Assessing Roadway Network Risk to Compound Flooding in Galveston County, Texas: An Integrated Hydrodynamic and Machine Learning Approach

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Background

- Coastal areas face severe flood risks from sea level rise, storm surges, and hurricanes that can lead to catastrophic floods.
- These coastal floods are serious threat to the various infrastructures especially they can cause breakdown in transportation networks. Which can lead to system failures, loss of human lives and properties.
- Detection of critical network vulnerabilities is fundamental to ensuring commuter safety and mitigating damage to transportation infrastructure.

Research Questions

- How accurately can hydrodynamic model predict coastal flooding due to Hurricane Ike?
- What areas of Galveston County, TX can be inundated due to a 100-year return period event?
- Which road network segments of Galveston County are most susceptible to coastal flooding?

Study Area and Data

- Galveston County, TX with an average elevation of ~3m.
- Surrounded by the Gulf of America (South) and Galveston Bay (North), it faces flooding risks from both directions.
- The road network supports 360,000+ residents.

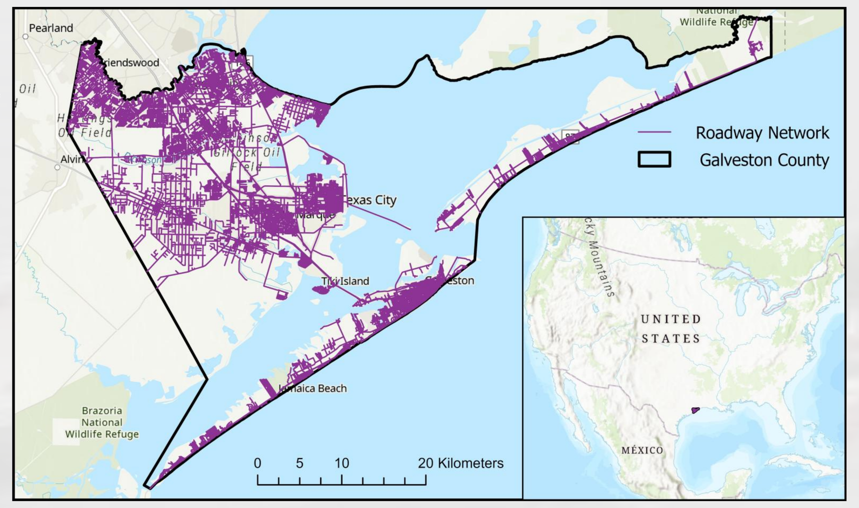

Fig. 1: Study Area

Table 1: Details of Data

Type	Data	Source	Spatial Resolution	Temporal Resolution	Data Collection Year	Remarks
Topographic Data	Projection File	Spatial Reference	NA	NA	NA	Input
	Digital Elevation Model (DEM)	USGS	3m	NA	2007	Input
Meteorological Data	Design Precipitation	NOAA ATLAS 14	NA	5minutes to 60days	NA	Input
	Historical Precipitation	NOAA NCEI	NA	Hourly	1946-1963 and 1993-2024	Auxiliary
Land Related Data	LULC	NLCD	30m	NA	2023	Input
	Soil Group	gSSURGO	NA	NA	2022	Auxiliary
	Impervious	NLCD	30m	NA	2023	Auxiliary
	CN	NLCD	NA	NA	NA	Input
	Manning's n	NLCD	NA	NA	NA	Input
Coastal Data	Sea Water Level	NOAA Tides and Currents	NA	Hourly	1904 to 2024	Input
GIS Files	City Boundary	City of Galveston	NA	NA	2022	Input
Flood Related Data	Depth	FEMA	NA	NA	2008	Validation
		HCFCD	NA	NA	2009	Validation
Transportation Data	Roadway Inventory	TxDOT	NA	NA	2023	Input
Socio-economic Data	Socio-economic Variables	SLD	NA	NA	2021	Input

Methodology

- Design precipitation were calculated according to NOAA Atlas 14 and TxDOT guidelines.
- Loss Method: SCS Curve Number; Transform Method: SCS Unit Hydrograph; Graph Type: Delmarva (PRF 284).
- Generalized Extreme Value (GEV) distribution found to be the best fit according to PPCC test.
- 100-year return period flood event considered with extreme precipitation.
- Storm surge event considered as Hurricane Ike (2008) event to calculate the stage hydrograph.
- Combined flood depth, roadway attributes, and socio-economic indicators to form the vulnerability dataset.
- Normalized and directionally aligned all variables for consistent clustering.
- Performed K-means++ clustering on PCA-refined features to group road segments by vulnerability patterns.
- Identified hotspots: Classified segments into distinct risk clusters to highlight the most susceptible.

