

**TECHNICAL NOTE** OPEN ACCESS

# A Stakeholder-Driven Approach for Enhancing Streamflow Monitoring Networks in Louisiana, USA

 Emad Habib<sup>1</sup> | Mohamed ElSaadani<sup>1</sup>  | Brian Miles<sup>1</sup> | Robert Miller<sup>1</sup> | Ehab Meselhe<sup>2</sup> | Mead Allison<sup>2</sup> | Kelin Hu<sup>2</sup>
<sup>1</sup>Department of Civil Engineering & Louisiana Flood Center, University of Louisiana Lafayette, Louisiana, USA | <sup>2</sup>Department of River and Coastal Engineering, Tulane University, Louisiana, USA

**Correspondence:** Emad Habib ([emad.habib@louisiana.edu](mailto:emad.habib@louisiana.edu); [habib@louisiana.edu](mailto:habib@louisiana.edu))

**Received:** 18 June 2024 | **Revised:** 29 January 2025 | **Accepted:** 13 February 2025

**Funding:** This work was supported by State of Louisiana Office of Community Development, Disaster Recovery and the U.S. Department of Housing and Urban Development (CDFA 14.228) (B-18-DP-22-001).

**Keywords:** geospatial analysis | hydrologic monitoring | modeling | network design | stage | stakeholder feedback | streamflow | watershed

## ABSTRACT

Effective streamflow monitoring networks are crucial for flood mitigation planning and water management operations. In Louisiana, USA, extreme rainfall, flat topography, and coastal-inland interactions necessitate enhancements to the sparse existing monitoring resources. This study introduces a stakeholder-driven approach to designing a streamflow monitoring network by integrating local expertise with geospatial process-based criteria. Our approach combines stakeholder input, gathered via web-based geospatial applications, with an automated scoring system. The system is based on hydrologic and geomorphic factors to prioritize gage placements while balancing regional needs and resource constraints. Implemented as part of the Louisiana Watershed Initiative (LWI), the network design addresses monitoring gaps, particularly in ungauged large watersheds and streams with complex flow regimes. The study highlights the importance of incorporating local knowledge into technical designs to support flood mitigation planning, real-time flood forecasting, and hydrodynamic model calibration. This framework can be adopted by other flood-prone regions worldwide to enhance flood monitoring and mitigation planning efforts.

## 1 | Introduction

Hydrometric information is crucial for water management, infrastructure design (e.g., reservoirs, water distribution systems, flood risk models), and assessing the impacts of climate change and hydrologic extremes (Mishra and Coulibaly 2009). This study focuses on surface water networks that collect streamflow data, including flow rates and water surface elevation in open waterways. The lack of adequate hydrometric data and the loss of such information due to budget constraints hinder effective flood risk management and predictive model design (Pyrce 2004; Hirsch and Norris 2001) and the assessment of urbanization and climate change impacts (Mishra and Coulibaly 2009). Monitoring at smaller scales is crucial in complex environments such as inland-coastal watersheds

with upstream–downstream dependencies (Saad et al. 2021; Bilskie and Hagen 2018). Flood impact in these areas is exacerbated by the sea level rise caused by the changing climate (Neumann 2000; Yu et al. 2022; Khojasteh et al. 2021). An example of these areas is Louisiana, a vulnerable coastal state at risk of expanding 100-year inundation zones by 2050 (Bates et al. 2021). Improving compound flooding models in such regions requires robust calibration and validation datasets through hydrometric networks that must capture the dynamics of estuarine and riverine management while balancing economic and environmental constraints (Khojasteh et al. 2021). While the current study focuses on flood risk, it also recognizes water quality concerns, positioning the current network design as a foundation for environmental modeling to support ecosystem health and resilience.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2025 The Author(s). Journal of the American Water Resources Association published by Wiley Periodicals LLC on behalf of American Water Resources Association.

## Summary

- Stakeholder engagement and incorporating communities' local knowledge are essential for the design and long-term sustainability of flood risk streamflow monitoring networks.

