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Quality of Stormwater Infrastructure Systems in Vulnerable Communities: Three Case Studies from Texas

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Abstract

A properly functioning local stormwater drainage system is essential for mitigating flood risks. This study evaluates the quality of roadside drainage channels in three underserved communities in Texas: the Sunnyside neighborhood in Houston (Harris County), a neighborhood in the City of Rockport (Aransas County), and the Hoehn *colonia* (Hidalgo County). These communities have a history of flooding, are highly socially vulnerable, and rely on roadside ditches as their principal stormwater drainage system for runoff control. Mobile lidar (Light Detection and Ranging) measurements were collected for 6.09 miles of roadside channels in these communities. The raw lidar measurements were processed to evaluate drainage conditions based on the channel's geometric properties, hydraulic capacity, and level of service. The assessment results are linked to a Geographic Information System (GIS) tool for enhanced visualization. Finally, the paper provides insights regarding the quality of stormwater infrastructure in the study communities and discusses their practical implications.

Keywords

asset management; infrastructure: condition; performance and demand; flood control; equity; stormwater infrastructure systems

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Note

[1] Colonias are unincorporated neighborhoods or communities along the U.S.-Mexico border that are characterized by substandard infrastructure and building practices.

Introduction

A properly functioning local stormwater drainage system is essential for mitigating economic, health, and safety risks communities face due to flooding. Failure of a local drainage system occurs when stormwater runoff overloads the system and floods the streets and surrounding low-lying areas. The impacts of these floods include property damage (Wobus et al., 2014; NASEM, 2019), safety risks (Ashley & Ashley, 2008; Sharif et al., 2014), and health risks from mold, mosquitoes, and contaminated floodwaters (Ahern et al., 2005; Lowe et al., 2013; ten Veldhuis et al., 2010). Improperly functioning stormwater management systems are more often found in low-income and minority communities due to inequitable development patterns and accompanying infrastructure investment or lack thereof (Hendricks, 2017; Van Zandt, 2019). Evaluating drainage infrastructure conditions at the neighborhood level can help public works agencies to develop maintenance and investment plans and mitigation strategies to guard against these impacts.

In this paper, we evaluate the drainage conditions of roadside channels in three underserved communities in Texas that are vulnerable to flooding and stormwater-related hazards: Sunnyside (a neighborhood within the City of Houston), Rockport (a neighborhood adjacent to the City of Rockport, Texas), and Hoehn (a *colonia*[1] in Hidalgo County, Texas). These communities have a history of flooding, are socially vulnerable, and rely on roadside ditches as their principal stormwater drainage systems for runoff control. We apply an automated inspection method (Lee & Gharaibeh, 2020; 2022) that use mobile lidar (light detection and ranging) data to assess the condition of roadside channels. The assessment results are compared and linked to a Geographic Information Systems (GIS) tool for enhanced visualization. The study design is illustrated in Figure 1.

The remainder of this paper is organized as follows: In the next section, an overview the relevant literature and current practices is provided followed by a description of the studied communities and the drainage condition assessment method. Then, we discuss our findings and the insights we derive from them about drainage problems in the studied communities. Finally, the research conclusions and practical implications are presented.

Review of the literature and Current practices

Assessment of Drainage Systems in Residential Areas

Systematic inspection and evaluation of drainage infrastructure aids both public works agencies and property owners in identifying problem areas and planning the allocation of financial resources to address these problems in the most cost-effective manner (Frank & Falconer, 1990; Molzahn & Burke, 1986). Manual visual inspection of drainage systems in residential areas remains common, especially in communities with limited resources. However, such manual methods can be time consuming and subjective, especially when utilizing quantitative measurements (Lee & Gharaibeh, 2020). To address this challenge, Oti et al. (2019) developed citizen science methods for collecting drainage condition data. Although Oti et al. (2019) found that volunteer citizen scientists can provide timely and high-quality data related to the conditions of drainage systems, they tend to have difficulties obtaining some geometric measurements, such as ditch slope. Mobile lidar technology offers opportunities to collect these data with high density and quality. However, the literature on applying mobile lidar methods for assessing drainage systems in residential areas remains limited. This paper contributes to filling this gap by demonstrating the utility of a recent mobile lidar method (Lee & Gharaibeh, 2020, 2022) in three Texas communities that use roadside drainage channels.

Design Standards

Grass-lined roadside channels (the focus of this paper) are commonly used in residential areas for stormwater drainage. These channels are graded to as-designed dimensions and lined with suitable vegetation for stable and safe conveyance of runoff. Current design guidelines call for the geometric properties of these channels (Figure 2) to meet certain standards. These properties require regular monitoring within and across street blocks to ensure that the runoff is collected effectively by the drainage system and conveyed to the discharge points.

Table 1 provides a summary of these design standards in several areas in the United States. While these design standards vary greatly among different public works agencies, they are generally set to meet flow, pollution, erosion, and safety requirements in their respective areas.

