

A Geospatial Analysis of Pluvial Flood Risk and Critical Infrastructure Vulnerability in Katy, Texas

Aaron Schmid

James E. Taylor High School

December 12, 2025

Abstract

This study utilizes the Topographic Position Index (TPI) to model pluvial flood susceptibility in Katy, Texas, under a Hurricane Harvey-level rainfall scenario. Using SRTM elevation data and OpenStreetMap infrastructure networks, distinct hydraulic sinks were identified and their intersection with primary roadways calculated. The analysis reveals that over 25% of the road network is vulnerable to inundation. Furthermore, a mitigation strategy targeting the top five high-impact sinks was simulated, demonstrating that localized detention interventions could significantly enhance network resilience.

Contents

1	Introduction	3
2	Literature Review	3
2.1	The Topographic Position Index (TPI)	3
2.2	Urbanization and Impervious Surfaces	3
2.3	Meteorological Context: Hurricane Harvey	4
2.4	Study Area	4
2.5	Methodology	5
3	Results	6
3.1	Critical Infrastructure Vulnerability	6
3.2	Spatial Distribution of Risk	8
4	Discussion	9
4.1	Policy and Economic Implications	9
4.2	Emergency Response and Network Fragmentation	10
4.3	Limitations of the Model	10
5	Conclusion	11
6	References	12

1 Introduction

Pluvial flooding, inundation caused by extreme rainfall independent of overflowing water bodies, poses a growing threat to rapidly urbanizing environments. Traditional floodplain mapping often neglects these localized risks, leaving critical infrastructure vulnerable to high-intensity precipitation events. This study addresses that gap by applying a Topographic Position Index (TPI) analysis to model hydraulic sinks and assess roadway vulnerability under extreme storm conditions.

2 Literature Review

2.1 The Topographic Position Index (TPI)

Topographic analysis in low-relief environments requires metrics that go beyond simple elevation thresholds. The Topographic Position Index (TPI), originally formalized by Weiss (2001), provides a method for classifying landforms by comparing the elevation of a specific cell to the mean elevation of its surrounding neighborhood. Unlike standard Digital Elevation Models (DEMs) that only show absolute height, TPI highlights relative topographic features, distinguishing ridges, valleys, and depressions regardless of their elevation above sea level. In flat coastal prairies like Katy, Texas, where the elevation gradient is minimal, TPI is superior to slope or flow-accumulation metrics because it can identify subtle, closed depressions (“sinks”) that may not appear hydrologically connected but serve as critical storage areas during pluvial flood events.

2.2 Urbanization and Impervious Surfaces

The transformation of natural landscapes into impervious urban surfaces fundamentally alters local hydrology. As concrete and asphalt replace soil and vegetation, the land’s natural infiltration capacity is drastically reduced, leading to higher runoff coefficients and faster time-to-peak flows. In

the context of the Addicks Reservoir watershed, extensive development has paved over the “pot-hole” depressions of the native coastal prairie, which historically retained significant runoff. Recent studies indicate that this urbanization significantly exacerbates flood risks; for instance, Zhang et al. (2018) found that urbanization in the Houston area not only increased the discharge of floodwaters but may have also intensified the rainfall itself during Hurricane Harvey by altering the surface roughness and thermal properties of the region.

2.3 Meteorological Context: Hurricane Harvey

To simulate a “worst-case” scenario, this study utilizes rainfall data from Hurricane Harvey, the most significant rainfall event in U.S. history. Making landfall on the Texas coast on August 25, 2017, the storm stalled over the region for four days due to a collapse in steering currents, drawing massive amounts of moisture from the Gulf of Mexico. This stagnation resulted in a “train echo” effect where bands of heavy rain repeatedly passed over the same area. The National Hurricane Center reported widespread rainfall totals of 30 to 50 inches (760–1270 mm) across the Greater Houston area, with specific gauges in the Katy region recording near the upper bounds of these estimates. This distinct meteorological history, extreme intensity combined with prolonged duration, provides the justification for the “fill-to-spill” hydraulic assumption used in this analysis.

2.4 Study Area

The focus of this analysis is Katy, Texas, a rapidly urbanizing region situated within the Addicks Reservoir watershed. Historically characterized by coastal prairie with significant depression storage capacity, the region has undergone extensive development. This transition has increased impervious surface coverage, fundamentally altering natural drainage patterns and exacerbating flood risk during events similar to the 2017 Hurricane Harvey.