Several regional efforts in the U.S. have emerged to assess flood risk and mitigate impacts, including the Harris County Flood Control District in Texas (HCFCD [n.d.](#)), Iowa Watershed Approach (Weber et al. [2018](#)), North Carolina Flood Risk Information System (LWI [n.d.](#)), and Louisiana Watershed Initiative (LWI [n.d.](#)). These initiatives develop hydrologic and hydraulic models to analyze flood risk and design mitigation measures, often recognizing the need for enhanced streamflow monitoring to support predictive models and real-time warnings.

Designing and enhancing streamflow monitoring networks includes statistical approaches (e.g., Slade et al. [2001](#)) and coverage-oriented approaches (National Research Council [2004](#)). While existing approaches provide quantitative metrics for optimizing the network design, they do not necessarily incorporate inputs or feedback from stakeholders. They also lack mechanisms for integrating local knowledge and historical information that communities have long acquired during past events. Such information is particularly important in inland-coastal environments where non-trivial channel connectivity, complex flow patterns, and unique flooding characteristics are prevalent. This study reports on an effort to enhance the design process of streamflow monitoring systems using two primary criteria: (a) incorporating stakeholders' input for desired gaging sites and (b) prioritizing gaging sites using geospatial quantitative scores that account for the physical characteristics of the streams and watersheds. The application is presented for the state of Louisiana, USA, and was conducted as part of the Louisiana Watershed Initiative (LWI [n.d.](#)). However, the approach can be generally applied to other regions with similar needs. Following this introduction, we present the detailed methodology of the network design approach, the main results, discussion, and concluding remarks.

## 2 | Methodology

The new monitoring network will complement existing stream gages in Louisiana, such as the Stream gaging Network (Eberts et al. [2019](#); Konrad and Anderson [2023](#)) operated by the United States Geological Survey (USGS) and the Coastwide Reference Monitoring System (CRMS, Steyer et al. [2003](#)) operated by the Louisiana Coastal Protection and Restoration Authority. Based on the available resources from LWI, 100 new streamflow monitoring sites need to be deployed across the state. Identifying these sites was based on soliciting suggestions from a comprehensive group of stakeholders while considering several important hydrologic and geomorphic factors, as explained next. A flowchart illustrating the overall methodology employed in this study is provided in Figure [S1](#), included in the [Supporting Materials](#) of this publication.

## 2.1 | Solicitation of Suggestions for New Gage Sites

### 2.1.1 | Gage Suggestions by Stakeholders

Regional and local experts, such as floodplain managers and public works engineers, have first-hand knowledge of their watersheds and where gages are most needed for mitigation and response efforts based on past flood events. Practicing local engineers also possess valuable knowledge on monitoring gaps and needs for model development. Therefore, the present study started by launching web-based geospatial applications to collect stakeholders' suggestions for new monitoring sites. Participants were required to provide information such as the justification and level of need for the proposed location. The apps also allowed participants to provide opinions on locations proposed by others. The apps were disseminated to stakeholders and presented at several in-person and virtual meetings.

The stakeholders constituted a diverse population of backgrounds and affiliations, including municipal and local (parish) government staff, engineering consultants, police juries, local drainage offices, and city engineers; staff from watershed districts and levee boards; state government agencies (e.g., Department of Transportation and Development, Governor's Office of Homeland Security and Preparedness, Department of Wildlife and Fisheries), federal government agencies (e.g., U.S. Fish & Wildlife Service, U.S. Army Corps of Engineers), and the general public.

A significant volume of feedback was received from the stakeholders. Roughly 100 stakeholders provided a total of 494 suggestions for new gauges (Figure [2](#)). However, only 485 locations were deemed relevant, and 9 were excluded because of erroneous or redundant entries. The number of gauge suggestions varied across the state, with the majority coming from the southern regions that extend along the Gulf Coast, followed by the northwestern and northeastern regions, and fewer suggestions in the north-central regions. This variability, despite efforts by the research team to reach stakeholders, reflects the spatial distribution of population concentrations and the level of watershed management activities across the state.

