR)	7141.94 (−14037.94 SLR)	
6–9 ft	32.29 (2245.91 SLR)	69.57 (371.07 SLR)	9919.53 (11979.84 SLR)	146.15 (355.11 SLR)	12796.07 (5296.78 SLR)	400.27 (2410.57 SLR)	4184.15 (1355.40 SLR)	2481.17 (5797.91 SLR)	23834.87 (11943.27 SLR)	
Above 9 ft	0.00 (2.30 SLR)	0.00 (9.30 SLR)	2945.95 (10323.92 SLR)	986.95 (1205.20 SLR)	5626.44 (21421.98 SLR)	1253.39 (1779.15 SLR)	23206.42 (27170.70 SLR)	1968.23 (2777.32 SLR)	27570.24 (53147.93 SLR)	**86.8% (90.2% SLR)**
Dike Protected Percentage in 'Greater than 9 ft'	**0.0% (−304.3% SLR)**		**66.5% (88.3% SLR)**		**77.7% (91.7% SLR)**		**91.5% (89.8% SLR)**			
2. Property Damage (Billions in US Dollars)	2.45 (6.89 SLR)	0.14 (1.58 SLR)	10.05 (10.69 SLR)	0.98 (5.90 SLR)	10.10 (11.18 SLR)	7.67 (10.26 SLR)	11.36 (11.38 SLR)	9.59 (10.94 SLR)	15.58 (11.46 SLR)	**45.9% (28.6% SLR)**
Dike Protected Percentage	**94.3% (80.5% SLR)**		**90.2% (44.8% SLR)**		**24.1% (10.4% SLR)**		**15.6% (3.9% SLR)**			

Table 3. Built environment impact comparison across all scenarios.

	10-Year Storm		Hurricane Ike		100-Year Storm		500-Year Storm		Protected in Total	Protected in Avg.
	Baseline	Dike	Baseline	Dike	Baseline	Dike	Baseline	Dike		
1. Inundated Street (Miles)	86.60 (241.81 SLR)	7.40 (47.05 SLR)	342.50 (358.49 SLR)	32.40 (193.71 SLR)	343.80 (370.76 SLR)	216.20 (332.14 SLR)	375.60 (376.41 SLR)	310.20 (355.62 SLR)	582.30 (418.96 SLR)	**50.7% (31.1% SLR)**
Protected	**91.5% (80.5% SLR)**		**90.5% (46.0% SLR)**		**37.1% (10.4% SLR)**		**17.4% (5.5% SLR)**			
2. Inundated Household Units	5518 (15523 SLR)	226 (3800 SLR)	26015 (28237 SLR)	3292 (12997 SLR)	26047 (29137 SLR)	24906 (28338 SLR)	29495 (29619 SLR)	27504 (29124 SLR)	31147 (28257.32 SLR)	**35.8% (27.6% SLR)**
Protected	**95.9% (75.5% SLR)**		**87.3% (54.0% SLR)**		**4.4% (2.7% SLR)**		**6.8% (1.7% SLR)**			
3. Inundation Affected People Number	7945 (26596 SLR)	1609 (4669 SLR)	47955 (52282 SLR)	4171 (21313 SLR)	48890 (54215 SLR)	47712 (52833 SLR)	54439 (54649 SLR)	51997 (53822 SLR)	53740 (55104.42 SLR)	**33.8% (29.4% SLR)**
Protected	**79.7% (82.4% SLR)**		**91.3% (59.2% SLR)**		**2.4% (2.5% SLR)**		**4.5% (1.5% SLR)**			
4. Inundated Industrial Land Use (Acres)	864.44 (864.44 SLR)	122.63 (441.19 SLR)	525.32 (1908.91 SLR)	307.80 (702.91 SLR)	1789.92 (1822.66 SLR)	551.52 (551.52 SLR)	1749.62 (2237.63 SLR)	707.81 (1113.23 SLR)	3239.54 (4024.79 SLR)	**65.7% (58.9% SLR)**
Protected	**85.8% (49.0% SLR)**		**41.4% (63.2% SLR)**		**69.2% (69.7% SLR)**		**59.5% (50.2% SLR)**			

Table 4. Building impact comparison across all scenarios.