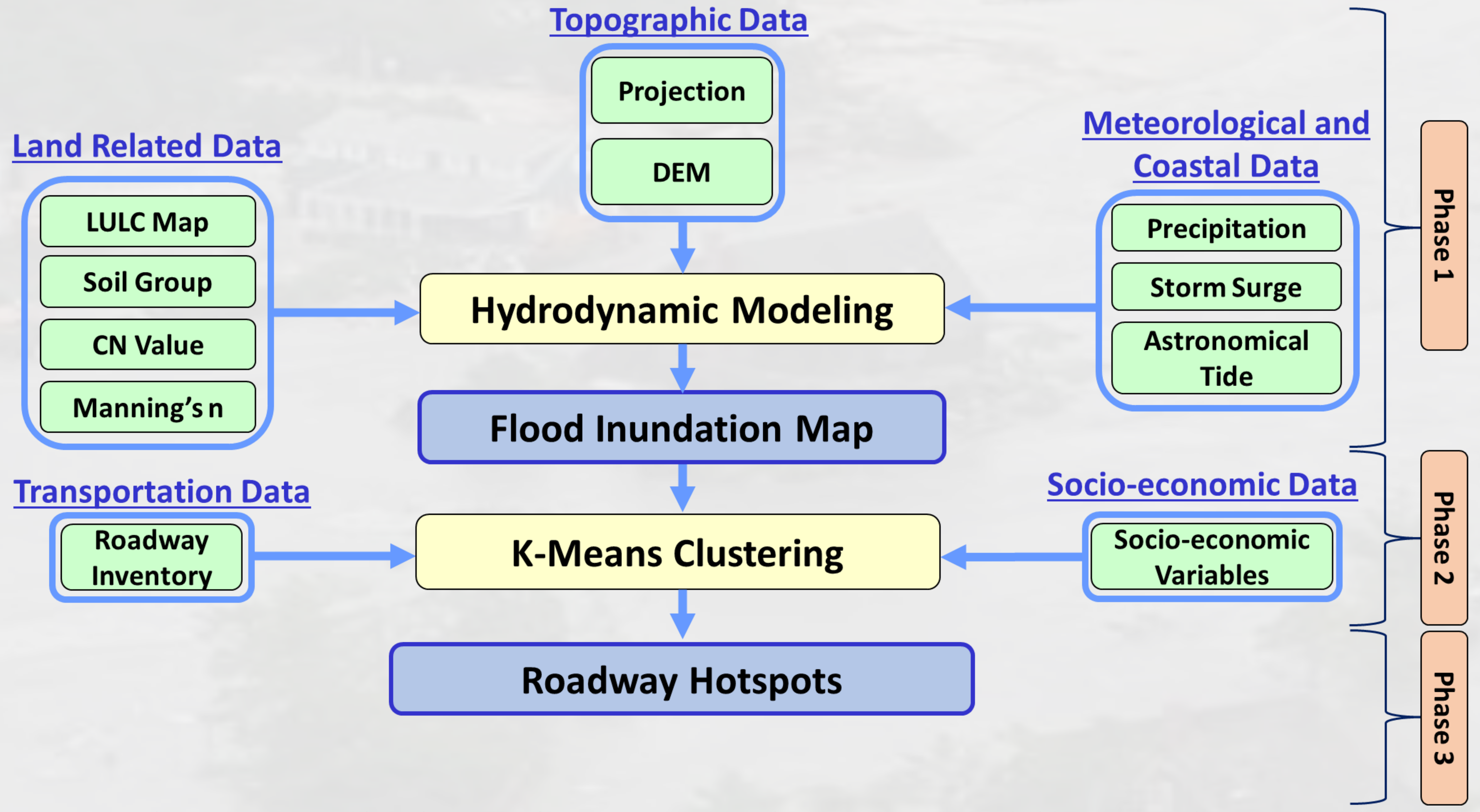

Fig. 2: Schematic Diagram for Flood Modelling and Susceptibility Analysis

Result 1. Case Study of 2008 Hurricane Ike

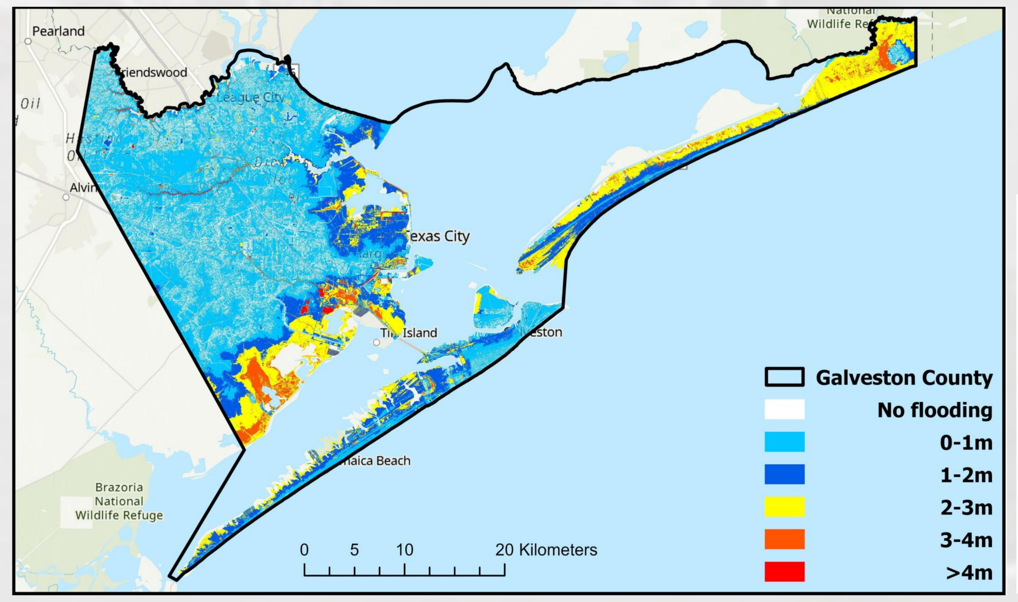

Fig. 3: Hurricane Ike Simulated Flood Map

- Hurricane Ike driven coastal flooding event was simulated, and a flood inundation map (Fig. 3) was developed.
- Simulated flood depths were compared (Fig. 4) with observed water depth from FEMA Mitigation Assessment Team Report values.