### 2.1.2 | Gage Suggestions by USGS and NWS

The analysis also incorporated suggestions from key agencies overseeing national streamflow monitoring (USGS) and hydrologic forecasting (National Weather Service, NWS); Figure [\(2\)](#). The USGS Lower Mississippi –Gulf Water Science Center provided two sets of suggestions: (a) 103 sites of historically discontinued gages (records ending in 1970 or later), which would extend historical records and benefit hydrologic modeling, and (b) 22 new locations identified by multi-model statistical analysis (Robinson et al. [2020](#); Worland et al. [2019](#)) to fill gaps in areas with complex hydrologic regimes. Similarly, the NWS Lower Mississippi River Forecasting Center suggested 42 locations, classified into two categories: locations lacking gages where NWS issues river forecasts and non-forecast locations where stage-only gages exist but would benefit from streamflow observations.

## 2.2 | Gaging Site Prioritization

The combined input from the stakeholders, NWS, and USGS resulted in 661 suggestions for new locations. Due to budgetary constraints, site prioritization was conducted to reduce this number to a fundable level of 100 sites, as described next.

### 2.2.1 | HUC 8 Watersheds Lacking Gages

The first prioritization criterion was to identify HUC 8 watersheds that are not currently monitored by any streamflow gages (Figure 1). To support future modeling efforts, especially at the regional scale, it is critical that each HUC 8 watershed in the state be monitored by at least one streamflow gage. HUC 8 watershed boundaries were obtained from the National Watershed Boundary Dataset (WBD; Jones et al. 2022). These sites will be referred to as Tier 1.

### 2.2.2 | Criteria-Based Automated Gage Site Scoring

Additional prioritization was performed using automated scoring with a set of quantitative hydrologic and geomorphic criteria that are relevant to modeling flood risk. Automated scoring was not designed to be the final word in gage selection but rather to highlight high-value sites. Aside from the Tier 1 locations, all proposed locations were assigned a composite gage score,  $GS$ , that represents a weighted average of a set of individual  $n$  scores:

$$GS = \frac{\sum_{j=1}^n w_j GS_j}{\sum_{j=1}^n w_j} * 100 \quad (1)$$

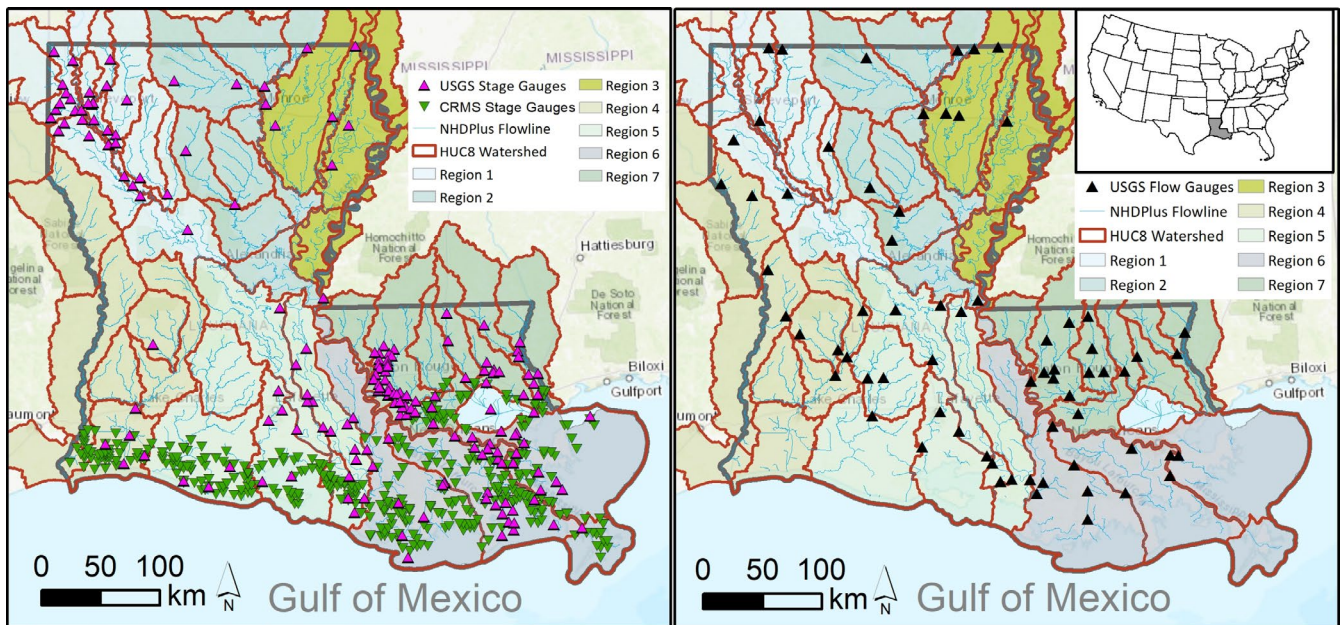
where  $w_j$  is the weight for gage score element  $GS_j$ . Each score element will have a value between 0 and 1 and represents a different watershed criterion described in the following sections. For the current analysis, all weights were assigned a value of 1; however, this formulation allows for further prioritization between the different scoring criteria.