	10-Year Storm		Hurricane Ike		100-Year Storm		500-Year Storm		Protected in Total	Protected in Avg.
	Baseline	Dike	Baseline	Dike	Baseline	Dike	Baseline	Dike		
1a. Total Inundated Bldg. Number	13532 (20470 SLR)	1411 (11400 SLR)	13528 (24661 SLR)	1358 (18433 SLR)	13531 (24668 SLR)	1411 (24669 SLR)	13528 (24669 SLR)	1411 (24664 SLR)	48528 (15322 SLR)	**89.7**% **(16.2**% **SLR)**
Inundated Percentage	54.2% (82.1% SLR)	5.7% (45.7% SLR)	54.2% (98.9% SLR)	5.4% (73.9% SLR)	54.2% (98.9% SLR)	5.7% (98.8% SLR)	54.2% (98.9% SLR)	5.7% (98.9% SLR)		
Dike Protected Percentage	**89.6**% **(44.3**% **SLR)**		**90.0**% **(25.3**% **SLR)**		**89.6**% **(0.1**% **SLR)**		**89.6**% **(0.0**% **SLR)**			
1b. Bldg. Number in Different Inundation Depth										
Less than 3 ft	6613 (1159 SLR)	1141(9137 SLR)	0 (3 SLR)	158(13432 SLR)	0 (2 SLR)	0 (3404 SLR)	0 (0 SLR)	0 (755 SLR)	5314 (−25564 SLR)	
3–6 ft	4203 (15411 SLR)	188 (1386 SLR)	1 (2 SLR)	297 (3080 SLR)	0 (0 SLR)	29 (4852 SLR)	0 (0 SLR)	0 (1935 SLR)	3690 (4160 SLR)	
6–9 ft	2291 (7940 SLR)	69 (659 SLR)	31 (9 SLR)	277 (1332 SLR)	1 (1 SLR)	208 (5725 SLR)	0 (1 SLR)	122 (4088 SLR)	1647 (−3853 SLR)	
Above 9 ft	425 (7872 SLR)	13 (211 SLR)	13496 (24647 SLR)	626 (589 SLR)	13530 (24665 SLR)	1174 (10668 SLR)	13528 (24668 SLR)	1289 (17886 SLR)	37877 (52498 SLR)	**92.4**% **(64.1**% **SLR)**
Dike Protected Percentage 'Above 9 ft'	**96.9**% **(97.3**% **SLR)**		**95.4**% **(97.6**% **SLR)**		**91.3**% **(56.7**% **SLR)**		**90.5**% **(27.5**% **SLR)**			
2a. Total Inundated Bldg. Acreage	999.82 (2339.67 SLR)	182.84 (881.81 SLR)	999.63 (1707.64 SLR)	179.60 (1293.53 SLR)	999.74 (1707.94 SLR)	182.84 (1707.61 SLR)	999.70 (1707.98 SLR)	182.84 (1707.88 SLR)	3270.7 7 (1872.4 SLR)	**81.8**% **(25.1**% **SLR)**
Dike Protected Percentage	**81.7**% **(62.3**% **SLR)**		**82.0**% **(24.3**% **SLR)**		**81.7**% **(0.0**% **SLR)**		**81.7**% **(0.0**% **SLR)**			
2b. Inundated Bldg. Acreage in Different Inundation Depth										
Less than 3 ft	486.25 (96.18 SLR)	124.43 (96.18 SLR)	0.00 (96.18 SLR)	11.89 (96.18 SLR)	0.00 (96.18 SLR)	0.00 (96.18 SLR)	0.00 (96.18 SLR)	0.00 (96.18 SLR)	349.93 (96.18 SLR)	
3–6 ft	315.75 (1091.73 SLR)	46.21 (110.93 SLR)	0.10 (0.06 SLR)	22.87 (199.91 SLR)	0.00 (0.00 SLR)	9.92 (320.04 SLR)	0.00 (0.00 SLR)	0.00 (154.73 SLR)	236.85 (306.18 SLR)	
6–9 ft	157.50 (578.28 SLR)	10.20 (63.88 SLR)	3.97 (0.60 SLR)	32.16 (75.54 SLR)	0.12 (0.07 SLR)	20.20 (720.17 SLR)	0.00 (0.01 SLR)	14.27 (284.59 SLR)	84.76 (−565.22 SLR)	
Above 9 ft	40.31 (573.49 SLR)	2.00 (21.37 SLR)	995.56 (1706.88 SLR)	112.69 (63.76 SLR)	999.62 (1707.83 SLR)	152.72 (379.07 SLR)	999.70 (1707.97 SLR)	168.57 (1188.86 SLR)	2599.21 (4043.11 SLR)	**85.6**% **(71.0**% **SLR)**
Dike Protected Percentage 'Above 9 ft'	**95.0**% **(96.3**% **SLR)**		**88.7**% **(96.3**% **SLR)**		**84.7**% **(77.8**% **SLR)**		**83.1**% **(30.4**% **SLR)**			

(*continued*)

Table 4. Continued.

