DATA-DRIVEN INSIGHTS FOR COASTAL WATER INFRASTRUCTURE RESILIENCE IN NORTH CAROLINA

by

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Abstract

Many towns and cities in North Carolina face growing obstacles in maintaining their stormwater systems. Aging infrastructure, limited budgets, and increasing storm risks challenge local governments to keep systems working and in compliance with environmental regulations (ASCE, 2025; Hunt, 2025; Institute for Emerging Issues, 2024). This study aims to identify how environmental and community factors are linked to stormwater system compliance and whether these risks align with investment prioritization by local leaders. Data were analyzed using interdisciplinary geospatial and statistical methods, including multiple regression and spatial lag modeling, to identify patterns between environmental risks, community characteristics, and stormwater compliance outcomes. The dependent variable captures the average percentage of quarters with stormwater violations from 2023 to 2025, reflecting persistent compliance challenges across counties. Findings revealed that environmental risk factors were not statistically significant predictors of compliance. Instead, urban classification and spatial dependence emerged as the strongest indicators of variation. Interviews with practitioners emphasized decision-making, prioritization, and resource constraints as central factors. Combining data and professional experience, this study offers a more complete understanding of system performance and management-level decision-making in North Carolina's communities.

Keywords: *stormwater infrastructure, management, data, North Carolina*

Introduction

The infrastructure of public and private structures that facilitate stormwater runoff is often invisible, where experts say that no signs are a sign of peak performance. Roads, ditches, and buildings are part of this stormwater system, along with water lines and local water bodies. Stormwater infrastructure minimizes flood risk and impact while also strengthening human connection, economic growth, and community health (Environmental Protection Agency, 2026). However, support for coastal water management infrastructure is a significant public management challenge in North Carolina. Many rural towns on North Carolina's coast are facing aging infrastructure, limited repair funds, and increasing environmental risks from flooding and storm events. These challenges not only strain local budgets but also pose significant public health risks that may be mitigated through improved water utility management. By leveraging existing resources in the office and the field, data-driven asset management can improve the resilience of these rural water systems.

When stormwater is improperly managed and monitored, damages, failures, and disruptions may occur. As the leading cause of urban water pollution, uncontrolled flooding degrades water quality and the environment (Weiss, Gulliver, and Erickson, 2007). The total number of miles of impaired rivers and streams in the United States has nearly doubled from 2010 to 2022, from 424,000 miles to over 703,000 miles, reflecting a trend of pollutant accumulation (ASCE, 2025). In dense areas, the failure of stormwater systems can easily interfere with interconnected communications, electricity, and public services. For example, residents trapped by road submersions suffer indirect economic losses from being unable to drive to work, not to mention the potential health hazards posed by waterborne *Vibrio* and *Staph* infections and gastrointestinal illnesses (Allen et al., 2018; Tasnia et al., 2025). Following exposure to these pathogens, stagnant floodwater causes further issues of mold growth, late-season mosquito blooms, and psychological harm among victims (Allen et al., 2018). These pressures are most acute in rural and under-resourced areas, where financial distress and systemic inequities leave vulnerable populations disproportionately exposed to environmental hazards and prolonged recovery periods (IPCC, 2023).

By leveraging existing data from the Environmental Protection Agency (EPA), the Federal Emergency Management Agency (FEMA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Census Bureau, this study aims to identify environmental and regulatory indicators that affect compliance outcomes in order to guide more proactive and cost-effective maintenance decisions. Rather than focusing on individual assets or permits, this project evaluates stormwater system performance at the county level to make recommendations for local government managers and policymakers. It will answer the questions of which environmental and institutional factors are associated with stormwater compliance and how risk factors align with the priorities of local managers. These results will provide a data-driven foundation to support more proactive, equitable, and cost-effective stormwater infrastructure planning in coastal North Carolina.

Stormwater Management in North Carolina

With water and wastewater, stormwater management plays a central role in sustainable development and environmental protection across North Carolina. Stormwater is defined as water that originates from rain and melted snow or ice that travels over ground-level surfaces (ASCE, 2025). Any precipitation that travels from the atmosphere to a water body without treatment can be considered stormwater. Although there is no national database of stormwater infrastructure, estimates indicate 3.5 million miles of storm sewers, 270 million storm drains, and 2.5 million stormwater treatment assets in the United States (ASCE, 2025).

Stormwater Infrastructure Challenges

Aging water infrastructure poses a widespread challenge across the United States, with the American Society of Civil Engineers (ASCE) estimating that $983 billion in investment into wastewater and stormwater will be required to have a "system-wide state of good repair" (ASCE, 2025). Rural systems are particularly vulnerable due to small customer bases, limited technical capacity, and chronic underinvestment relative to their urban counterparts. In coastal North Carolina, vulnerabilities are exacerbated by sea-level rise, saltwater intrusion, and stormwater surges, which accelerate pipe degradation and increase contamination risks (NCDEQ, 2023). Increased urbanization, combined with climate-driven changes in rainfall, is an additional risk factor in the rapidly growing state.

Stormwater management systems (SMS) across the United States face significant pressures that threaten their long-term functionality, particularly in communities with limited structural or financial resources. More than 60% of stormwater utilities identify aging infrastructure as a critical challenge to maintaining functional systems (ASCE, 2025). This issue involves an additional time-sensitive element, given the simultaneous increases of urban development and the incidence of major storm events; "As the area covered by impervious surfaces expands at a rate of 1% every five years, impacts of stormwater runoff increase and can lead to urban flooding" (ASCE, 2025). The average household bill for stormwater expenses has increased, along with rising capital and maintenance costs, but not enough to completely meet funding needs. Nearly a third of the utilities polled by Black & Veatch in 2021 reported that their current funding is inadequate for basic operation and maintenance (ASCE, 2025).

Urban drainage structures have largely been designed based on historical storm events without adjusting for recent climate adaptations (Hathaway et al., 2023). This network of curbs, gutters, and millions of miles of pipes is known as “gray” infrastructure. It is an element of stormwater control measures (SCM) designed to transport stormwater from impervious urban areas to local water bodies (EPA, 2025). As urbanization increases with current population trends and developing cities, natural infiltration through vegetation is less common. Aging infrastructure causes maintenance and repair issues when decades-old pipes that were never inventoried begin to fail. The backlog of necessary maintenance has grown significantly, and deferring repairs only increases the likelihood of flooding and poor water quality (ASCE, 2025).

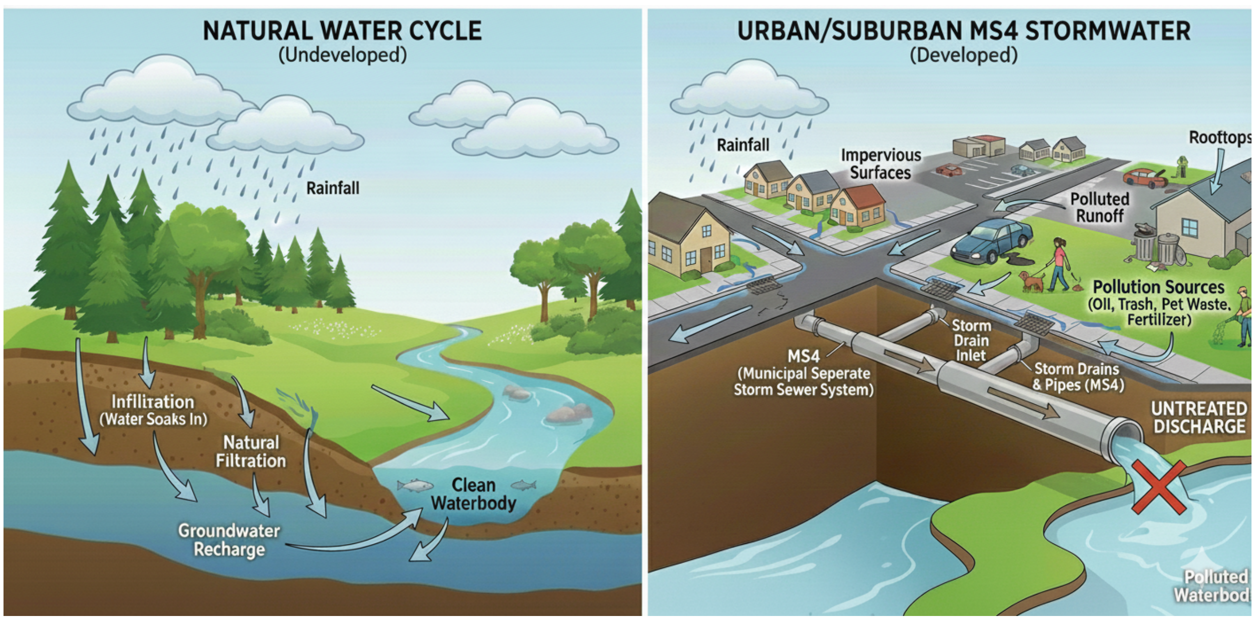

Figure 1. Urban vs. Rural Stormwater Management.
Source: Susquehanna Township (2026)

One of the greatest shortcomings of gray infrastructure is its limited adaptability compared to the evolution of natural watersheds, as shown in Figure 1 (Chen et al., 2023; Hathaway et al., 2023). One manager in North Carolina noted, “Stormwater lags, 20 to 50 years behind other buried infrastructure, in folks even valuing and placing the importance on that system." While municipal separate storm sewer system (MS4) stormwater infrastructure was developed to be "out of sight, out of mind" in congested urban spaces, it does not account for the accumulation of contaminants as the distance between initial runoff and the water body increases. Green infrastructure has been popularized to fill this gap, as it is intended to reduce stormwater travel and production. In some land-planning and engineering contexts, these practices are referred to as "low-impact development" (LID), which falls under the umbrella of green infrastructure (EPA, 2026, "Nonpoint"). Adopted widely, LID can be implemented to treat stormwater in ways that work alongside nature and take advantage of a watershed's natural ecological and hydraulic processes.