**2.2.2.1 | Mean Impervious Percent.**  $GS_i$  is the score that prioritizes gage placement in urbanized areas as an indication of increased flood risk. Percent impervious data was extracted from the National Land Cover Database, NLCD, (Homer et al. 2004) and were used to calculate the ratio of mean impervious percentage,  $imp$ , (Figure 3) in the HUC12 where the proposed gage is located to the maximum impervious percentage,  $max(imp)$ , of all proposed gages in the same HUC 8:

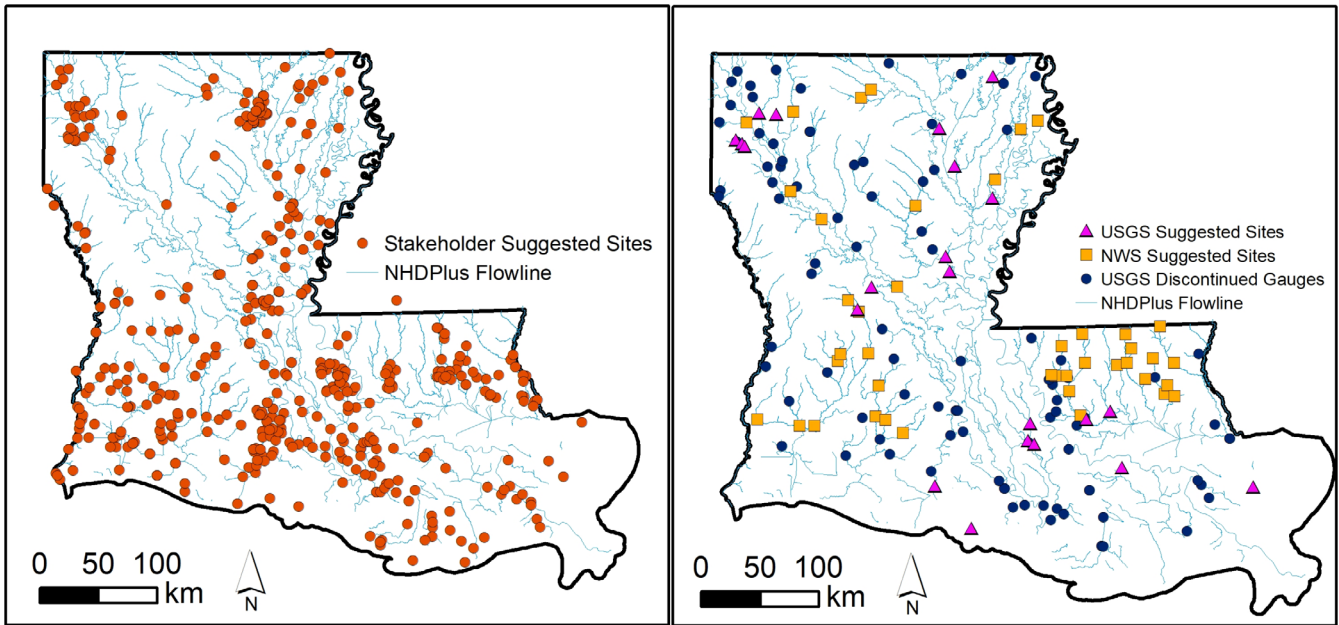
$$GS_i = \begin{cases} 0, & i < 1 \\ \log(imp)/\log(max(imp)), & i \geq 1 \end{cases} \quad (2)$$