Study Communities

The case studies are located in the City of Houston, Harris County (Sunnyside community), Aransas County (Rockport community), and Hidalgo County (Hoehn community) (Figure 3). The evaluated roadside drainage ditches consist of 1.40 miles (nine street blocks) in Hoehn, 1.67 miles (10 street blocks) in Sunnyside, and 3.02 miles (20 street blocks) in Rockport. We chose these communities because they are underserved, vulnerable to flooding, and utilize roadside open channels as their primary system for runoff control.

A summary of key climate, socioeconomic, and physical characteristics of these three communities is provided in Table 2. In 2018, the Centers for Disease Control and Prevention (CDC) Social Vulnerability Index (SVI) for these communities ranged between 0.75 and 0.96, which indicates high social vulnerability relative to the US. The SVI ranks every census tract (subdivisions of counties for which the Census collects statistical data) based on percentiles of 15 social factors, including poverty, lack of access to transportation, crowded housing, unemployment, minority status, and disability. A high SVI indicates that the sub-population may be expected to have a lower capacity to prepare for, respond to, and recover from flooding disasters. Percentile ranking values range from 0 to 1, with higher values indicating greater social vulnerability.

The objective here is not to test whether social inequities exist in public works services, although that would be a useful task for future research. Rather, this article provides an assessment of the quality of stormwater infrastructure in socially vulnerable communities. Price (1980) suggested that every government can test itself to determine whether inequities in public works services exist by neighborhood, ethnic classification, or income groups. He concluded that the consideration of need and equity in decision analysis does not mean any lessening of efficiency and effectiveness in delivering public works services. He points out that what is needed is to ask: “Who is receiving services and whose need is being neglected?” (Price, 1980).

Drainage Evaluation Method

The raw field measurements consist of lidar point clouds that were collected using a single laser mobile lidar system. The mobile lidar system collected approximately 400,000 points per 0.1-mile section at a driving speed of 20 mph. The lidar data point clouds were converted to grids with transverse and longitudinal increments of 2 inches. This grid size was selected to capture the smallest dimensional requirement of roadside channels in the study areas.

The lidar data were processed using a computerized method developed by Lee and Gharaibeh (2020, 2022) to determine the geometric properties of the roadside channels in the three study areas. These geometrical properties include ditch depth, longitudinal slope, bottom width, and front side slope and back side slope. Then, the geometric properties of the roadside channels were analyzed to determine the channel’s compliance with design standards, cross-sectional area, hydraulic capacity, and level of service (LOS).

To determine channel hydraulic capacity, Manning’s equation with trapezoidal cross-section was utilized (Holland, 1998) (Equation 1). Manning’s equation assumes that the flow is uniform, steady flow, throughout the channel. Under this assumption, the water surface slope is the same as the channel bottom slope. This assumption creates limitations for Manning’s equation because the actual flow conditions may not be strictly uniform and steady due to debris flow, very high-gradient channels, and irregularities in the channel shape and surface. Nonetheless, Manning’s equation remains widely used for designing drainage channels where the goal is to find the channel geometric properties and surface roughness that allow for draining stormwater as quickly as possible.

$$Q = \left(\frac{1.49}{n}\right) * A * R^{\frac{2}{3}} * \sqrt{S} \tag{1}$$

Q = Flow rate (ft^3 /s)

n = Manning’s Roughness Coefficient (an indicator of the roughness characteristics of the channel surface and the friction applied to the flow by the channel surface)

R = Hydraulic Radius (ft) = A/WP

A = Flow cross-sectional area (ft^2)

WP = Wetted perimeter of flow (ft)

S = Channel longitudinal slope (ft/ft)

Due to the variation in precipitation, the ratio of capacity to precipitation was used to compare the three communities on an equal level. The ratio of capacity to precipitation was calculated using (Equation 2).

$$Capacity\ to\ precipitation\ Ratio = \frac{Channel\ Capacity}{Precipitation} \quad (2)$$

Channel Capacity = Flow rate (ft^3 /s) computed using Equation 1

Precipitation = Precipitation depth for 2-, 10-, and 100-year return period storms (see Table 1).

The geometric properties were checked against the county standards (Table 3) on a pass/fail basis to assess compliance and determine the LOS. As Aransas County does not have standards for channel depth, bottom width, and longitudinal slope, the evaluation of these properties in the Rockport community was based on Harris County's standards. Both (Harris and Aransas) are coastal counties that have similar flooding issues.

The LOS is defined as the ratio of the number of passing standards to the total number of measured standards. To determine the LOS, the channels on each street were divided into 150-ft sections. Then, for each 150-foot section, each measured geometric property (bottom width, depth, side slopes, and longitudinal slope) was compared to the county's design standards to determine whether or not it met the standard. If the measured property satisfies the county standard, it is considered 'Pass;' otherwise, it is considered 'Fail.' The ratio of the number of passing properties to the total number of measured properties (five properties) is the section's LOS (Equation 3).

$$\mathrm{LOSl}_i = \frac{N_P}{5} * 100 \quad (3)$$

LOS_i: Level of service for channel section i.