Some of these practices include permeable paving to allow rainfall to reach the soil, rain gardens and swales to slow water flow and trap pollutants with vegetation, and tree pits or passive irrigation to reduce runoff into local systems (Global Designing Cities Initiative, 2026; see Figure 2). Increasing green spaces in urban areas has been proven to provide vast community benefits, from cleaning waterways and reducing erosion to cost savings by including stormwater maintenance in capital improvement projects (EPA, 2025). Furthermore, human health is improved by urban greening, findings which are supported by the "Green Cities: Good Health" research collection (University of Washington, 2018). When an area's infrastructure is reliable, there is greater community building, job opportunities, and crime prevention. Despite its potential, there is hesitancy to widely implement green stormwater infrastructure (GSI) to ensure equitable outcomes and long-term solutions (Taguchi et al., 2020). This doubt is a result of unintended social, ecological, and human health consequences often overlooked in planning.

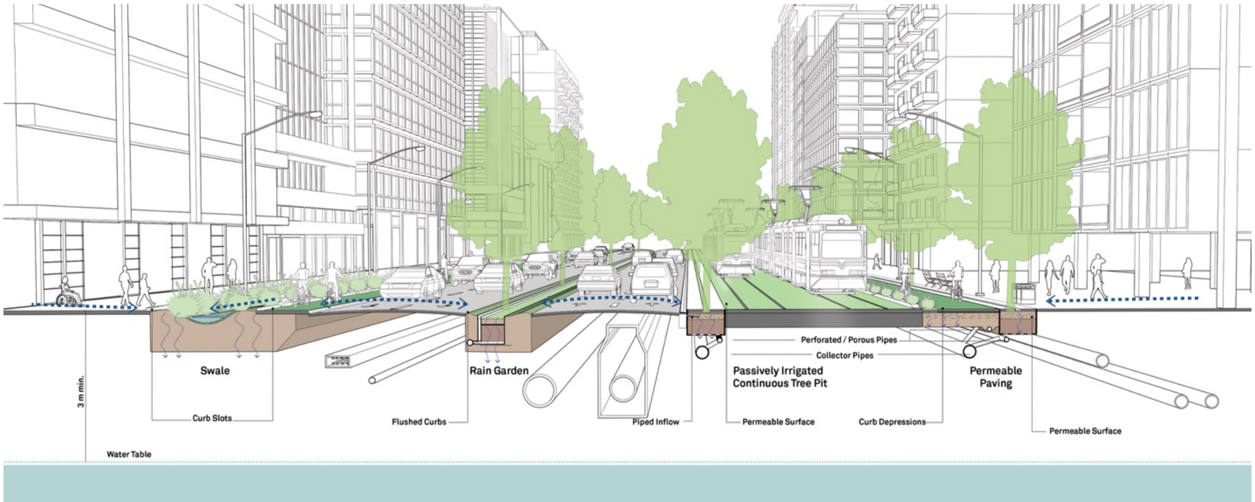

Figure 2. Green Water Infrastructure.
Source: Global Designing Cities Initiative, Global Street Design Guide (2026)

Data reporting and monitoring requirements for stormwater and public water systems in the United States are generally scaled to population size (NCDEQ, 2025). Namely, larger populations require more frequent monitoring and reporting to their state-level regulatory bodies and the Environmental Protection Agency (EPA) at the federal level to ensure safety and regulatory compliance. Reporting requirements vary based on which entity holds primacy as the designated authority to run a Public Water System Supervision (PWSS) Program (EPA, 2025).

Under the Safe Drinking Water Act of 1974 (SDWA), states, tribes, and territories may seek EPA approval to administer their own programs. Most states, including North Carolina, have primacy over their jurisdictions and submit data quarterly to the EPA's Safe Drinking Water Information System (SDWIS) and its Fed Data Warehouse (NCDEQ, 2025). Violation thresholds can change based on the number of samples required, which is also a proxy for population size. For example, one positive result for coliform bacteria in a small system (fewer than 40 samples per month) is classified as a violation. However, large systems should classify violations as occurring in more than 5% of the 40 or more monthly samples (NCDEQ, 2025).

Based on the EPA's Enforcement and Compliance History Online (ECHO) database, a violation can be categorized as: Release, Dump/Buried, Spill, Spray, Fill, or Falsified. These ensure that stormwater is in compliance with environmental laws and regulations, namely the Clean Water Act of 1972 (EPA, 2026, "Summary"). A "Release" is any unauthorized discharge of pollutants, such as construction runoff or wastewater infiltration. "Dump/Buried" refers to the illegal disposal of waste materials either in ditches or on-site. A "Spill" is an accidental release of liquid pollutants that can enter waterways via stormwater. "Spray" often comes from everyday practices and can involve pesticides and runoff from pressure washing. "Fill" involves blocking waterways or drainage systems with unauthorized material (soil, debris). Based on the EPA violation report submission form, "Falsified" includes tampering or misrepresenting "documents, permits, certifications, or any other records required by environmental statutes" (EPA, 2026). Falsification may also include not following best management practices as outlined.

The EPA determines reporting complexity by categorizing municipal separate storm sewer systems (MS4s) into two population-based phases. Phase I MS4s represent medium and large cities or counties with populations of 100,000 or more. These systems are subject to more rigorous requirements; for instance, approximately 63% of Phase I systems have developed formal stormwater asset management plans (ASCE, 2025). Phase II MS4s are smaller systems in urbanized areas, such as smaller cities, public universities, or hospitals. Only about 35% of these smaller systems have implemented asset management plans, and they generally have lower emergency response planning rates (29%) than their larger counterparts (ASCE, 2025).

Data-Driven Methods in Stormwater

From a management perspective, data-driven asset management has emerged as a strategy for improving the resilience and cost-effectiveness of public utilities. Predictive analytics allow utilities to forecast failures and optimize maintenance schedules, but rural agencies often lack the resources or data infrastructure to implement such tools (NCDEQ, 2024). Recent advances in open environmental and regulatory data, particularly with the EPA's stormwater compliance records, FEMA floodplain mapping, NOAA storm event databases, and the National Land Cover Database (NLCD), create new opportunities for local governments to apply these approaches on a statewide scale.

This paper addresses a gap in the literature around how state-level environmental datasets can serve as proxies for local asset conditions in under-resourced jurisdictions. Prior studies have modeled failure risk using utility-level data (Kleiner & Rajani, 2001). Still, few have integrated regulatory outcomes, environmental exposure, and institutional capacity to assess system-wide vulnerability in coastal contexts. Government and academic work increasingly integrates geospatial and equity-focused analyses; GeoAI and digital twin modeling have been used to assess flood impact in projects led by researchers in North Carolina (Tasnia et al., 2025). By combining environmental data science, geospatial analysis, and public administration theory, this study connects coastal communities to realistic, data-based solutions.

Governance & Management

Local governments often prioritize infrastructure investments based on urgency, necessity, and political considerations rather than purely technical risk assessments (IPCC, 2019; Kleiner & Rajani, 2001). High-traffic assets, like major bridges or critical economic corridors, are frequently favored over the routine maintenance of aging systems, which results in significant project backlogs. Compliance is limited by funding gaps and acute workforce shortages in specialized roles, such as dam inspectors, transit operators, and water technicians (ASCE, 2025). Political constraints, including the inability to raise federal and state user fees or the risk of assistance becoming taxable income for residents, further complicate long-term regulatory adherence (ASCE, 2025).

Governance frameworks utilize collaborative platforms and “backbone organizations” to act as strategic intermediaries, facilitating vital coordination between public agencies and private consultants or stakeholders (Ansell & Gash, 2018). However, effective interagency coordination is often challenged by divergent institutional responsibilities and siloed planning processes that prevent integrated risk management (Allen et al., 2018). Literature reveals that inclusive community engagement and the co-production of knowledge are essential to improve public understanding of inconspicuous hazards. Without proactive outreach, public expectations—such as the belief that roadway expansion will permanently reduce congestion—may not align with actual environmental and systemic risks.

Significant capacity gaps exist between jurisdictions; rural areas are disproportionately “financially distressed” and lack the extensive ratepayer base needed to spread costs, leading to lower adoption of formalized asset management plans. In contrast, while large urban areas often possess greater technical resources, they more often face failures during extreme events due to dense and interdependent networks (ASCE, 2025).

Methodology

This project uses publicly available datasets from federal and state organizations to assess environmental and operational risk factors that threaten the resilience of rural water systems in coastal regions. By integrating stormwater violation data, floodplain exposure, storm events, land cover characteristics, and institutional capacity indicators, the study identifies priority areas for infrastructure investment and resilience planning. These findings provide a data-driven foundation for local governments to align their infrastructure improvement priorities with environmental risks and regulations.

Applicable research questions include, “What environmental and institutional factors are associated with stormwater system compliance outcomes in North Carolina counties?” and “How do these risks align with infrastructure prioritization decisions made by local managers?”