**2.2.2.2 | Cumulative Drainage Area.**  $GS_a$  is the score accounting for the drainage area served by the new site (Figure 3). The score is calculated as the cumulative drainage area ( $A_d$ ) of the stream reach, provided with the National Hydrographic Dataset flowline network Version 2 value-added attributes, NHDPlus V2 (VAAs) (McKay et al. 2012), on which the proposed gage is located. The cumulative drainage area is then scaled by the maximum cumulative drainage area of all proposed gages in the same HUC 8:

$$GS_a = \frac{\log(A_d)}{\log(max(A_d))} \quad (3)$$



**FIGURE 1** | Distribution of existing USGS stage (magenta triangles, left) and flow (black triangle, right) gages across Louisiana. Additional stage measurements are also available through CPRA's CRMS stations (green upside triangles).



**FIGURE 2** | Left panel: Gage locations suggested by stakeholders. Right panel: Locations suggested by USGS staff for new sites (triangles) and for redeploying discontinued sites (circles), and by NWS staff with category (1) where NWS issues river forecasts but currently lacks gages and category (2) where stage-only gages currently exist, but river forecasts would benefit from these additions.

**2.2.2.3 | Channel Slope.**  $GS_{slp}$  is the score due to reach slope. Areas with flat slopes exhibit more complex flow regimes (e.g., reverse flows and backwater effects) and are more prone to flooding. Figure 3 shows low slopes predominant in the northeast (i.e., Mississippi alluvial valley) and the coastal zone. The score  $GS_{slp}$  was calculated as the slope of the NHD reach ( $slp$ ) where the gage is located, scaled by the maximum slope for all proposed gages in the same HUC 8:

$$GS_{slp} = \begin{cases} 0, & slp \leq 0 \\ 1 - (\log(slps * 1,000,000) / \log(\max(slps * 1,000,000))), & slp > 0 \end{cases} \quad (4)$$

**2.2.2.4 | Flood Zone.**  $GS_{fz}$  is the gage score due to in a FEMA flood zone and is intended to prioritize areas that are officially designated as flood-prone (Figure 3):

$$GS_{fz} = \begin{cases} 0, & fz = 'X' \text{ or } fz = 'OPEN WATER' \text{ or } fz = 'AREA NOT INCLUDED' \\ 1.0, & fz = 'A' \text{ or } (fz = 'AE' \text{ and } fst = 'FLOODWAY') \\ 0.5, & \text{for all other floodzones} \end{cases} \quad (5)$$