N_p: Number of Pass in the ditch section

T_f: Total Number of Fails within Study Area

To assess the prevalence of different failure types, a failure frequency was computed for each geometric property as a percentage of the total number of failures in the study area (Equation 4).

$$Failure_p = \frac{N_f}{T_f} * 100 \quad (4)$$

Where:

$Failure_p$ = Property p frequency of failure within the study area

N_f = Number of fails in property p within the study area

T_f = Total number of fails within the study area

Results and Discussion

Assessment of Channel Geometric Properties and LOS

The geometric properties' pass/fail evaluation results for the Sunnyside community are shown in Table 4. The channel side and longitudinal slopes are the predominant types of failure in this community. More than half of the channels are not in compliance with the side slope and longitudinal slope requirements, suggesting that these issues require greater attention to ensure that the roadside channels in this community can convey stormwater runoff as designed. Only one channel does not meet the requirement for bottom width. Overall, the Sunnyside community has an average LOS of 77%, with 20.8% standard deviation.

The geometric properties' pass/fail evaluation results for the Rockport community are shown in Table 5. All channel bottom widths meet the standards. The longitudinal slope was the most frequent failure, responsible for 42.3% of all failures, followed by channel backslope and depth (34.6% and 23.1% of all failures, respectively). Hence, channel longitudinal slope, backslope, and depth are the primary concerns. The average LOS in this community is 72.6%, with 16.6% standard deviation.

In the Hoehn community (Table 6), the most common failures were in ditch bottom width and longitudinal slope, with 45% and 42.5% failure frequencies, respectively. All streets in Hoehn failed to meet the ditch bottom width standard. Seventeen (out of 18) ditch sections failed the longitudinal slope standard. In contrast, there were no failures in front slopes. These results suggest that both the bottom width and the longitudinal slope need work to improve the drainage system in the Hoehn community. The average LOS in this community is 52.2% (the lowest among the three study areas), with 17.7% standard deviation.

Overall, the three communities have high frequency of failures in longitudinal slope. Therefore, they are likely to have hydraulic capacity issues, as longitudinal slope affects the ditch flow capacity. Failures in the other geometric properties (bottom width, depth, and side slopes) affect the channel's cross-sectional area, which in turn affects the hydraulic capacity.

Comparative Analysis of Studied Communities

To compare the overall drainage conditions in the three communities, three comparisons are made: LOS, channel hydraulic capacity, and capacity to precipitation ratio. For all statistical comparisons in this section, the Shapiro–Wilk test was utilized to determine whether the data were normally distributed. If the data were proven to be normally distributed, the analysis of variance (ANOVA) was used to compare the ditch properties across the three communities. If the data were not normally distributed, the Kruskal–Wallis H test was utilized.

Level of Service (LOS)

The LOS of each ditch section was calculated as an overall indicator of the ditch's compliance with design standards. As discussed earlier, the LOS is defined as the ratio of the number of passing properties to the total number of measured properties. A ditch section with a LOS of 100 is in ideal condition (all five geometric properties meet the design standards); whereas a ditch section with a LOS of 0 is in very poor condition (none of the five geometric properties meets the design standards). The average LOS and 95% confidence interval for each community were compared as shown in Figure 4. Overall, the LOS in the three communities is low, especially in the Hoehn community. For example, Hoehn's median LOS of 52% indicates that the roadside ditches in this community fail to meet the design standards about 48% of the time.

Hydraulic Capacity

Channel capacity, or flow rate, was estimated using Equation 1. For comparison purposes, the channels were assumed to flow at full depth. Since all channels in this study are natural channels with vegetation cover, capacity is normalized for Manning's Roughness Coefficient (n), allowing the capacity comparisons to be influenced by the channel's longitudinal slope and cross-sectional area only.

As shown in Table 7, the channels in the communities of Hoehn and Sunnyside have significantly smaller cross-sectional area ($p < 0.01$), resulting in lower capacity in comparison to Rockport. Even when accounting for differences in precipitation, Rockport channels remain superior to the channels in Sunnyside and Hoehn. These results indicate that Sunnyside and Hoehn are more poorly equipped than Rockport to handle expected precipitation levels at their respective localities.

Visualization

The evaluation results were integrated into a GIS tool to assist municipal authorities and property owners improve the quality of drainage systems in their communities. Municipal authorities can use the GIS tool to plan drainage maintenance and flood mitigation projects. The general public can also use these GIS maps to stay informed about areas prone to flooding in their communities and hold authorities accountable to take action to improve infrastructure quality. For example (Figure 5), the user can visualize the LOS results in a color-coded map and charts (green, yellow, and red indicating good, fair, and poor LOS, respectively). The map is linked to the full dataset, enabling the user to access detailed information and videos taken during the field survey to identify the causes of poor condition and identify appropriate remedies.