This study uses the county as its unit of analysis within North Carolina. This state serves as a generalizable frame of reference for other states, given its diverse geography. From mountains to coast, as well as its agricultural centers and urban centers, patterns identified in North Carolina can easily be applied to similar areas across the country. The dependent variable is stormwater compliance performance, operationalized as the presence or count of stormwater-related regulatory violations. An average percentage of quarters with violations over a 3-year time period (“mean_violation_totalpctn”) serves as the primary dependent variable because it is normalized and comparable, accounting for the differences in the number of facilities between North Carolina counties of various sizes and populations.

Some violations do not cause severe environmental impacts like oil spills and may be ‘administrative’ in nature. However, tracking all types of these violations is essential because they may signal systemic causes of more severe compliance failures. By including all violations, the study ensures a fair comparison across counties with varying numbers of facilities while identifying patterns of poor governance that could worsen environmental risks over time.

The first set of independent variables serves as the environmental exposure indicator, and it is represented by floodplain coverage, storm events, and impervious surface coverage. The second set comprises indicators of institutional capacity, as shown by population size and urban classification. These variables, as outlined in Appendix A, serve as proxies for countywide system stress and environmental exposure, which may influence overall compliance outcomes and infrastructure performance.

H1: Counties with greater floodplain coverage and higher storm events are more likely to experience stormwater compliance violations.

H2: Larger and urban counties are more likely to experience stormwater compliance violations than smaller and rural counties.

H3: Counties with higher impervious surface coverage are more likely to experience higher stormwater compliance risk.

Stakeholders

This research is intended to inform public managers, engineers, and policymakers who are responsible for firsthand stormwater infrastructure planning and regulatory compliance. Key stakeholders include city and county managers, public works directors, stormwater utility staff, including engineers and surveyors, regional planners, and state regulatory agencies. North Carolina residents and outside visitors are also important stakeholders, as they frequently come into contact with stormwater infrastructure across the state through daily interactions and are often most aware of the gaps in maintenance and repair. One manager recognized, "In terms of public services staff, it's not necessarily an engineer who is seeing all of it."

Primary stakeholder engagement occurred through interviews in the form of short oral surveys conducted with individuals from the Future Forward Water Infrastructure Forum and the North Carolina City and County Managers Association Winter Conference, as outlined in "Methods". With these engagements, stakeholder responses reflect practitioner perspectives on prioritization criteria, perceived drivers of stormwater-related risk, barriers to compliance, and alignment or misalignment between data-based risk indicators and real-world decision-making.

This qualitative component ensured more realistic and applicable solutions, accounting for individual experience and perspectives within North Carolina communities throughout the study.

Dataset Description

The quantitative data used in this study are drawn entirely from public and preexisting datasets. Aside from the relevance to this research, the following datasets were selected for their accessibility and municipal-level aggregation. Compliance records from federal agencies and public spatial data reflect the current state of stormwater and wastewater systems in North Carolina. Additionally, they are current and comprehensive within a bounded timeline, meeting the needs of this research study.

Municipal stormwater violation records were obtained from the U.S. Environmental Protection Agency's (EPA) Enforcement and Compliance History Online (ECHO) database. While most data for ECHO is extracted weekly, compliance data is extracted from the Safe Drinking Water Information System (SDWIS) and updated every three months. Compliance data for the following analysis (CWA_13QTRS_COMPL_HISTORY) was downloaded on January 24, 2026, and includes thirteen (13) quarters, three years plus three months, derived from the Quarterly Noncompliance Report (QNCR) Code. Violations vary from environmental pollution to managerial shortfalls, but this study uses the standard EPA definition of a violation. It does not distinguish between violation type (e.g., falsification versus spill), only violation incidence.

The list includes the following values: S = Significant Noncompliance, V = Violation Identified, U = Unknown, and _ = No Violation Identified, using the aforementioned order to determine priority where multiple permits are present (ECHO, 2026). All elements of the dataset were updated between July 16, 2025, and January 24, 2026, and data were cleaned using Statistical Analysis Software (SAS). The dependent variable was calculated in a couple of steps.

First, I found the percentage of quarters within a three-year period during which each facility had violations using only S and V. A smaller percentage indicates a smaller number of violations within a 3-year period. Then, for each county, I found the average percentage of quarters where facilities in that county were in violation.

The Federal Emergency Management Agency (FEMA) operates a National Flood Hazard Layer (NFHL) that provides spatial floodplain boundaries, downloaded as S_FLD_HAZ_AR. This database includes A, AE, AH, and AO, which are all part of the "A" zones, or high-risk areas. These zones were consolidated along with VE, the most critical zone designation in the NHFL due to the added danger of storm-induced velocity waves. Using this single variable for the total square miles of flood zone area by county, we found the percentage of total county area classified as a flood zone. This percentage was the floodplain variable used for visualization and to calculate the risk of stormwater compliance violations within flood-prone zones.

The National Oceanic and Atmospheric Administration's (NOAA) Storm Events Database provides county-level storm event counts, which will be used as a proxy for flood exposure in North Carolina counties. Any storm events between January 1, 2023 and December 31, 2025 were downloaded and included in this variable if they contained one of the following flood categorizations: "Flood" (n = 94), "Coastal Flood" (n = 28), "Lakeshore Flood" (n = 0), or "Flash Flood" (n = 724). The final storm event variable included a total of 846 flood events, with at least one event in 94 out of the 100 counties.

The National Land Cover Database (NLCD) provides percent impervious surface data, with every pixel representing 900 square meters of land area. This dataset aggregated Fractional Impervious Surface Data values to county boundaries and incorporated them into geospatial visualization and analysis. Two raster layers, made of pixels as opposed to vector images, were created for geospatial data within North Carolina state lines and coded based on average impervious surface from zero to one hundred percent; one colored by individual pixel and the other colored by county average. This variable was coded using a 20% threshold; all pixels where impervious surface area was 20% or less were recorded as zero (0%), and all pixels where impervious surface area was over 100% was recorded as a missing value and known error.

Finally, the institutional variables were obtained from the U.S. Census Bureau. These included measures of community capacity: population size and the urban classification of a county. The population variable was used as a raw count by county from the 2024 Census data. Urban designations were drawn from the U.S. Office of Management and Budget (OMB). Their definitions are consistent with United States Census data and distinguish between land and population recorded either inside or outside of incorporated municipalities (U.S. Census Bureau, 2025). Counties were assigned ordinal numerical values of 1, 2, or 3, corresponding with metropolitan, micropolitan, and non-core, respectively. An alternative model was also analyzed that treated urban classification as a categorical variable for metropolitan, micropolitan, and non-core. Metropolitan or urban counties have populations over 50,000 people; micropolitan counties have over 10,000 but fewer than 50,000; and non-core or rural counties have fewer than 10,000.

Table 1: Descriptive Statistics Per County

Variable	Mean	SD	Median	Min	Max
Quarters with violations	0.06	0.04	0.05	0.02	0.20
Impervious surface	0.03	0.36	0.01	0.02	0.22
Flood zone	0.13	0.12	0.09	0.01	0.59
Flood events	8.46	10.59	5.00	0.00	79
Population	110,460	185,701	52,768	3,517	1,232,444
Urban classification	1.84	0.85	2	1	3

N = 100

Table 1 summarizes descriptive statistics for all variables included in the analysis (N = 100). The dependent variable, mean percent of quarters with stormwater violations, has a mean of 0.06, with values from 0.02 (2%) to 0.20 (20%) and moderate variation. Impervious surface coverage ranges from 1.5% to 22.43%, with a relatively low median (1.33%), suggesting a right-skewed distribution in more urban areas. Flood zone coverage is low on average (mean = 0.13), with some counties experiencing substantially higher exposure. Flood events show the most variability, with a mean of 8.46 flood events and a maximum of 79 flood events, indicating that certain counties experience significantly more floods and related stress.

Population also varies considerably, with a mean of approximately 110,000 and a median of 52,768. This data reflects the composition of North Carolina, with several highly populated counties alongside many smaller jurisdictions. Urban classification has a median of 2, indicating primarily mid-level urban counties in the state. These patterns highlight great variation in environmental exposure and community characteristics, providing a basis for examining how these factors relate to stormwater compliance outcomes in the subsequent analyses.

FAIR Principals

The datasets used in this research comply with FAIR data principles, meaning that they are all findable, accessible, interoperable, and reusable in support of good stewardship of scientific data management. To ensure adherence to FAIR data principles, the secondary databases used are open source. Primary source data and the final manuscript will be entered into *ScholarShip*, East Carolina University’s data repository for university-affiliated work.

Methods

This project applied a mixed-methods, interdisciplinary data analytics approach, in accordance with Exempt Certified research studies by the East Carolina University & Medical Center Institutional Review Board under submission UMCIRB 26-000293.

Geospatial analysis was conducted using QGIS and GeoDa software. QGIS overlaid municipal boundaries with FEMA floodplains and impervious surface data. It performed calculations to compare floodplain coverage and impervious surface in each county. QGIS visualized spatial patterns of stormwater violations and environmental exposure and was also used to produce static maps as visual outputs for further science communication. Meanwhile, GeoDa supported exploratory spatial data analysis (ESDA), including Moran's I to test for spatial autocorrelation in stormwater violations. This software was used to find Local Indicators of Spatial Association (LISA), identifying spatial clusters of high or low compliance risk. These analyses determined whether stormwater compliance outcomes were spatially clustered or randomly distributed across North Carolina. In doing so, we ensured that geographic transformation was accounted for and that all points were projected to the same level.