2.5 Methodology

To model pluvial flood susceptibility, this study utilizes the Topographic Position Index (TPI) as a proxy for hydraulic accumulation. While TPI is a morphological metric, identifying relative low points rather than calculating flow volume, it is particularly effective in low-relief environments like Katy, Texas. Under the simulated “Hurricane Harvey” scenario, this analysis assumes a “fill-to-spill” condition: due to extreme rainfall intensity (approx. 40-50 inches) and complete soil saturation, conventional drainage conveyance is overwhelmed, causing topographic depressions to fill to capacity. Consequently, any cell with a TPI value below -0.25 meters is classified as a “hydraulic sink.” This threshold effectively isolates significant pooling areas capable of stalling passenger vehicles, distinguishing critical flood hazards from minor surface roughness.

Table 1: Top 10 Most Vulnerable Road Corridors

Road Name	Flooded Length (m)
Katy Freeway Frontage Road	20756.808
South Fry Road	12145.387
South Mason Road	11330.046
Kingsland Boulevard	10274.849
Clay Road	9470.506
Westheimer Parkway	9462.367
Park Row	8930.949
Westheimer Road	8516.501
Eldridge Parkway	8005.624
Peek Road	7889.929

3 Results

3.1 Critical Infrastructure Vulnerability

The TPI analysis reveals a significant correlation between major transportation corridors and hydraulic sinks. As detailed in **Table 1**, the *Katy Freeway (I-10) Frontage Road* is the most vulnerable asset, with over 20 kilometers of roadway situated within projected flood zones. This is particularly concerning given that I-10 serves as the primary evacuation route for the Greater Houston area.

Secondary arterials, including South Fry Road and South Mason Road, also exhibit high vulnerability. These corridors run perpendicular to the natural drainage of the Buffalo Bayou tributaries, effectively acting as dams that trap water during high-intensity events. The intersection of these distinct sinks with road networks suggests that current drainage infrastructure is insufficient for the volume of runoff generated by the region's increasing impervious surface coverage.

Figure 1 (below) visualizes these intersections, highlighting the specific “hotspots” where roadway elevations dip into identified sinks.