Practical Implications and Conclusions

The roadside channels were evaluated for three underserved communities in Texas using an automated inspection method that uses mobile lidar data. These case studies demonstrate that the mobile lidar technology offers an opportunity for monitoring the condition of drainage channels in residential areas in systematic manner. Specific insights from the case studies and suggested future work are summarized as follows.

Design and Condition of Drainage Channels

The average LOS ranged between 52 (Hoehn) and 77 (Sunnyside). However, the channels in Hoehn and Sunnyside have significantly smaller cross-sectional area than those in Rockport, resulting in lower hydraulic capacity. The median channel capacity in Rockport is 1.47 times that in Sunnyside and 2.4 times that in Hoehn. Even when accounting for differences in precipitation, Rockport channels remain superior to the channels in Sunnyside and Hoehn. These results lead to two general findings: (1) the quality of the drainage infrastructure systems in all three communities is low, and (2) there is an inverse relationship between social vulnerability (measured in SVI) and the quality of drainage infrastructure. Sunnyside and Hoehn have lower drainage infrastructure quality and higher social vulnerability than Rockport.

Although Sunnyside has the lowest Capacity to Precipitation ratio in most cases, it has the highest LOS. This finding suggests that the geometric design standards for the Sunnyside channels may not be adequate to ensure carrying the expected runoff. Therefore, we suggest that Harris County should consider examining and revising these standards.

All three communities have high frequency of failures in channel longitudinal slope. These failures reduce the channel flow capacity, as longitudinal slope affects capacity directly. The frequency of failure in the other geometric properties (bottom width, depth, and side slopes) varied across the three communities. These failures reduce the channel’s cross-sectional area, which in turn reduces the hydraulic capacity. For Hoehn and Rockport, the geometric standards appear adequate; however, the channels geometric conditions (especially longitudinal slope) need to be brought up to standards.

Suggested Future Work

Future work could build on the work presented in this paper to (1) address other types of drainage systems in residential areas (e.g., green infrastructure, curb-and-gutter systems), (2) integrate other infrastructure components that could affect drainage (e.g., sidewalks, street pavement), (3) account for the positive impacts of strategically planted vegetation (e.g., reduced runoff) versus the negative impacts of random and overgrown vegetation (e.g., flow blockage), and (4) develop and test hypotheses to determine if and where disparities in public works services exit–an opportunity for interdisciplinary research combining engineering and social sciences.

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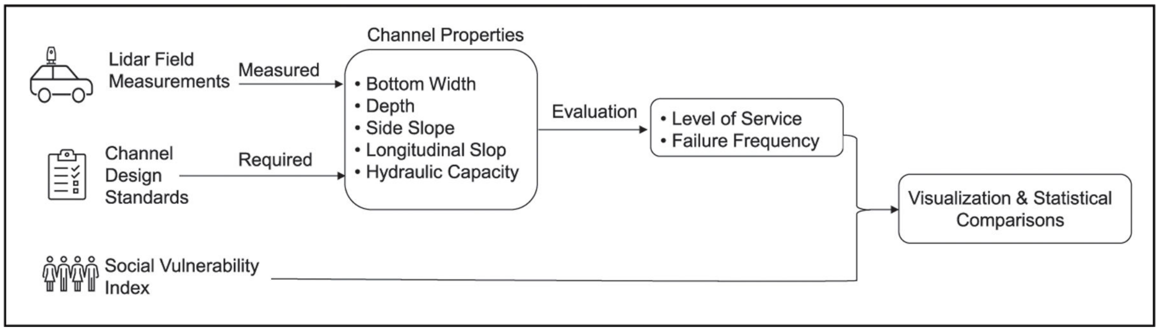

Figure 1.

Study Design.