Geospatial and data visualization techniques were used to display spatial patterns of compliance and environmental risk and support the interpretation of relationships between variables. Datasets were downloaded and cleaned, standardized by county, and relevant to the three-year span of approximately January 2023 to December 2025. These maps will also be useful to communicate results to non-expert audiences, including many of the stakeholders themselves. Visual outputs will include maps, scatterplots, and regression models.

Statistical modeling assessed the relationship between stormwater compliance outcomes and environmental and institutional predictors. Multiple regression was used to estimate the probability that a county experiences one or more stormwater violations based on floodplain coverage, storm events, impervious surface coverage, population size, and urban classification. These statistical models identified significant predictors of stormwater compliance risk and quantified their impact.

Semi-structured interviews were conducted with stakeholders from the North Carolina City and County Managers Association (NCCCMA) Winter Seminar on January 28th and January 29th, 2026, in Winston-Salem, North Carolina, as well as the Future Forward Water Infrastructure Forum (FFWIF) on February 25th, 2026, in Morehead City, North Carolina. While several interviews were completed in person, most interviews were completed online via telephone call or Microsoft Teams meeting. Each interview was preceded by an acknowledgement of the IRB Consent Letter for Expedited Survey Research (Appendix B). Those who were recorded gave verbal and/or written consent, followed by the questions as outlined in Appendix C, tailored as needed to the individuals' experience and responses.

A thematic analysis of these conversations provided qualitative data on infrastructure prioritization practices and risk perception. See Appendix C for the interview instrument and Appendix D for the anonymized list of interview participants' roles and organizations. Responses were coded using deductive (based on the literature) and inductive (based on the data) approaches to identify common prioritization criteria, perceived barriers, and divergences between data-based risk indicators and practitioner experiences. This mixed-methods design allowed quantitative findings on stormwater compliance risk to be compared with and presented alongside qualitative insights. Integration assessed whether municipalities experiencing higher modeled risk also report greater infrastructure challenges or different prioritization strategies, strengthening the study's applied relevance and interpretive depth.

Visualization & Results

Following the identification, collection, and cleaning of all datasets, five independent variables were used to summarize the spatial distribution of compliance events. Maps below display the distribution of environmental and institutional risk factors: storm events, flood zone, impervious area, population, and urban classification. Initial modeling was completed in ArcGIS, and additional maps were created in QGIS (Figures 3-9). Subsequent statistical and geospatial analysis was conducted using GeoDa before final visualization (Figures 10-12 and Tables 2-4).

Geospatial Analysis

Based on preliminary geospatial visualizations, the highest density of violations is concentrated in the Raleigh-Durham and Charlotte metropolitan areas. While Figure 3 represents the location of each of the individual stormwater violations, the independent variable used in statistical analysis was adapted to be an average per facility to account for the greater number of facilities in larger counties, as visualized in Figure 4.

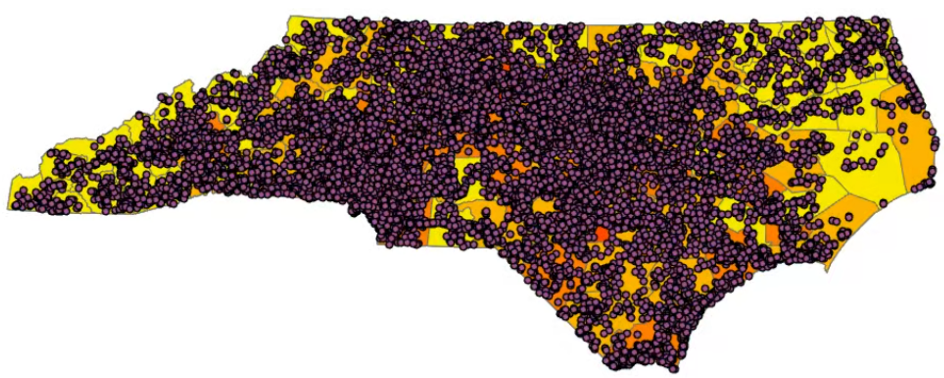

Figure 3. Locations of Reported Violations (n = 23,211).
Source: ECHO, October 2022—December 2025

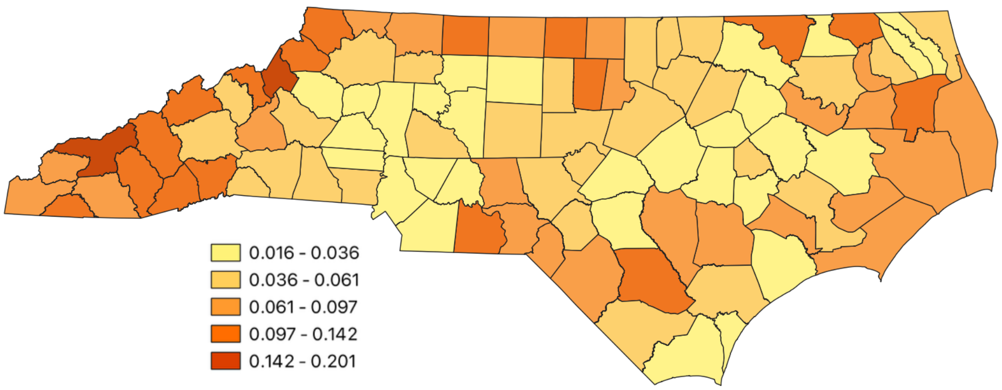

Figure 4. Average Stormwater Violations Per Facility.
Source: ECHO, October 2022—December 2025

The choropleth maps in Figure 5, Figure 6, Figure 7, and Figure 8 use graduated natural breaks (Jenks) into five classes as the classification method. This ensures that class variance is minimal while the variance between classes is maximal. While the majority of counties experienced between one (1) and 36 flood events between 2023 and 2025, Wake County was an outlier, as seen in central North Carolina in Figure 5. Out of 79 total flood storm events, all but two of those reported in Wake County were categorized as "flash floods" (n=77).

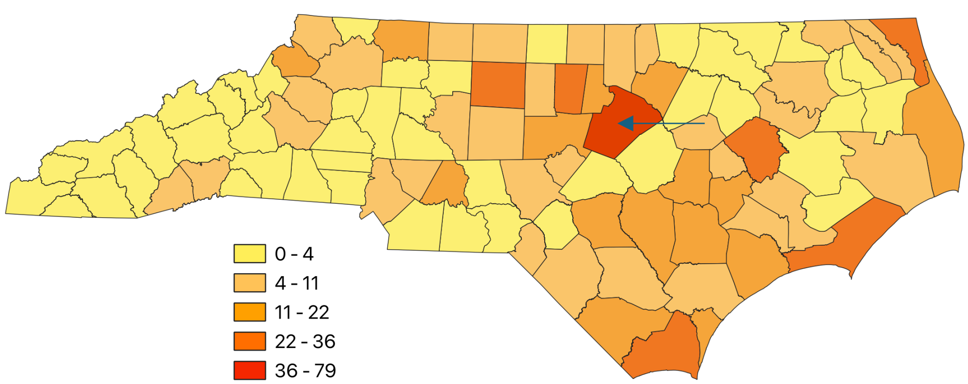

Figure 5. Total Count of Flood Storm Events.
Source: NOAA, January 2023—December 2025

There is a clear gradient pattern in the percentage of county area in the flood zone (see Figure 6). The percent flood zone steadily decreases from east to west, with a slight jump in the foothills of the Appalachian Mountains. Coastal counties of Currituck** (59%), Carteret**** (56%), Tyrrell*** (55%), and Camden* (47%) have a noticeably higher flood zone percentage. This variable was visualized as an average of the total county area to account for size variation.

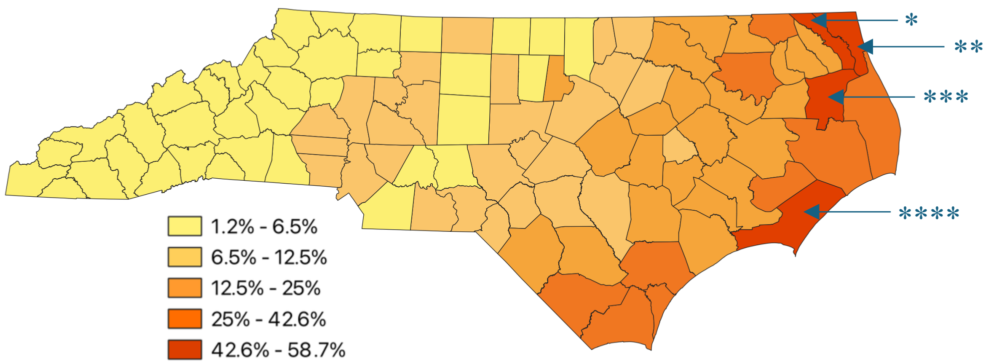

Figure 6. Percent of County Area in Flood Zone.
Source: FEMA NFHL, 2026

Meanwhile, the impervious surface visualization from the NLCD's Fractional Impervious Surface Data shows a more even distribution across North Carolina counties (see Figure 7). New Hanover County in the southeast was the only coastal county to demonstrate a relatively high percentage of impervious land area at nearly 17.2%. Another outlier was Mecklenburg, with elevated percentages of impervious land area in all surrounding counties with a shared border.