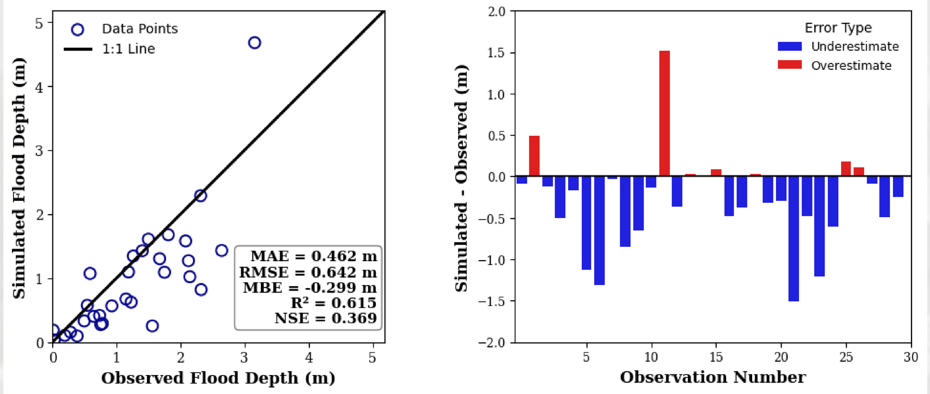

Fig. 4: Flood Depths Comparison

Table 2: Model Validation Statistics

Metric	Value
MAE	0.46 m
MBE	-0.30 m
RMSE	0.64 m
NSE	0.37
KGE	0.44
R^2	0.62

- The simulated flood depths differ from the observed depths by 0.46 m and the model explains 62% of the variability in observed flood depth.
- The KGE and NSE values are 0.44 and 0.37 that shows the model is moderately capturing the pattern and for an uncertain scenario like hurricane these numbers are considered good.