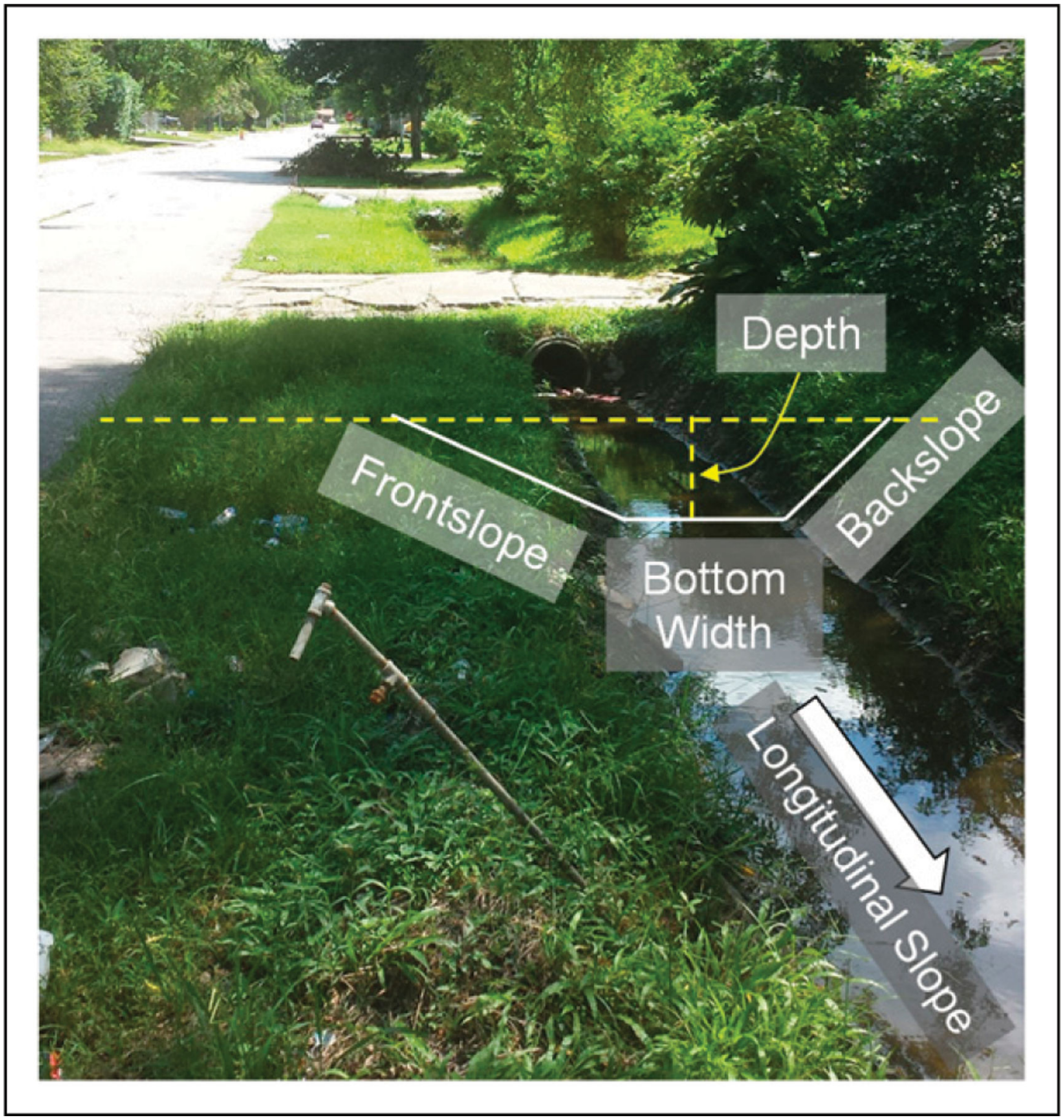

Figure 2.

Key Geometric Properties of Roadside Channels.