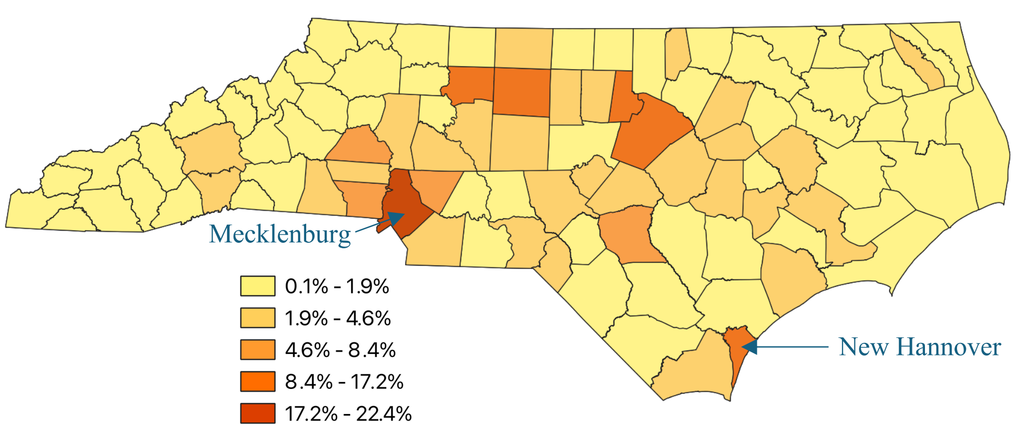

Figure 7. Average Percent Impervious Land Area.
Source: National Land Cover Database, 2024

The population map in Figure 8 follows a similar visual pattern to Figure 7. A comparison of the spatial distribution between impervious land area and population shows overlapping regions of high intensity, specifically in Mecklenburg and Wake counties. The population variable was mapped by raw count based on numbers from the 2024 U.S. Census.

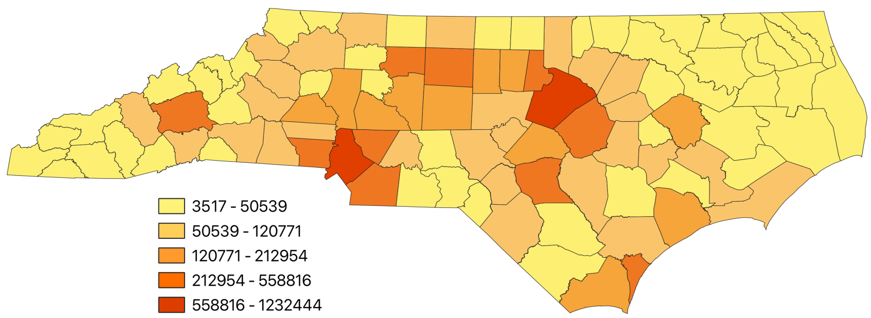

Figure 8. Population. *Source: U.S. Census, 2024*

The second non-environmental independent variable, urban classification, was visualized in Figure 9 and coded under three classes. Both shades of purple represent urban counties as classified by the U.S. Census and the federal Office of Management and Budget (OMB); yellow counties are classified as non-core, rural counties. Interestingly, there were no standalone metropolitan counties, but seven non-core counties had one or no shared borders with a fellow non-core county, in no particular pattern, across the state.

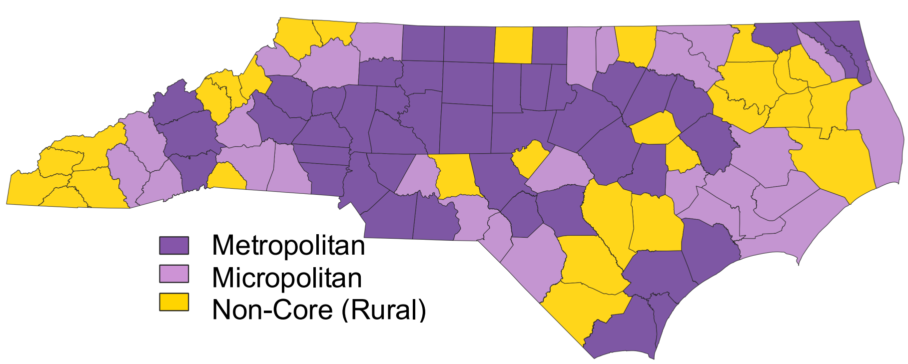

Figure 9. Urban Versus Rural Classification.
Source: OMB Definitions, 2023

Statistical Analysis

A multiple regression analysis was conducted to examine whether impervious surface, flood zone, flood events, population, and urban classification predicted compliance violations (Table 2). The overall multiple regression model (MRM) was statistically significant, $R^2 = .24$, adjusted $R^2 = .20$, $F(5, 94) = 5.89$, $p < .001$. Together, the five predictors accounted for 19.8% of the variance in stormwater violations. Urban classification was the strongest predictor of violations, $b = 0.014$, SE = 0.00, $t(100) = 3.07$, $p < .05$, 95% CI [0.005, 0.022]. The positive coefficient suggests that urban counties have a positive relationship with violation incidence. While the multicollinearity condition number was low, 8.35, the Jarque-Bera test result of 24.35 indicates that the residuals are not normally distributed ($p < .00001$). An alternative model was analyzed that treated urban classification as a categorical variable. No substantive changes in results were found. Compared to non-core (rural) counties, metropolitan counties have 2.8% fewer stormwater compliance violations, and micropolitan counties have 1.7% fewer violations.

Table 2: Multiple Regression Model

Variable	*b*	*SE*	*t*-Statistic	Probability
Constant	0.048	0.011	4.364	<.001
Impervious surface (%)	-0.003	0.002	-1.345	.182
Flood zone (%)	-0.041	0.029	-1.376	.172
Flood events	0.000	0.000	0.867	.389
Population	0.000	0.000	-0.263	.793
Metropolitan v. rural	-0.028	0.009	-3.082	.003**
Micropolitan v. rural	-0.017	0.009	-1.849	.068

* $p < .05$, ** $p < .01$

A univariate local indicator of spatial analysis (LISA) was first conducted on the raw dependent variable, revealing significant High-High clusters in the western mountainous region and Low-Low clusters in the central Piedmont (see Figure 10). Each LISA produced a cluster map that identifies hot spots, cold spots, and spatial outliers; the corresponding significance map highlighted how many of those patterns were statistically significant. While the central Low-Low clusters were weakened by the model's predictors, significant High-High clusters persisted in the west. The persistence of these significant clusters in the residuals ($p < .05$) confirms that the OLS model failed to account for all spatial dependence, justifying a spatial lag specification.

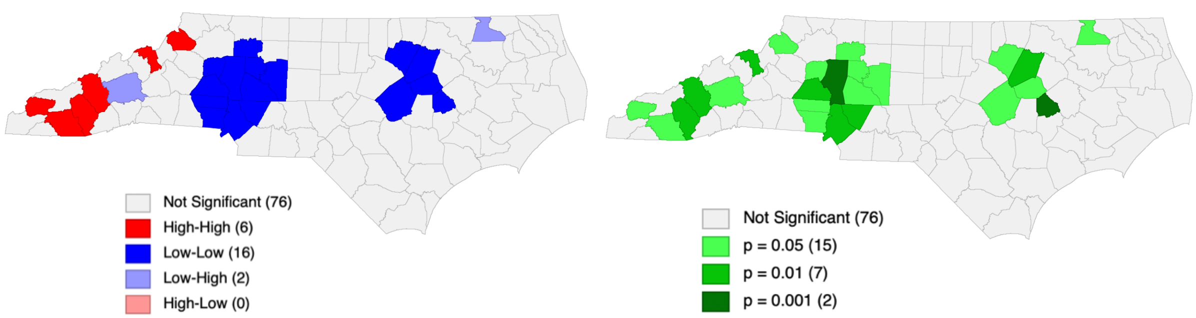

Figure 10. LISA Cluster Map (left) and Significance Map (right) of Violations.

After running the OLS regression, a second LISA was performed on the residuals using the Univariate Local Moran's I (see Figure 11). This map displayed the same three significant clusters, confirming that the MRM is missing a key variable to explain cluster behavior.

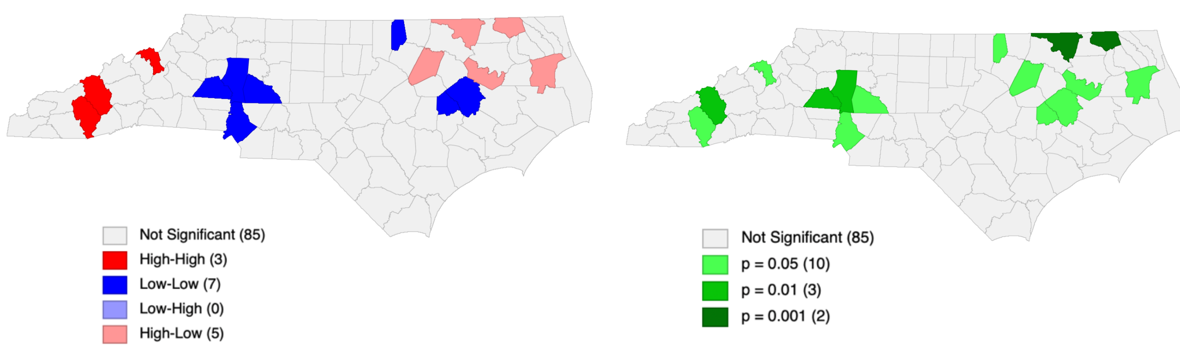

Figure 11. LISA Cluster Map (left) and Significance Map (right) of Residuals.