	10-Year Storm		Hurricane Ike		100-Year Storm		500-Year Storm		Protected in Total	Protected in Avg.
	Baseline	Dike	Baseline	Dike	Baseline	Dike	Baseline	Dike		
3. Total Inundated Historic Bldg.	1121 (4672 SLR)	27 (463 SLR)	9568 (10173 SLR)	410 (3733 SLR)	9481 (10305 SLR)	9783 (10237 SLR)	10306 (10306 SLR)	10081 (10300 SLR)	10175 (10723 SLR)	**33.4% (30.2% SLR)**
Dike Protected Percentage	**97.6% (90.1% SLR)**		**95.7% (63.3% SLR)**		**-3.2% (0.7% SLR)**		**2.2% (0.1% SLR)**			
4a. Total Inundated Improvement Value (Billion in US Dollars)	1.72 (5.27 SLR)	0.09 (1.05 SLR)	8.01 (8.34 SLR)	0.64 (4.57 SLR)	7.87 (8.71 SLR)	6.07 (8.00 SLR)	8.86 (8.87 SLR)	7.50 (8.53 SLR)	12.16 (9.04 SLR)	**46.0% (29.0% SLR)**
Dike Protected Percentage	**94.9% (80.1% SLR)**		**92.1% (45.1% SLR)**		**22.8% (8.1% SLR)**		**15.3% (3.9% SLR)**			
4b. Inundated Improvement Value in Different Inundation Depth (Billion in US Dollars)										
Less than 3 ft	1.59 (4.57 SLR)	0.08 (0.91 SLR)	1.89 (0.56 SLR)	0.52 (3.95 SLR)	1.16 (0.18 SLR)	2.93 (2.99 SLR)	0.14 (0.01 SLR)	2.38 (2.25 SLR)	−1.13 (−4.79 SLR)	
3–6 ft	0.12 (0.59 SLR)	0.004 (0.13 SLR)	4.55 (2.50 SLR)	0.03 (0.42 SLR)	3.42 (0.73 SLR)	2.82 (3.84 SLR)	0.55 (0.19 SLR)	3.83 (3.94 SLR)	1.96 (−4.32 SLR)	
6–9 ft	0.00 (0.11 SLR)	0.00 (0.00 SLR)	1.24 (4.34 SLR)	0.03 (0.04 SLR)	2.77 (3.19 SLR)	0.15 (0.85 SLR)	2.36 (0.73 SLR)	0.89 (1.86 SLR)	5.30 (5.61 SLR)	
Above 9 ft	0.00 (0.00 SLR)	0.00 (0.00 SLR)	0.33 (0.94 SLR)	0.06 (0.16 SLR)	0.52 (4.61 SLR)	0.17 (0.31 SLR)	5.80 (7.95 SLR)	0.40 (0.48 SLR)	6.03 (12.54 SLR)	**90.6% (92.9% SLR)**
Dike Protected Percentage 'Above 9 ft'	**0.0% (0.0% SLR)**		**82.0% (83.3% SLR)**		**67.8% (93.2% SLR)**		**93.1% (% SLR)**			

all the outputs). Further, the Ike Dike seems highly effective in protecting the built environment under the 10-year and Ike scenarios, which are much more frequent than 100-year and 500-year storms. The ability to combat recurrent storms is a prime strength of the coastal spine.

Building impact analysis

Visualizing both buildings and inundation layers in 3D enables the ability to better understand the impact of the coastal barrier on each individual building across all storm scenarios. We examine the percentage of inundated buildings and number of inundated buildings, including historic buildings (built 50 years ago), and improvement value in different inundation depths (below 3 ft, 3 ft-6ft, 6 ft-9ft and above 9 ft) (source: https://noaa.maps.arcgis.com/apps/MapSeries/index.html?appid=d9ed7904d-bec441a9c4dd7b277935fad&entry=1). If the storm level increases, the building inundation depth and acreage of inundated area will also increase. However, the Ike Dike can significantly reduce the number of buildings and acreage of an inundation depth above 9 ft, protecting 92.4% (current) and 64.1% (with SLR) of the inundated buildings – 85.6% (current) and 71.0% (with SLR) inundated building acreage respectively. For all storms with a 2.4 ft SLR, the coastal spine would not reduce the number of inundated structures significantly, but still drastically decreases inundation depth. When considering all storm events (10-year, Hurricane Ike, 100-year, and 500-year), the inundated improvement value totals $26.46 Billion (current) and $31.19 Billion (with SLR), outweighing the cost of implementing the Ike Dike ($28.8 Billion). Across all storm and storm with SLR scenarios, the Ike Dike would protect $12.16 Billion (46.0%) and $9.04 Billion (29.0%) in improvement value from inundation, respectively. However, the Ike Dike would protect more improvement value in small to intermediate-scale storms (10-year and Hurricane Ike) than in larger-scale storms (See Table 4 for all outputs).