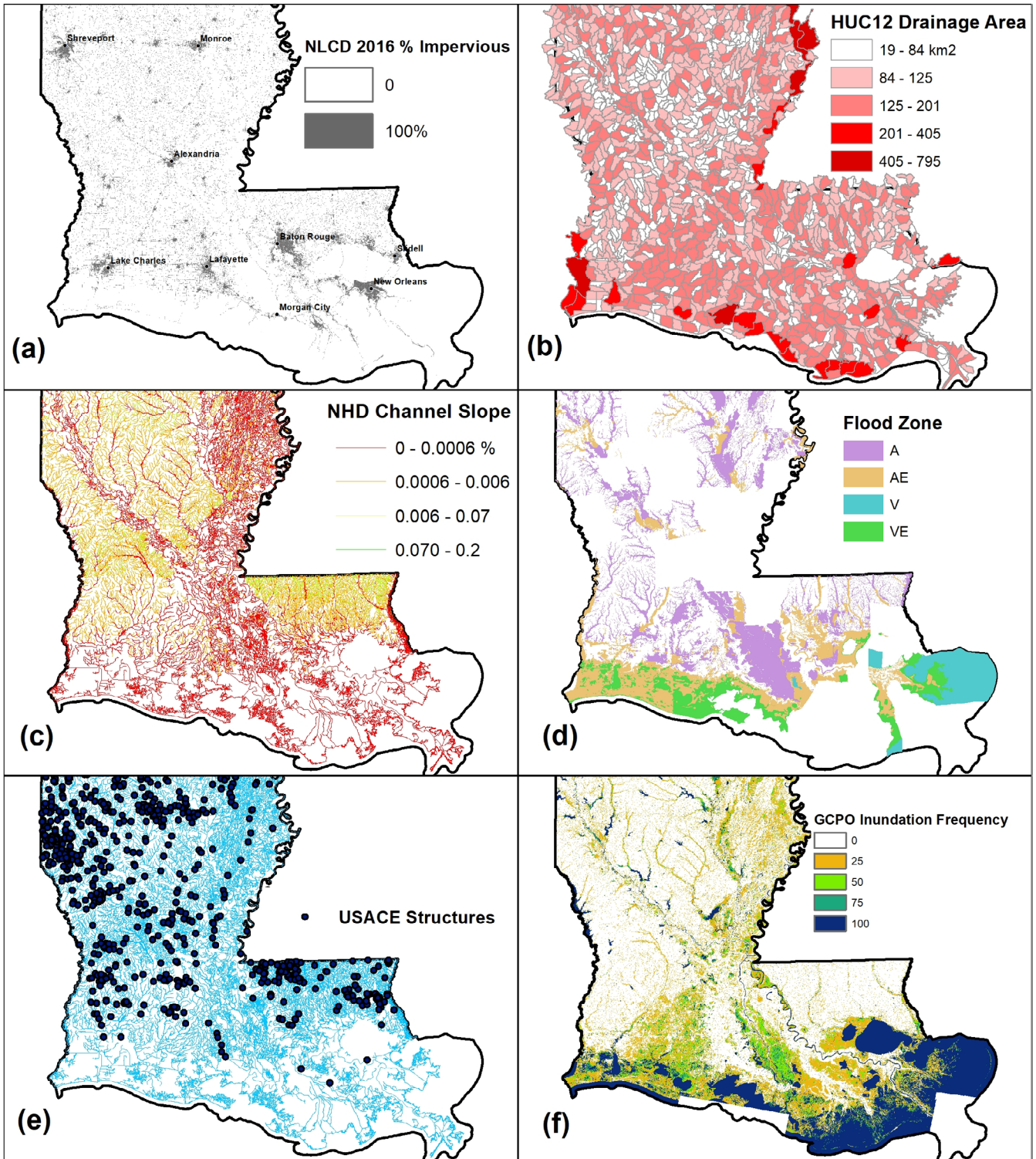
where  $fz$  is the FEMA flood zone, and  $fst$  is its category. These zones are defined as follows: Zone A are areas with documented flooding but where flood depths are not quantified; Zone AE is the 100-year flood zone where flood depth was calculated through detailed hydraulic models; floodway is a corridor reserved to discharge the base flood without increasing the water's surface elevation by more than a designated height. Proposed gage locations in zone "A" received a score of 1.0 since these locations lack base flood elevations and would benefit most from the additional information. Likewise, gages in Zone AE that are also within floodways were assigned a score of 1.0 to reflect the increased sensitivity to flood risk to changes in land use. Other flood zones were assigned a lower score of 0.5, and locations that are not in a flood zone were given a  $GS_{fz}$  score of 0.