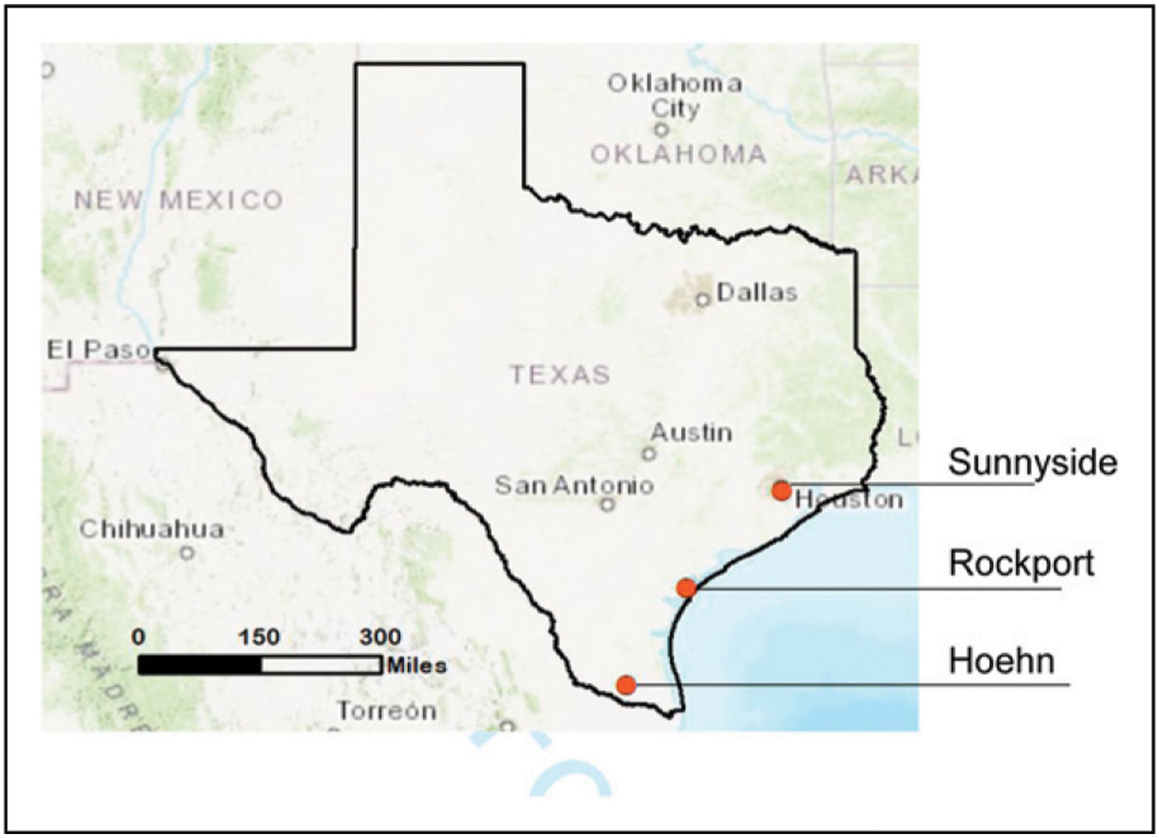

Figure 3.
Sites of Case Studies.

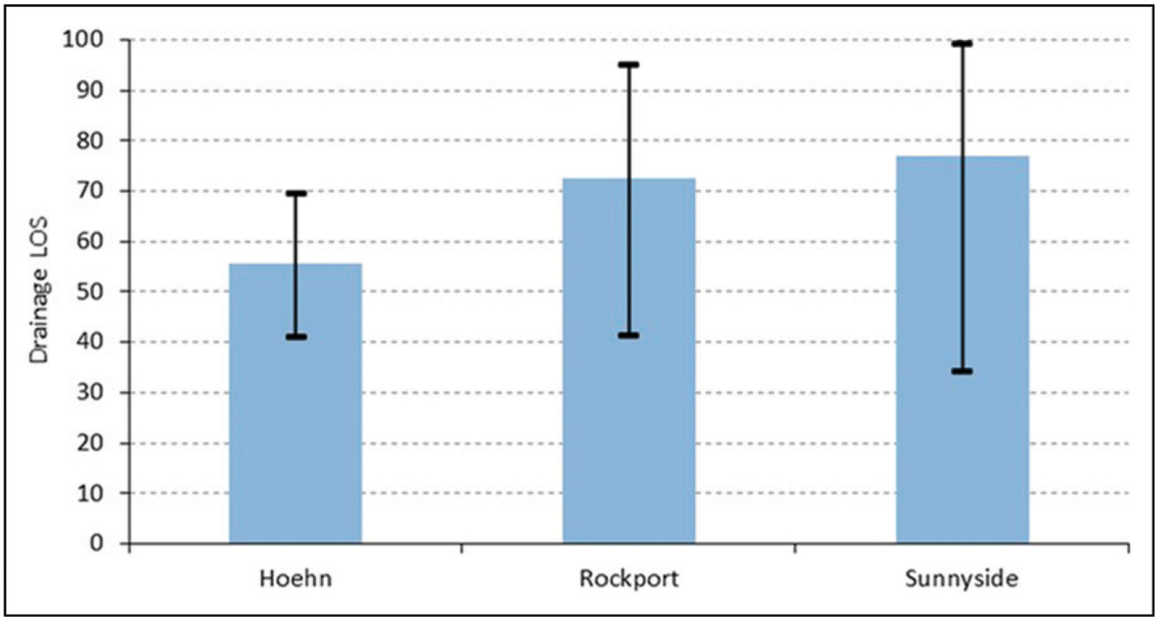

Figure 4.

Roadside Drainage LOS for the Three Communities (average values are shown as columns and 95% confidence intervals are shown as vertical lines).

Indigo St

Year	2021
Jurisdiction	Hidalgo County
Street Name	Indigo St
Street Side	Left
Start Longitude	-98.213773408
Start Latitude	26.343433745
End Longitude	-98.21407257
End Latitude	26.3434794140001
Beginning Marker	98213773-26343434
End Marker	98214073-26343479
Length(ft)	150
Roadside Drainage Type	Vegetation-Lined Ditch
Bottom Width(ft)	1.26
Depth(ft)	1.46
Front Slope(%)	-39
Back Slope(%)	60
Longitudinal Slope(%)	0.07
Low Point	No
Level Of Service (LOS)	20
LOS Class	0-39.99 (Poor)
Inspection Date	May 2021
Video Hyperlink	View
Profile Hyperlink	View

Figure 5.

Illustration of the Drainage Assessment GIS Tool (Hoehn Community).

Table 1.

Roadside Channel Geometric Standards used by Different Public Works Agencies.