- Overall, the model is underestimating the flood depths.
- However, the extent of the flood map is quite similar to the HCFCD observed flood map.

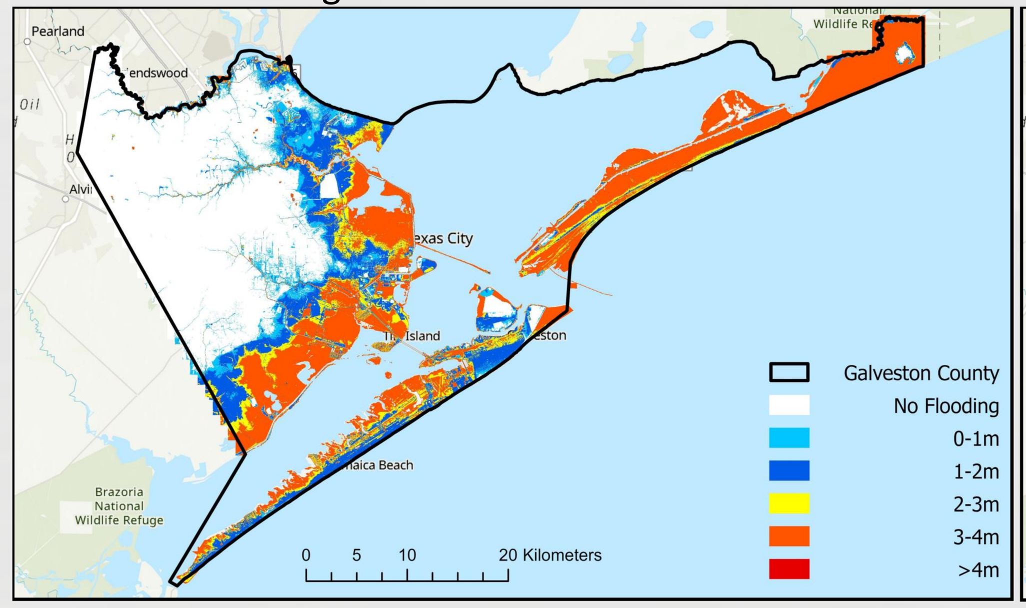

Fig. 5: HCFCD Hurricane Ike Flood Map

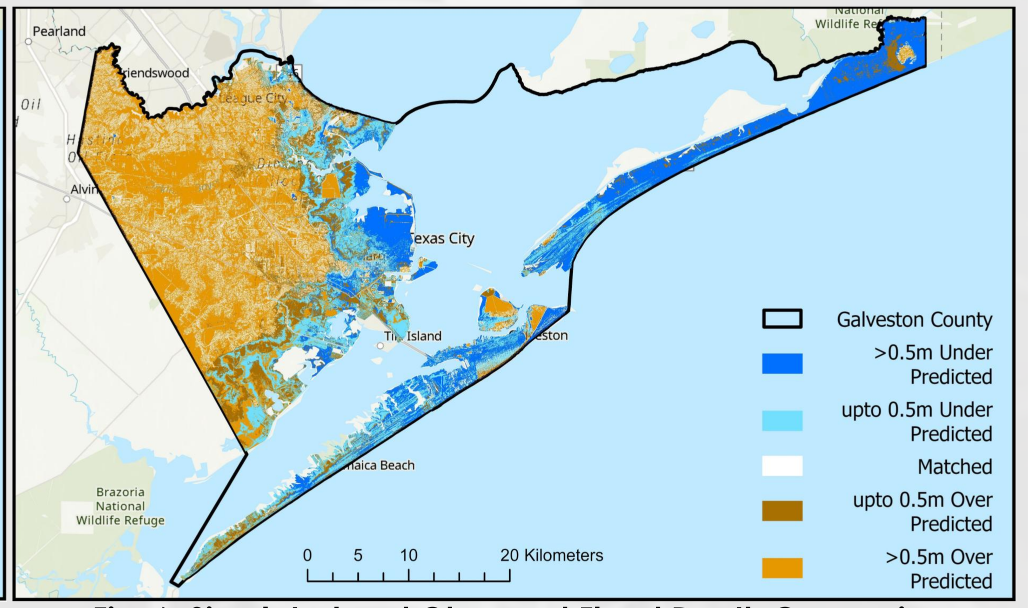

Fig. 6: Simulated and Observed Flood Depth Comparison

Result 2. 100-Year Design Flood Map

- This is done to predict the flood depth of each road segment.
- Depths exceeding 2 m occur primarily in southern Galveston Island and near major bay-facing corridors.
- Moderate flooding (1–2 m) extends inland along drainage pathways and developed neighborhoods.
- Shallow flooding (0–1 m) is distributed throughout much of the county.