The Moran scatterplot of OLS residuals (Moran's I = .035) depicted in Figure 12 below indicates a weak global spatial autocorrelation, suggesting that while the model performs well on average across North Carolina, localized patterns of error may still exist. A spatial regression analysis was then conducted to determine if there was any bias from proximity to surrounding counties. Weight neighbors were defined using “queen” contiguity, in which observations share a boundary line or point. In other words, any county that shared an immediate border with another county was considered its neighbor.

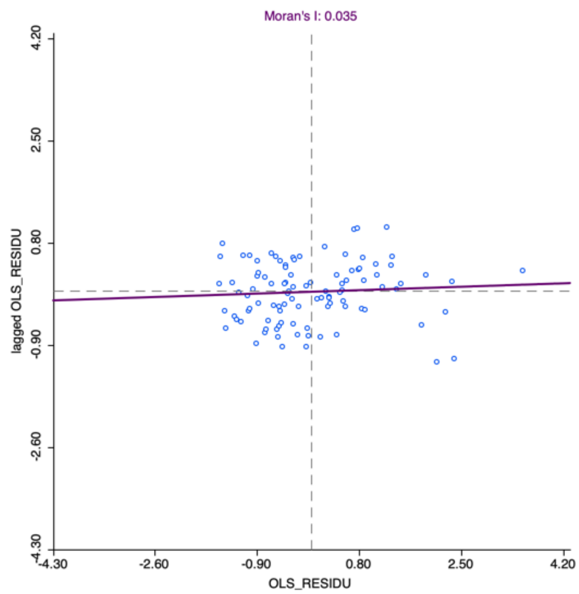

Figure 12. Moran Scatter Plot of Residuals.

Diagnostics for spatial dependence indicated significant spatial autocorrelation (Table 3). Although both Robust LM Lag (*p* = .002) and Robust LM Error (*p* = .015) were significant, the higher significance of the Robust LM Lag test suggests that a Spatial Lag Model is the most appropriate specification for this data. This indicates that in at least one county, the mean violations are influenced by a spillover effect from a neighboring county.

Table 3: Spatial Regression Results

Test	MI/DF	Value	Probability
Moran's I (error)	0.071	1.534	.125
Lagrange Multiplier (lag)	1	4.653	.031*
Robust LM (lag)	1	9.278	.002**
Lagrange Multiplier (error)	1	1.214	.271
Robust LM (error)	1	5.839	.016
Lagrange Multiplier (SARMA)	2	10.492	.005**

* $p < .05$, ** $p < .01$

The spatial lag (SLM) model was significant ($\rho = 0.26$, p = .043), shown in Table 4, confirming that geography was a missing variable in the initial MRM. The SLM was more statistically significant than the MRM, at $R^2 = .28$. The positive rho coefficient ($b = 0.261$) indicates that if violations increase in neighboring counties, the violations in the target county are likely to increase as well, and that they are not randomly distributed. While urban classification is still highly significant ($b = 0.011$, $p = .006$), it is slightly reduced in the spatial lag model to filter out spatial clustering effects. Impervious surface, flood zone, and population variables remained non-significant in both models, confirming that these factors truly do not have a linear relationship with stormwater compliance violations in North Carolina, even when accounting for neighborhood contexts.

Table 4: Spatial Lag Model

Variable	*b*	*SE*	z-Value	Probability
W_Violations (ρ)	0.261	0.129	2.028	**.043***
Constant	0.034	0.013	2.719	.007**
Impervious surface (%)	-0.002	0.002	-1.101	.271
Flood zone (%)	-0.035	0.028	-1.274	.203
Flood events	0.000	0.000	0.779	.436

Population	0.000	0.000	-0.340	.734
Urban classification	0.011	0.004	2.274	.006**

* $p < .05$, ** $p < .01$

Thematic Analysis

Over the course of five weeks, a total of ten (10) interviews were conducted with engineers, managers, and manager-engineers (individuals with professional experience as both a manager and an engineer). All participants were English-speaking, over 18 years of age, and employed in full-time positions within the state of North Carolina at the time of their interview. Interviews lasted between fifteen (15:00) and forty (40:00) minutes, with a median duration of 18:00 minutes. Codes were identified using notes and transcripts from each interview at the level of meaning units (N = 262). Each quote, whether a phrase or several sentences, was coded by meaning unit based on the applicable topic. If one meaning unit related to multiple topics, it was coded once for each topic. Twenty-six (26) meaning units were coded two times or more. A structured codebook (Appendix E) was maintained to ensure consistency throughout the process.

From these codes, five (5) themes emerged:

1. *Institutional capacity* refers to factors that influence the ability of local governments to implement and enforce stormwater programs, such as data capacity, financial constraints, inequality, staffing, and technical expertise: "The town of Belhaven… has to do the same as Charlotte, but with a fraction of the resources that the city of Charlotte would have."
2. *Environmental risk* is the potential for harm or damage to the natural environment. This theme includes the same environmental variables used in the quantitative analysis, including climate change, extreme weather events, flood exposure, impervious surface, and storm events: "As we move on, more municipalities will be

required to deal with stormwater whether they want to or not, because we're seeing it now, especially at our coast, groundwater levels are rising systematically, with more impacts from smaller storm events."

3. *Development pressure* is the demand and forces driving land or community growth and construction, like population and urban growth or land use change: "It's almost at the point where we've got to look at the state from an urban perspective and a rural perspective because the problems are so different."
4. *Governance* involves the system of rules, practices, and processes guiding authority and driving how important decisions are made, including stakeholders and their agendas. Decision-making, partnerships, political pressure, prioritization, public engagement, and reactive maintenance were categorized here: "It's out of sight, out of mind, as long as the water's not ponding in my street or on my yard," and "They address something when it tears over, when it breaks, or when a sinkhole opens up."
5. Finally, *compliance and enforcement* were identified as when participants spoke of ensuring adherence to laws and regulations through monitoring and penalties. Enforcement strategy and compliance challenges fell under this theme: "DEQ and the NPDES permitting has a requirement for that, but folks are still trying to get a complete and comprehensive system map."

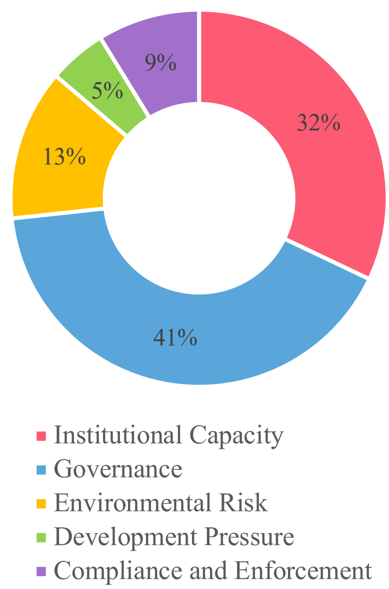

Figure 13: Emerging Themes.

Governance was most frequently mentioned for nearly every stakeholder (n = 108), followed by institutional capacity (n = 84), each theme accounting for over one-third of the total codes (Figure 13). To determine how individual roles might have influenced the most prevalent themes, raw counts for each code and their corresponding theme were then sorted by the type of individual from which they came (see Table 5). 80% of the interview participants held a fully or partially managerial role in their organization, yet this governance-centered pattern persisted even after excluding the five participants classified as managers alone. With only engineers and manager-engineers, 39% and 33% of codes fell into the "governance" and "institutional capacity" themes, respectively.

Out of the twenty-six (26) meaning units that had at least two unique codes each, "Governance" accounted for over 80% of the pairs. Codes that fell under the "Governance" theme shared a meaning unit with another code twenty-one (21) times. The most frequently occurring code in a pair was "decision-making", which occurred in eight pairs alongside "partnerships", "prioritization", and "public engagement". "Technical expertise" was the second most popular code, occurring in six pairs. Meaning units that were coded multiple times were also compared by theme. The most common pair was Governance-Governance themed codes (n = 5), with Governance-Capacity pairs following closely behind (n = 4).

Table 5: Pivot Table by Organizational Role

Themes & Codes	Manager & Engineer	Manager	Engineer	Total
Compliance and Enforcement	**5**	**14**	**4**	**23**
Compliance challenges	3	6	1	10
Enforcement strategy	2	8	3	13
Development Pressure	**1**	**9**	**3**	**13**
Land use change	1	4	2	7
Population/urban growth		5	1	6
Environmental Risk	**4**	**19**	**11**	**34**
Climate change		5	4	9
Extreme weather events	1	1	2	4
Flood exposure	2	8		10
Impervious surface		4	2	6
Storm frequency	1	1	3	5
Governance	**31**	**61**	**16**	**108**
Decision-making	7	18	5	30
Partnerships	4	9	5	18
Political pressure	2	4	1	7
Prioritization	9	21	3	33
Public engagement	4	5	1	10
Reactive maintenance	5	4	1	10
Institutional Capacity	**22**	**42**	**20**	**84**
Data capacity	8	14	6	28
Financial constraints	9	14	4	27
Inequality	1	3	3	7
Staffing	1		3	4
Technical expertise	3	11	4	18
Grand Total	**63**	**145**	**54**	**262**

Interview participants also rated the stormwater systems with which they worked for overall vulnerability (1 = Very low; 5 = Very high) and confidence in completeness (1 = Not confident; 5 = Very confident) using Likert scale responses (N = 9). Several individuals acknowledged the increased risk of vulnerability for coastal communities, and largely reported themselves as more vulnerable than not (*Mdn* = 4); one answered, "While we're not on the beach or the coast, which would be a five, I would put us between a three and a four." Over half of the respondents reported a low confidence in completeness (*Mdn* = 2). Interestingly, the only three respondents who rated their confidence level at 5 out of 5 were all managers in their roles.