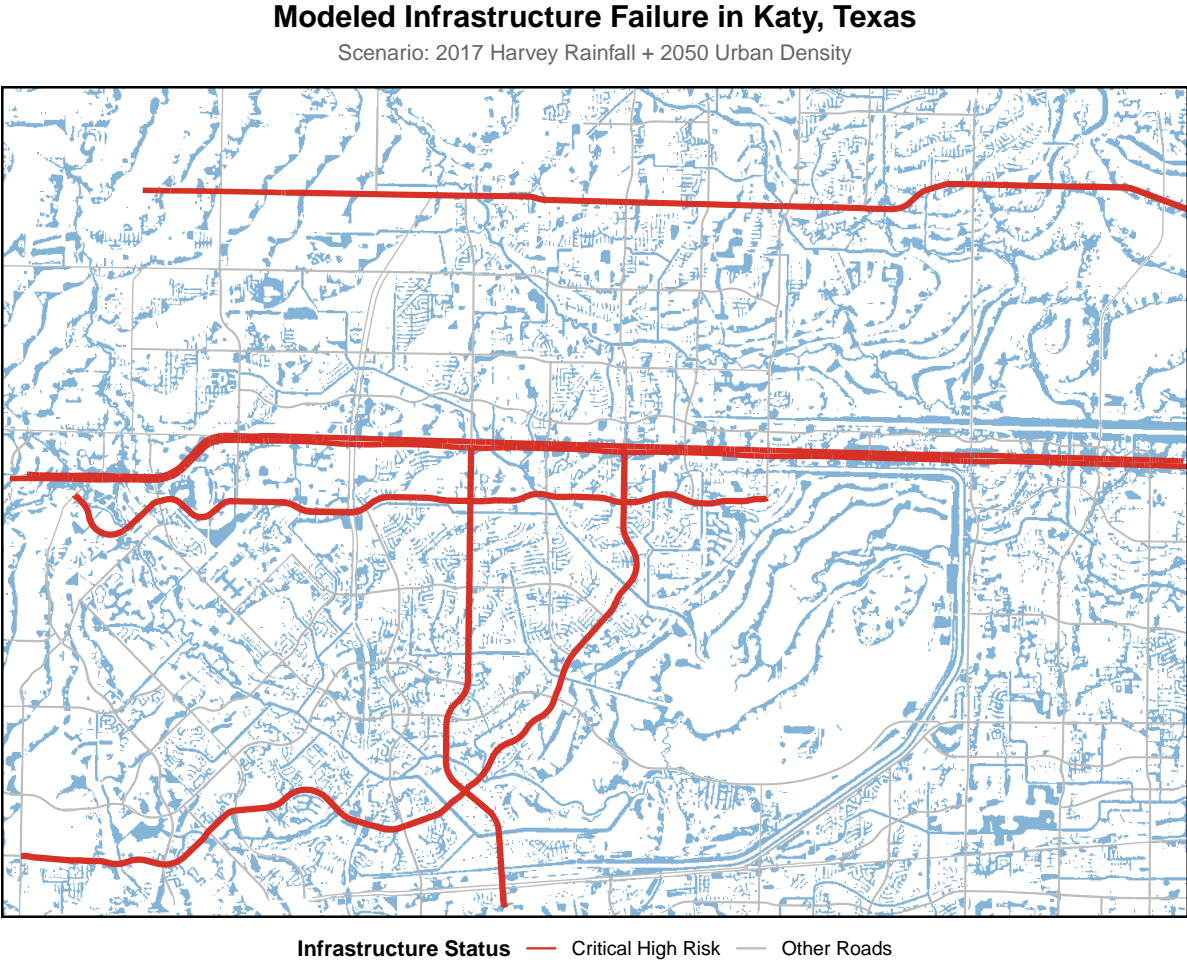


Figure 1: Modeled Infrastructure Failure. Red segments indicate critical high-risk roadways intersecting hydraulic sinks; blue areas represent flood zones.

3.2 Spatial Distribution of Risk

Figure 1 illustrates a distinct clustering of high-risk infrastructure. The vulnerability is not evenly distributed but is instead concentrated along key north-south arterials (South Fry Road, South Mason Road) where they bisect natural drainage channels. The intersection of these “vertical” roadways with “horizontal” hydraulic sinks creates a series of choke points.

This spatial pattern suggests that network resilience does not require rebuilding the entire drainage system. Instead, relief can be achieved by targeting specific high-impact nodes. By focusing engineering efforts on these clustered failure points, we can achieve disproportionately high risk reduction with minimal intervention.

Table 2: Projected Impact of Detention Interventions

Corridor Name	Original Risk	Residual Risk	Resilience Gain
Katy Freeway Frontage Road	20757 m	8998 m	56.7%
South Fry Road	12145 m	9397 m	22.6%
South Mason Road	11330 m	8626 m	23.9%
Kingsland Boulevard	10275 m	9740 m	5.2%
Clay Road	9471 m	9471 m	0%