City/County/State	Depth	Bottom width	Side slope (V/H)[u]	Longitudinal slope (%)
Harris County, TX[a]	1.5 ft–4 ft	>2 ft	1/2–1/3	>0.1
Aransas County, TX[b]	NA	NA	<1/4	NA
Hidalgo County, TX[c]	1.5 ft–6.5 ft	>3 ft	1/2–1/8	>0.1
Houston City, TX[d]	<4 ft	>2 ft	<1/3	>0.1
Galveston County, TX[e]	1.5 ft–4 ft	>2 ft	<1/2–1/3	>0.1
Cook County, IL[f]	>3 ft	>2 ft	<1/3	>0.3
King County, WA[g]	NA	>2 ft	1/2–1/3	>0.5
Lincoln City, NE[h]	NA	NA	<1/4	<1
Jefferson County, CO[i]	<5 ft	>4 ft	<1/4	NA
Douglas County, CO[j]	<5 ft	NA	<1/4	<0.6
District of Columbia[k]	NA	4 ft–8 ft	<1/3	<2
Honolulu City & County, HI[l]	>1.5 ft	2 ft–8 ft	<1/3	<2
Marion County, OR[m]	>1 ft	>2 ft	<1/3	>0.5
Fort Wayne City, IN[n]	NA	NA	<1/3	>0.5
Clark County, NV[o]	1ft-5 ft	>5 ft	<1/3	>0.4
Hillsborough County, FL[p]	2 ft–3.5 ft	>3 ft	<1/4	>0.1
Fairfax City, VA[q]	NA	>3 ft	<1/3	NA
Charlotte City, NC[r]	NA	NA	<1/2	NA
Tulsa City, OK[s]	NA	NA	<1/4	<1

[a] Storey, 1988.

[b] Aransas County, 2012.

[c] Hidalgo County Planning Department, 2018.

[d] Haddock & Kanwar, 2022.

[e] Badger, 2013.

[f] Aransas County, 2012, Clark County, 2020).

[g] Brater, 2016.

[h] San Diego County 2005.

[i] Lincoln Country, 2000.

[j] Jefferson County Planning and Zoning Division, 2019.

[k] Douglas County., 2008.

[l] Hoffmann et al., 2012, Tregoning & Bellamy 2019.

[m] City and County of Honolulu Department of Planning and Permitting, 2000.

[n] Marion County Public Works, 1990, 2012).

[o] Fort Wayne City, 2017.

[p] Clark County, 1999.

[q] Hillsborough County, 2015.

[r] City of Fairfax, 2017.

[s] City of Charlotte, 2014.

[t] City of Tulsa, 2017.

[u] V/H: Vertical to horizontal ratio.

Table 2.

Characteristics of the Case Study Communities.

Characteristic	Sunnyside	Rockport	Hoehn	Three-County Average (Harris, Aransas, & Hidalgo)
2018 Census Tract	3312, Harris County, TX	9503, Aransas County, TX	23504, Hidalgo County, TX	–
Precipitation Depth (100-year storm)[a]	17.30 in	14.30 in	10.7 in	–
Precipitation Depth (10-year storm)[a]	8.89 in	7.95 in	5.99 in	–
Precipitation Depth (2-year storm)[a]	5.18 in	4.89 in	3.65 in	–
Developed land[b]	100%	96.49%	71.04%	–
-High-intensity	5.17%	1.60%	0%	–
-Medium-intensity	49.10%	11.82%	20.9%	–
-Low-intensity	41.34%	53.67%	41.8%	–
-Open space	4.39%	29.39%	8.34%	–
Population density[c] (per acre)	5.84	0.65	0.95	–
Race/ethnicity[c]				
-Hispanic	14.84%	27.69%	92.4%	55.5%
-Non-Hispanic black	82.00%	1.37%	0.3%	7.77%
-Non-Hispanic white	3.16%	70.94%	6.12%	32.8%
Median household income[d]	$26,845	$39,091	$30,665	$47,803
% of households below the poverty level[d]	26.04%	10.52%	30.92%	11.08%
Median year structure built[d]	1964	1980	1999	1989
2018 Social Vulnerability Index[e]	0.96	0.75	0.91	0.83

[a] NOAA’s National Weather Service Precipitation-Frequency Atlas, 24-hour duration with 90% confidence interval.

[b] MRLC (Multi-Resolution Land Characteristic Consortium) – NLCD (National Land Cover Database) 2016 Land Cover (CONUS) (2019).

[c] U.S. Census – 2018 ACS (American Community Survey) 5-year Estimates, (2019).

[d] U.S. Census – 2014–2018 ACS (American Community Survey) 5-year Data Profile, & 2018 ACS 5-year Estimates, (2019).

[e] 2018 CDC/ATSDR (Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry) SVI Nationwide Comparison.

Table 3.