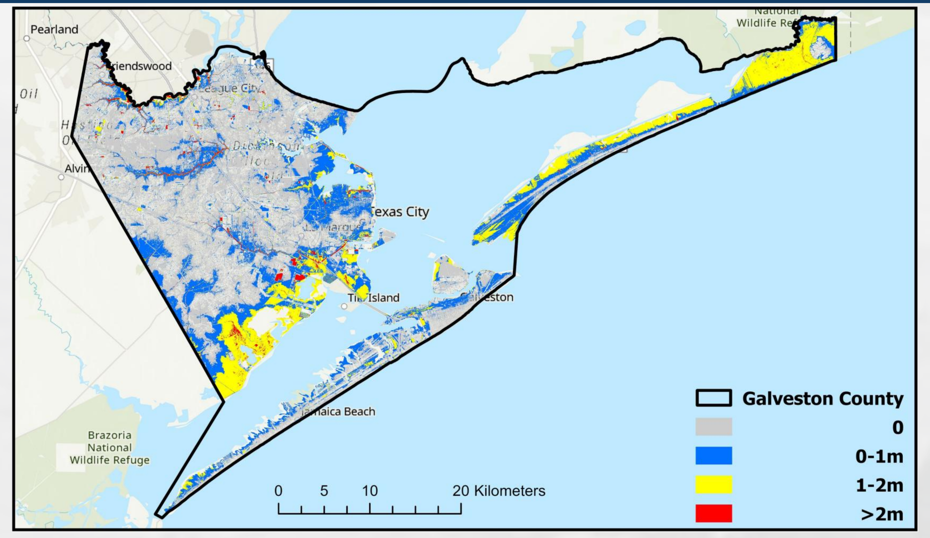

Fig. 7: 100-year Return Period Flood Depth Scenario

Result 3. Roadway Hotspots

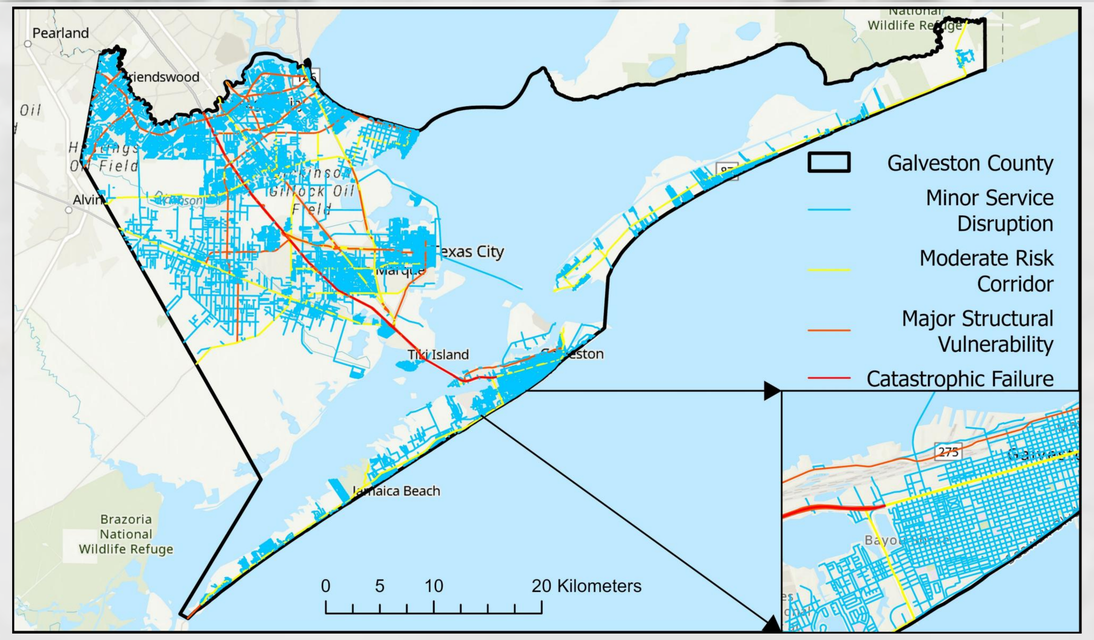

Fig. 8: Roadway Hotspots

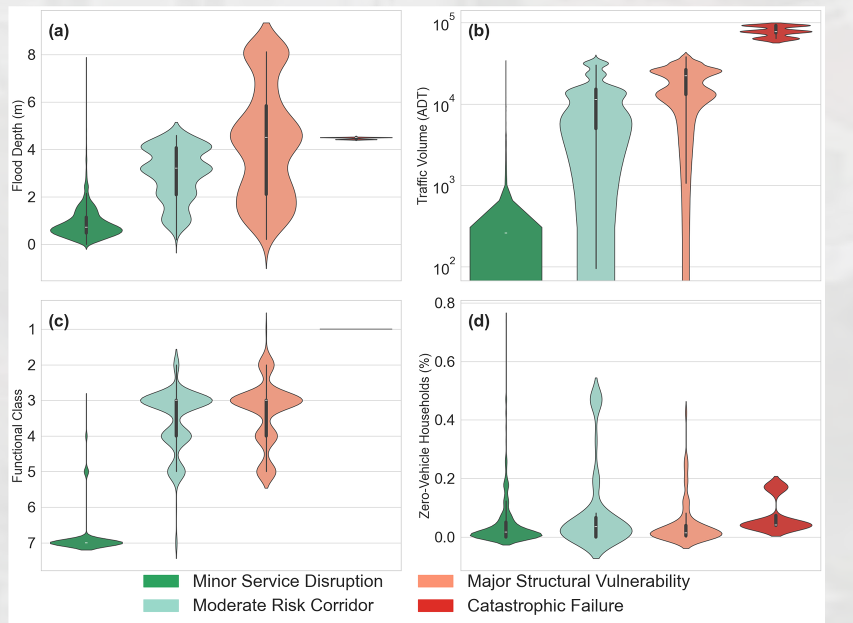

Fig. 9: Key Distributions for the Clusters

- Segments exposed to >1–2 m or >2 m flooding predominantly fall into the Major Structural Vulnerability and Catastrophic Failure classes, especially along major roadways.
- Inland areas with shallower flood depths (0–1 m) correspond mainly to Minor Service Disruption and Moderate Risk Corridor clusters, reflecting lower physical damage potential but possible localized disruptions.
- The violin plots show how key indicators—flood depth, AADT, functional class, and zero-vehicle households—vary across these four vulnerability categories.

Conclusion

- The hydrodynamic model exhibits an underestimation (MBE = -0.30 m), which is primarily attributable to the assumption of spatially uniform rainfall intensity across the study domain.
- The clustering reveals four distinct vulnerability regimes across Galveston County, driven jointly by flood depth, roadway importance, traffic demand, and neighborhood socioeconomics.
- Higher-risk corridors align with major traffic routes and deeper inundation, indicating system-level mobility disruption rather than isolated flooding.

Future Work

- The study will be extended do comparisons with Hurricane Harvey (2017) event.
- Water velocity will be incorporated into the risk analysis to get more comprehensive result.
- The developed flood map will be incorporated with traffic simulation to find out the susceptible roads due to traffic disruption.

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