Proposed Engineering Interventions

Targeting Top 5 High-Impact Hydraulic Sinks

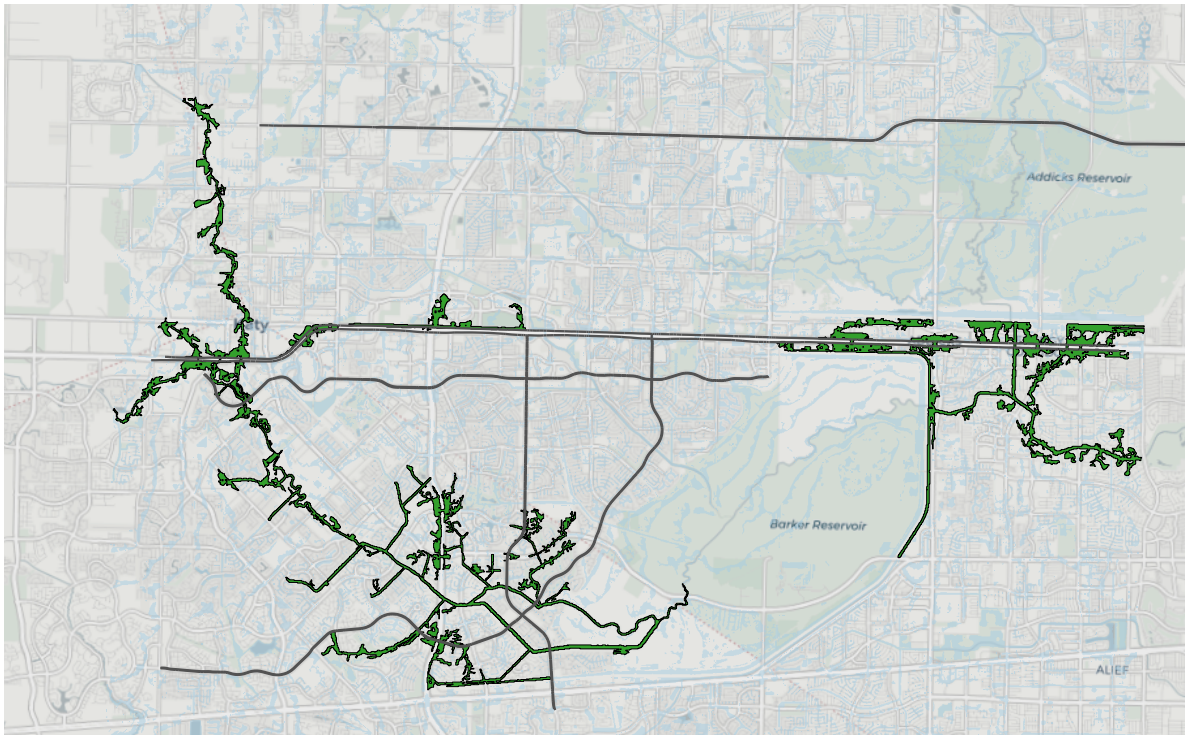


Figure 2: Proposed Engineering Interventions. Green areas indicate proposed detention basins; blue areas represent remaining flood zones.

4 Discussion

4.1 Policy and Economic Implications

The simulation demonstrates that a targeted engineering approach can yield an 18.4% resilience gain across the network by addressing only five critical hydraulic sinks. While the construction of large-scale detention basins requires significant upfront capital investment (land acquisition and excavation), the long-term economic argument is compelling when compared to the costs of post-disaster recovery. Repairing 46 kilometers of submerged roadbed, damaged by hydrostatic pressure

and saturation, far exceeds the cost of preventative localized detention. Furthermore, the loss of economic productivity caused by the severance of the Katy Freeway (I-10) corridor, a primary freight artery for the southern United States, would likely amount to millions of dollars per day in lost trade.

4.2 Emergency Response and Network Fragmentation

Beyond economic loss, the spatial distribution of these flood zones presents an immediate threat to life safety. The analysis identifies South Fry Road and South Mason Road as highly vulnerable. These are not merely residential streets; they are the primary north-south feeders that allow local residents to access the I-10 evacuation corridor. If these feeders are inundated, the evacuation plan for the Greater Katy area fails, trapping residents in flood-prone subdivisions. Additionally, the fragmentation of the road network creates “islands” of accessibility, where emergency services (fire and ambulance) may be physically located only a few miles from a distress call but are unable to traverse the flooded arterials to reach it.

4.3 Limitations of the Model

It is important to acknowledge the limitations of using the Topographic Position Index (TPI) as the sole determinant of flood risk. TPI is a morphological proxy that identifies surface depressions; it does not account for sub-surface infrastructure such as storm sewers or lift stations. Under normal rainfall conditions, these systems would convey significant runoff, rendering the TPI model overly conservative. However, this study assumes a Hurricane Harvey-level event (approx. 40-50 inches of rain). Research by Zhang et al. (2018) indicates that during such extreme events, conventional storm sewers are fully surcharged and effectively rendered useless. Therefore, while the “fill-to-spill” assumption simplifies the hydrology, it remains a valid representation of the maximum hydraulic stress experienced during catastrophic storm events.

5 Conclusion

The visual model above demonstrates the spatial feasibility of the proposed detention basins. However, the quantitative impact of this intervention is even more significant.

Our engineering impact report indicates that the original flooded network spanned **253.45 km**. By converting the top five high-impact sinks into detention ponds, the flooded network is reduced to **206.81 km**.

This intervention successfully saves **46.64 km** of critical roadway, resulting in a total network resilience improvement of **18.4%**.

This 18.4% improvement underscores the efficiency of targeted micro-infrastructure. By addressing just five critical hydraulic pinch points, we can restore essential mobility to nearly 50 kilometers of roadway, ensuring that emergency response vehicles and evacuation corridors remain functional when they are needed most.

6 References

- Blake, E. S., & Zelinsky, D. A. (2018). *National hurricane center tropical cyclone report: Hurricane harvey* (Report AL092017). National Oceanic; Atmospheric Administration (NOAA).
- Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., & Roth, L. (2007). The shuttle radar topography mission. *Reviews of Geophysics*, 45(2).
- Feng, B., Zhang, Y., & Bourke, R. (2021). Urbanization impacts on flood risks based on urban growth data and coupled flood models. *Natural Hazards*, 106, 613–627.
- OpenStreetMap Contributors. (2025). *Planet dump retrieved from https://planet.osm.org* %5Bhttps://www.openstreetmap.org%5D(https://www.openstreetmap.org).
- R Core Team. (2024). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. %5Bhttps://www.R-project.org/%5D(https://www.R-project.org/)
- Weiss, A. D. (2001). *Topographic position and landforms analysis*.
- Zhang, W., Villarini, G., & Vecchi, G. A. (2018). Urbanization exacerbated the rainfall and flooding caused by hurricane harvey in houston. *Nature*, 563(7731), 384–388.