Discussion

This research determines how well the coastal spine system will protect Galveston Island across different storm scenarios under the current sea level and a 2.4 ft SLR. According to the ADCIRC inundation model, western Galveston Island will experience at least 6 ft inundation without the Ike Dike; but with the Ike Dike, only small a portion of the bay side will experience below a 3 ft inundation depth. In the short term, the Ike Dike provides significantly added protection for people, property, and ecosystem against all storm scenarios. In the long term, these protections tend to diminish over time with SLR, but still have significant protective impacts on regional ecosystem especially, such as supporting marine life growth and maintaining freshwater balance when operating flood gates (Duc Tran et al. 2018; Lee and Lee 2007; Merrell et al. 2011). Such loses in protection vary, however, depending on the measure examined. For transportation and housing, the protection tends to diminish the most with SLR; but for industrial land uses and protected population, these two variables have the most continued protection, despite SLR. Further, in the very long term, by 2200, much of the island will be inundated due to flooding from SLR on the bay side. So, while current surge protection is maximized with the Ike Dike, unless a full dike ring is developed, the long-term effects of SLR may prohibit the extreme cost of implementing the linear spine.

According to the inundation area results from the 16 storm scenarios, 61% (76% in SLR scenario) of Galveston Island will be inundated if a 500-yr storm occurs, even with the Ike Dike. Therefore, non-structural solutions must be sought as part of a comprehensive flood mitigation strategy. Since the Houston-Galveston area is experiencing rapid population growth and urban expansion, more attention should be paid to land use and land cover changes and their effects on the amplification of flood damages. Land cover change models can help predict impervious areas; higher imperviousness in urban areas can increase surface runoff amounts and slow infiltration speed, increasing flood severity (Gori et al. 2019; Kostelnick et al. 2013). This pattern, then, increases the probability of inundation in areas of high-intensity development (Brody et al. 2011); on the other hand, land use prediction model can also estimate the potential flood-vulnerability of vacant land or greenspace (K. O. Atoba et al. 2021), which is beneficial in determining buyout locations prior to development occurring (K. Atoba et al. 2021)

Despite the merits of this study, some limitations should be further addressed in future research. In terms of 3D CityEngine Models, there are three limitations. First, the CityEngine Web Scene in 3ws format size is usually too large to upload to the CityEngine Web Viewer. This is of course, also dependent on internet speed and computer performance, but can decrease accessibility and interactivity. Second, the quality of the 3ws format model must be relatively compressed compared to the original model in CityEngine. This is because the 3ws format is unable to render realistic trees, grass, and curbs. Finally, the model itself is still static in terms of user-interaction, and is unable to display dynamic storm surge scenarios; it can, therefore, only display the flood or SLR scenarios in static views. Finally, although this research evaluates the physical and demographic dynamics with different flood scenarios, we do not consider social vulnerabilities such as poverty, income and education level.

Conclusions

This research visualizes a city in 3-dimensional format using LiDAR point cloud data processed in ArcGIS Pro and Open Street Map obtained from CityEngine and links these data to ACRIRC raster outputs. The model then integrates this 3D simulation to the built environment metrics such as flood inundation and flood depth. One of the strengths of this study is that the 3D urban model is reproducible for any site with available LiDAR point cloud and Open Street Map data. In terms of learning difficulty in building the flooded 3D urban model, our project is easily manageable for landscape, planning, or architecture-related fields for students, researchers, or professionals, even without programming knowledge.

However, the findings suggest that the Ike Dike may not be the best-practice for preventing flooding related to SLR in the extreme long term due to SLR. The dike will, however, provide significant protection in the short term, especially for intermediate scaled storm events (10 yr and 10 to 100 yr return periods). It should be noted that, the 10-, 100-, and 500-year scenarios refer to expected return periods for storm surge flooding for such storms, not for flooding from heavy rainfall events (which can occur in tropical cyclones but are not considered in these ADCIRC scenarios).The effectiveness of Ike Dike to protect against flood events varies when examining socioeconomic measures. It is quite effective in protecting industrial land uses and populations, but less effective in protecting streets and household units, when considering both storm intensity increase and long-term SLR. Therefore, more efforts should be devoted to coupling non-structural strategies, such as land use/land cover changes, policy evaluation, and green infrastructure with the engineered infrastructure, should it be implemented.

Lastly, future research should explore more capabilities to examine flood impacts in 3D models in game engines with vivid animations and online user-friendly platforms, such as ArcGIS StoryMaps (https://storymaps.arcgis.com/). On such platforms, researchers can easily integrate 3-dimensional models with performance statistics across a myriad of storm scenarios, enabling users to have full access to evaluate the spatial impacts of a coastal barrier system or other mechanisms

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author, Z.Cai.

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