A Pearson correlation was conducted to examine the relationship between perceived vulnerability and confidence in data completeness for each participant. Results indicated a moderate positive association ($r = 0.38$), suggesting that respondents who perceived higher levels of vulnerability also tended to report slightly higher confidence in data completeness. However, given the small sample size and ordinal nature of the data, this relationship is unlikely to be statistically significant and may be influenced by different institutional or governance factors.

Discussion

None of the environmental risk factors (flood exposure, flood events, and impervious surface) was a statistically significant predictor of stormwater compliance violations. Instead, urban classification and spatial dependence emerged as the strongest predictors of county-level variations, supporting only H2. Alongside interview findings, these data-driven results suggest that stormwater is not and should not be perceived as a purely environmental or technical challenge. Instead, effective stormwater management is a function of institutional capacity and administrative decision-making that varies based on a municipality's institutional capacity. Interview participants consistently emphasized decision-making processes, prioritization, and resource constraints as central factors to compliance outcomes.

Initial hypotheses predicted that environmental factors might be a unique limitation for coastal communities, but geospatial visualization revealed that these variables are common in urban cities as well. OMB was the standalone statistically significant predictor of stormwater violations ($p < 0.01$), likely representing key differences in urban and rural classification, including administrative capacity and regulatory scrutiny. Urban classification may therefore capture these factors not directly measured in the model, making it a stronger predictor of compliance outcomes than individual environmental variables.

Furthermore, spatial dependence indicates that stormwater compliance is not isolated within county boundaries. Violations in one county are influenced by conditions in neighboring counties, reflecting shared environmental systems, regional development patterns, and potentially overlapping governance practices.

The thematic analysis, particularly governance-related code pairings involving institutional capacity, suggests that decision-making processes and resource constraints are intertwined in shaping compliance outcomes. Environmental risk was rarely discussed in isolation, reinforcing the regression results that exposure alone is an insufficient explanatory variable. One interviewee noted, “It's not as science-driven anymore, it's more policy and need by these communities,” in reference to best management practices. There was a moderately positive association between perceived vulnerability and confidence in data completeness based on scored responses. This indicates that jurisdictions facing greater environmental risk may invest more heavily in data systems or possess greater institutional awareness of stormwater challenges. As another manager shared, “It’s one thing to know a pipe is there. It’s completely different to see the joint failure 50 feet under.” However, the low median value for confidence in completeness indicates that data limitations remain a widespread constraint for institutions.

Several supported and competing mechanisms were identified using a combination of the MRM results and thematic analysis of the same independent variables. First, the relationship between capacity and an increased average of violations indicated that urban complexity is accompanied by greater infrastructure stress, monitoring and reporting, and development pressure. Second, flood-prone counties were associated with fewer violations. This indicated that there may have been a greater opportunity for risk adaptation, meaning more learning, preparedness, or stricter regulation. Third, more flood events were associated with more violations. Interestingly, estimated flood risk and actual flood incidence had opposite effects. Predictable patterns without the strain allow counties to grow, while active infrastructure stress suggests that stormwater systems perform poorly when overwhelmed.

Table 6. Connecting Quantitative and Qualitative Results

Finding	Explanation
Nonsignificant flood risk	Systems are reactive, not risk-based
Nonsignificant population	Capacity ≠ size; small areas struggle
Weak impervious factor	Data gaps limit planning
Significant institutions	**Governance + funding = outcomes**

Interviews with engineers, managers, and state officials contextualized both of these weak predictors and stronger institutional cues (see Table 6). Counties with greater urban and administrative complexity exhibit more violations. Flood exposure may be associated with improved compliance, while repeated flood events may strain infrastructure capacity. As a whole, the most prevalent themes pertained to governance and management, even among non-manager participants. Individuals who emphasized environmental risk also tended to reference governance constraints, suggesting that exposure does not necessarily determine outcomes. In the engineering world, "We say, 'There's always a storm with your name on it. All bets are off.'" It may be more insightful to examine *how* institutions respond to that environmental exposure.

Practitioner Recommendations

Based on the presence of spatial dependence, managers and engineers should take advantage of these geographic connections and strengthen regional coordination across North Carolina. One county may do everything perfectly, but still be subject to the stormwater management success of another county upstream. There is an opportunity for more collaborative governance at the watershed level and partnership with neighbors.

Data accessibility can be a limiting factor to effective infrastructure management, and was one of the biggest obstacles to this study's quantitative analysis. Local data tracking is inconsistent, but there are opportunities for improvement under a statewide, standardized, and open-source asset management platform. Particularly in cases where small, rural towns cannot afford proprietary software, the state must step in to provide accessible options. Looking at the significance of urban classification, this study revealed that a one-size-fits-all policy model is not an effective approach to stormwater management. Instead, governments would benefit from incentivizing planning and risk adaptation. Some local governments simply are not equipped for proactive management, which requires slack resources that often do not exist. However, grants should reward towns that proactively map their infrastructure and seek partnerships. Managers may find new metrics helpful: "Planning grants are opportunities to do an asset inventory assessment." This may jump-start funding before a disaster rather than only after a pipe bursts.

Funding was a central concern for local managers and engineers, and this study explored various statewide and federal funding opportunities. One manager shared, "Local government units look for free money first, especially if it's out there." Several stakeholders had firsthand experience with connecting governments to grants and organizations to meet their needs. These included the SRF Green Project Reserve Loan program, which is a loan program versus a grant program, grant writing workshops, DEQ funding application training with Asset Inventory & Assessments (AIA), and Merger/Regionalization Feasibility Studies (MRF). Another interview participant mentioned the Local Assistance for Stormwater Infrastructure Investment (LASII) program, which has since stopped receiving funding but might stand as a successful resource distribution model for future programs. This individual also recommended data infrastructure investments, as “the more [governments] know about their system, the chance of them getting funded increases.” The NCCCMA Winter Seminar and the FFWIF produced diverse stakeholder interviews and may serve as future venues for partnerships and data-sharing initiatives.

Ethical Considerations

Throughout the research design, data collection, and analysis phases, steps were taken to ensure the responsible use of data and the protection of participants. Interview participants were informed of the purpose of the study, the voluntary nature of their participation, and their right to withdraw at any time without consequence (Appendix B). Consent was obtained prior to participation, and no identifying information was included in reporting. Given that participants include engineers, managers, and state officials who may operate within relatively small professional networks, particular attention was given to removing or generalizing identifiable references in interview excerpts and thematic summaries to protect anonymity.

The use of administrative and environmental datasets may raise considerations of data interpretation and accuracy. While the county-level compliance records and environmental indicators were publicly available or derived from public sources to create the database used in this study, there is a risk of overgeneralization when interpreting aggregated data. To prevent this, results are framed at the system level by county rather than attributing any correlation or causality to individual actors or specific agencies.

Interview data contextualized statistical relationships rather than confirming predetermined conclusions. This helped avoid confirmation bias, given the study's interest in governance and institutional capacity as explanatory factors. Although differences in compliance outcomes are reported, these findings are not intended to evaluate performance in a disciplinary sense. Instead, violation presence was used to understand how independent variables like institutional capacity, environmental conditions, and spatial dependencies interact to shape observed patterns. To align with these goals, emphasis was placed on systemic constraints and structural variation rather than individual accountability.

Limitations

Sourcing all data from existing datasets across different agency sites may have created discrepancies and complicated the data-cleaning process. The data that does exist, particularly from the EPA, seems to be largely point-based at the facility level and may not include an equal or accurate representation of an entire county or municipality. This uneven monitoring coverage is an especially relevant concern, as many coastal counties are largely rural. This research was carried out across the course of a semester, and time constraints limited the opportunity for deeper qualitative validation or improving the models used.

The dependent variable, average percent of quarters with stormwater violations from 2023–2025, captures temporal patterns in violations but may not fully reflect the severity, duration, or context of individual events. This measure provides a useful summary of compliance frequency over time but may not account for short-term fluctuations. While the interviews provide context, the relatively small sample size limits generalizability across all jurisdictions included in the quantitative dataset. Interview data reflect perceptions of institutional capacity and decision-making processes, which may not align with administrative realities.

Impervious surface variable uses a threshold (20%), which is not a limitation for this research but ultimately limits precision. Aggregating the impervious surface variable as was done is better suited for this research to limit unnecessary clutter. There were limited options to look at geographic patterns in the firsthand interview data, as many of the participants in my population were representatives of statewide operations. It may be beneficial to account for relative geography in qualitative data in addition to the quantitative spatial analysis. Although connecting quantitative and qualitative findings strengthens interpretive validity, there are differences in scale between county-level statistical analysis and individual-level interviews.

Stormwater compliance data from 2023 to 2025 should be interpreted with several temporal limitations in mind. In September of 2024, Hurricane Helene caused record-breaking rainfall and catastrophic flooding across North Carolina, particularly in the western part of the state (RTI International, 2025). Major flooding can increase the discharge of pollutants and system failures, while simultaneously leading agencies to prioritize emergency response and recovery. Inspection frequency and reporting consistency may potentially have been reduced during this time. Therefore, observed violation rates may reflect both true increases in system stress and temporary changes in enforcement or documentation practices.

Modifications to regulatory frameworks during this time may have also impacted the results. Stormwater compliance is governed under the National Pollutant Discharge Elimination System (NPDES) program and the Clean Water Act, administered by the U.S. EPA and at the state level by NCDEQ. Between 2023 and 2025, there have been updates to federal guidance (revisions to industrial stormwater permitting and MS4 program guidance) and state-level program adjustments in permit requirements and fee structures (NCDEQ, 2025, “MS4”; EPA, 2026, “Stormwater”). These may influence how violations are defined, monitored, and recorded.