Standards for evaluating channel geometric properties in the study areas

County	Depth	Bottom width	Side slope (V/H)	Longitudinal slope (%)
Sunnyside (Harris County)[a]	1.5 ft–4 ft	>2 ft	1/2–1/3	>0.1
Rockport (Aransas County)[b]	NA	NA	< 1/4	NA
Hoehn (Hidalgo County)[c]	1.5 ft–6.5 ft	>3 ft	1/2–1/8	>0.1

[a] (Arthur L. Storey J, 1988; Arthur L.).

[b] (Aransas County, 2012).

[c] (Hidalgo County Planning, 2018).

Table 4.

Pass/Fail (P/F) Evaluation of Channel Geometric Properties in Sunnyside.

Street Block	Side	Bottom Width	Channel Depth	Front Slope	Back Slope	Longitudinal Slope
1	L	P	P	F	F	F
	R	P	P	F	P	P
2	L	P	P	P	P	P
	R	P	F	P	P	P
3–1	L	F	P	P	F	F
	R	P	P	P	P	F
3–2	L	P	P	P	P	F
	R	P	P	P	P	P
4–1	L	P	P	P	P	P
	R	P	P	F	F	P
4–2	L	P	P	F	P	P
	R	P	P	P	P	P
5–1	L	P	F	P	P	P
	R	P	F	F	P	F
5–2	L	P	P	P	P	P
	R	P	F	P	P	P
6–1	L	P	P	F	F	P
	R	P	P	F	P	F
6–2	L	P	P	F	P	P
	R	P	P	P	P	P
Frequency of Failure, %		4.4	17.4	34.8	17.4	26.1

Table 5.

Pass/Fail Evaluation of Channel Geometric Properties in Rockport.

Street Block	Side	Bottom Width	Channel Depth	Front Slope	Back Slope	Longitudinal Slope
7–1	L	P	P	P	P	F
	R	P	P	P	F	F
7–2	L	P	P	P	P	F
	R	P	P	P	F	F
7–3	L	P	P	P	P	P
	R	P	P	P	F	P
7–4	L	P	P	P	P	P
	R	P	F	P	P	P
7–5	L	P	F	P	P	F
	R	P	F	P	F	F
10–1	L	P	P	P	F	P
	R	P	F	P	P	P
10–2	L	P	P	P	F	F
	R	P	F	P	P	F
10–3	L	P	P	P	P	F
	R	P	P	P	P	F
10–4	L	P	P	P	F	P
	R	P	P	P	F	P
10–5	L	NA[a]	NA	NA	NA	P
	R	P	F	P	F	F
Frequency of Failure, %		0.0	23.1	0.0	34.6	42.3

[a] NA: Data not available.

Table 6.

Pass/Fail Evaluation of Channel Geometric Properties in Hoehn.

Street Name	Side	Bottom Width	Depth	Front Slope	Back Slope	Longitudinal Slope
Hoehn Dr	L	F	F	P	F	P
	R	F	P	P	P	F
Ivory St	L	F	P	P	P	F
	R	F	F	P	P	F
Levender St	L	F	P	P	P	F
	R	F	F	P	P	F
Indigo St	L	F	P	P	P	F
	R	F	P	P	P	F
Crimson St	L	F	P	P	P	F
	R	F	P	P	P	F
Russet St	L	F	P	P	P	F
	R	F	P	P	P	F
Ebony St	L	F	P	P	P	F
	R	F	F	P	P	F
Peach St	L	F	P	P	P	F
	R	F	P	P	P	F
Lilac St	L	F	P	P	P	F
	R	F	P	P	P	F
Frequency of Failure, %		45.0	10.0	0.0	2.5	42.5

Table 7.

Channel Capacity.

	Sunnyside		Rockport		Hoehn			
Channel Property	**m**[b]	**Median**	**m**[b]	**Median**	**m**[b]	**Median**	***p*-Value**	**Significance**[a]
Longitudinal Slope (%)	20	0.120	19	0.093	18	0.065	6.80E-12	***
Cross-sectional Area, ft^2	20	12.22	19	19.63	18	10.20	1.59E-08	***
Channel Capacity[c], ft^3 /s	20	$0.57/n$	19	$0.84/n$	18	$0.35/n$	-	-
Capacity to Precipitation ratio (100-year storm)[c]	20	$0.03*n$	19	$0.06*n$	18	$0.03*n$	0.029	***
Capacity to Precipitation ratio (10-year storm)[c]	20	$0.06*n$	19	$0.11*n$	18	$0.06*n$	0.031	***
Capacity to Precipitation ratio (100-year storm)[c]	20	$0.11*n$	19	$0.17*n$	18	$0.10*n$	0.035	***

[a] $p < 0.01$: ***, $p < 0.05$: **, $p < 0.1$ *.

[b] m: Number of ditch sections.

[c] n: Manning's Roughness Coefficient. All studied channels have similar surfaces (earth, straight, and uniform surface with short grass). Therefore, the channel capacity and capacity-to-precipitation ratio are expressed in terms of n.