Long-term climate pressures, including sea level rise in eastern North Carolina, affect a community's drainage capacity and increase their risk of chronic flooding. This may not be captured in the short-term scope of this study; sea level rise contributes to overall system stress and may interfere with the relationships between environmental risks and compliance outcomes.

Future Steps

Future research could focus on data that centers on capacity variables such as funding, infrastructure age, and staffing. Other factors to consider might be whether a county has access to economic support specialists or regional grant-writing assistance programs and resources. These omitted variables may have provided deeper insight into how governance and institutional capacity predict stormwater compliance. Each county has a count of annual violations by facility name. However, for the purposes of this study, violation presence did not exist on the county level. This poses a future opportunity for analysis at the facility level or in more specific geospatial areas. Looking at the distribution of violations by watershed or geographic region may help account for spillover effects from spatial clusters. One interview participant mentioned the North Carolina Flood Risk Information System (FRIS) as a useful data source for research specific to the state. Although it is not as transferable to nationwide research like FEMA and NOAA, the official flood maps include database-driven and digital "flood hazard data, models, maps, risk assessments, and reports," and may better apply to further research areas.

Conclusion

This study examined the relationship between environmental risk factors, governance structures, and stormwater compliance outcomes across counties. Using an interdisciplinary applied data analytics approach, measures of geospatial, statistical, and thematic analysis were integrated into the research methods. These findings contribute to both public administration and environmental management by demonstrating how publicly available datasets can be leveraged to support evidence-based infrastructure decision-making in resource-constrained counties. Contrary to two out of three initial hypotheses, environmental risk factors were not statistically significant predictors of stormwater compliance violations. Instead, urban classification and spatial dependence were the strongest determinants of variation across counties, supporting H2.

The results suggest that stormwater compliance is shaped less by environmental exposure alone and more by structural or governance-related conditions. Urban classification appears to capture broader differences in administrative capacity, regulatory oversight, and development intensity that are not directly measured by environmental variables. Spatial dependence further supports that compliance outcomes are influenced by neighboring counties. Qualitative findings reinforce the effectiveness of broader regional systems and partnerships over isolated administration. Interviews with practitioners consistently emphasized decision-making processes, resource constraints, and institutional capacity as central to stormwater compliance outcomes. This analytical framework for stormwater compliance risk assessment is repeatable and actionable for local managers, driven by their own knowledge and experiences. By focusing on county-level outcomes rather than asset-level data, this research offers a practical and scalable approach to infrastructure resilience planning in North Carolina.

Appendix A: Variables

Variable	Definition/Date	Source	Link
Dependent Variable			
Average Violation (%)	Average percent of quarters with stormwater violations per county from 2023-2025	EPA ECHO Data Downloads – NPDES Compliance	ECHO Exporter Version 2.0 https://echo.epa.gov/files/echodownloads/echo_exporter.zip.
Environmental Exposure			
Floodplain Coverage (%)	Percent surface area in square miles within the 100-year flood hazard zones (A+AE+AH+AO+VE) out of total county area, 2026	FEMA National Flood Hazard Layer (NFHL)	https://hazards.fema.gov/femaportal/NFHL/Download/ProductsDownLoadServlet?DFIRMID=37&state=NORTH CAROLINA&county=&fileName=NFHL_37_20260116.zip
Storm Flood Events	Count of storm events classified as a flood per county, including Flood, Flash Flood, Coastal Flood, and Lakeshore Flood from 2023-2025	NOAA Storm Events Database	https://www.ncei.noaa.gov/stormevents/choosedates.jsp?statefips=37,NORTH%20CAROLINA
Impervious Surface (%)	The average value of impervious land per county, where everything below 20% is recorded as 0, 2024	USDA National Land Cover Database, Fractional Impervious Surface Data	https://www.mrlc.gov/viewer/ https://www.mrlc.gov/data
Institutional Capacity			
Population	Population estimate from U.S. Census, 2024	U.S. Census	co-est2024-chg-37.xlsx
Urban Classification	Census/OBM metropolitan designation of incorporated or not: metropolitan, micropolitan, or non-core (rural), 2023	U.S. Census	https://www.census.gov/cgi-bin/geo/shapefiles/index.php?year=2025&layergroup=Urban+Areas

Appendix B: IRB Consent Letter

Consent Letter for Expedited Survey Research

Dear Participant,

I am a student at East Carolina University in the Department of Political Science I am asking you to take part in my research study entitled, **"Data-Driven Insights for Coastal Water Infrastructure Resilience in North Carolina**."

The purpose of this research is to better understand the issues in local stormwater management systems. By doing this research, I hope to provide a data-driven foundation for governments to align their priorities for infrastructure improvements with environmental risks and community input. Your participation is completely voluntary. We will not be able to pay you for the time you volunteer while being in this study.

You are being invited to take part in this research because you are either a manager, government engineer, or private sector engineer who addresses stormwater issues in eastern North Carolina. The amount of time it will take you to complete this interview is 20-30 minutes.

If you agree to take part in this audio-recorded interview, you will be asked questions that relate to common prioritization criteria, perceived barriers, and divergences between data-based risk indicators and practitioner experiences. Your interview aims to offer further individual insight and contextualize data analyses. Audio recordings will be transcribed at the earliest opportunity and promptly destroyed. Transcriptions will be reviewed and destroyed after 3 years. Only my faculty advisor, Dr. Olga Smirnova, and I will have access to these files. If you choose to participate in an interview, please indicate your consent:

____ Agree to be recorded
____ Disagree to be recorded

This research is overseen by the University and Medical Center Institutional Review Board (UMCIRB) at ECU. Therefore, some of the UMCIRB members or the UMCIRB staff may need to review your research data. However, the information you provide will not be linked to you**.** Therefore, your responses cannot be traced back to you by anyone, including me.

Please call Katie Wagner at 919-750-3122 for any research-related questions. If you have questions about your rights when taking part in this research, call the University and Medical Center Institutional Review Board (UMCIRB) at 252-744-2914 (days, 8:00 am-5:00 pm). If you would like to report a complaint or concern about this research study, call the Director of Human Research Protections at 252-744-2914.

You do not have to take part in this research, and you can stop at any time. If you decide you are willing to take part in this study, continue with the interview scheduling process.

Thank you for taking the time to participate in my research.

Sincerely, Katie Wagner (Principal Investigator)

Appendix C: Interview Instrument

1. What is your current role and organization?
2. On a scale of 1-5, how would you rate the overall vulnerability of your stormwater infrastructure to flooding and storm events? (1 = Very low; 5 = Very high)
3. What factors most influence your prioritization of stormwater maintenance or upgrades?
4. Which data sources do you use in stormwater planning and decision-making?
5. How confident are you in the quality and completeness of the stormwater data in your jurisdiction? (1 = Not confident; 5 = Very confident)
6. What are the main barriers you face in stormwater infrastructure management?
7. Have you implemented (or considered) data-driven decision tools for asset management?
8. What additional data, if any, would improve your ability to prioritize stormwater?

Appendix D: Interview Participants

IDN	Organization
2	Beaufort, NC
3	Chadbourn, NC
9	Jacksonville, NC
4	KCI Engineering Firm
1	McAdams Engineering Firm
5	McGill Engineering Firm
10	Mid-East Commission
8	Nags Head, NC
7	NC Department of Public Safety, Eastern NFIP
6	NC DEQ, Wastewater & Stormwater Unit

	Managers	Engineers	Managers & Engineers	Total
Local Governments	3	0	1	4
Engineering Firms	0	2	1	3
State Agencies	2	0	1	3
Total	5	2	3	**N = 10**

Appendix E: Interview Codebook

Theme	Defninition	Code	Definition
1. Institutional Capacity	Ability of local governments to implement and enforce stormwater programs.	1. Staffing	Availability of personnel
		2. Financial Constraints	Budgetary or income limits on investment
		3. Technical Expertise	Specialized skills and knowledge
		4. Data Capacity	Ability to collect, manage, and analyze data
		5. Inequality	Uneven distribution of resources, opportunities, or risks
2. Environmental Risk	Potential for harm or damage to the natural environment; includes environmental variables used in quantitative analysis.	6. Flood exposure	Presence of flood-prone areas
		7. Storm frequency	How often storms occur in a given area
		8. Impervious surface	Surfaces that prevent water absorption
		9. Extreme weather events	Rare and severe weather phenomena
		10. Climate change	Long-term alteration of weather patterns
3. Development Pressure	The demand/forces driving land and community growth and construction.	11. Population/urban growth	Increasing number of people and city expansion
		12. Land use change	Transformation of land
4. Governance	The system of rules, practices, and processes guiding decision-making and authority.	13. Political pressure	Influence of political entities or stakeholders on decisions
		14. Prioritization	Decision-making about resource allocation
		15. Reactive Maintenance	Repair or upkeep performed after a failure occurs
		16. Decision-Making	The act of selecting among options to guide actions
		17. Public Engagement	Involvement of community members
		18. Partnerships	Cooperative relationships between organizations or groups
5. Compliance and Enforcement	Ensuring adherence to laws and regulations via monitoring, penalties.	19. Enforcement Strategy	Planned approach to ensure compliance
		20. Compliance Challenges	Difficulties encountered in meeting or enforcing requirements

Appendix F: List of Tables and Figures

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