**2.2.2.5 | Hydraulic Control Structures.** Proposed gage locations that monitor hydraulic structures that alter stream flow (e.g., gates, dams, flow diversions) and flood response were prioritized.  $GS_{dam}$  is the score due to proximity to hydraulic control structures listed in the US Army Corps of Engineers (USACE) structure database and the National Inventory of Dams (Figure 3). Gage sites near USACE-listed structures were given a score of 1.0, while other locations were given a  $GS_{dam}$  score of 0.

**2.2.2.6 | Discontinued USGS Gage Sites.**  $GS_{USGS}$  is the score assigned to a discontinued USGS stage or stream-flow gage site (Figure 2). Gage locations monitoring the same hydrologic features as those of the 103 discontinued sites were assigned a  $GS_{USGS}$  score of 1.0, while other sites were assigned a score of 0.0. The intent of this score is to build on the already available historical record of USGS discontinued gages and to take advantage of existing, albeit abandoned, gage infrastructure.

**2.2.2.7 | Proximity Between Gages Suggested by USGS, NWS, and Stakeholders.**  $GS_{stakeholder}$  is the score assigned to locations suggested by USGS or NWS that are near stakeholder-suggested gages (Figure 2). This criterion will prioritize USGS or NWS suggested gages if they are near stakeholder suggestions. These locations were given a score of 1.0; other gages were given a score of 0.0. Stakeholder-suggested gages that would monitor the same hydrologic features (e.g., NHD reach) as these USGS or NWS-suggested sites were removed from the analysis to avoid repetition.

**2.2.2.8 | Inundation Frequency.**  $GS_{if}$  accounts for inundation frequency derived from the Gulf Coastal Plans and Ozarks (GCPO) LCC inundation frequency mosaic dataset (Allen 2016; Figure 3). The GCPO inundation frequency ( $if$ ) value (0–100) at each proposed site was scaled by the maximum value for all proposed sites in the same HUC 8 where the new gage is proposed:



**FIGURE 3** | Spatial representation of the different geomorphic variables included in the scoring algorithm.

$$GS_{if} = \begin{cases} 0, \max(if) = 0 \\ if/\max(if), \max(if) > 0 \end{cases} \quad (6)$$

### 2.3 | Criteria for Coastal Station Selection

The coastal zone of Louisiana is a low-elevation land area proximal to the land-ocean interface where the principal source

of flooding will be astronomical and meteorological tides and storm surges rather than riverine flooding. However, given that many extreme precipitation events are associated with tropical storms that can generate additional flooding from storm surges, these areas cannot be overlooked for gauging and flood risk modeling. Further, compound flooding can worsen flooding risks further inland by funneling storm surge upriver and stream channels, slowing, and even reversing floodwater into upland watersheds.

The inland extent of the coastal zone can be defined by different boundaries (e.g., mean salinity concentration, tides, storm surge runoff, elevation). However, for practical purposes, the FEMA-designated coastal zone (FEMA Risk MAP [n.d.](#)) that encompasses all or a portion of 20 Louisiana coastal parishes (Figure 3) was used. Three primary criteria were followed in identifying new gage locations in the coastal region:

- a. Upland-coastal interface: These are points at which HUC 8 trunk channels, or larger HUC12 tributary channels, cross into the coastal zone. Outlets of major HUC12 tributaries are selected when they converge to an HUC 8 trunk channel within the coastal zone. These key points capture the inland runoff entering the coastal zone and serve as funnels for storm surges into upland parts of coastally connected watersheds. Thus, their gauging will allow models to better predict compound flood risk.
- b. Gulf Interface: These locations represent larger channelized locations where storm surge enters the coastal zone at the land-sea interface and at confined exchange points between large coastal water bodies (e.g., estuaries and lakes) as the surge proceeds inland. Calibrating compound flooding models requires gaging at these locations of bi-directional discharge to quantify volumes and pathways of surge and ebb surge compounded by runoff from associated storm precipitation.
- c. Critical flux exchanges: These locations represent hurricane floodgates in bayous and navigation channels, as well as levee protection systems. These represent possible monitoring points to assess surge (immediately outside) or runoff backup (immediately inside). They capture critical

fluxes generated by surge moving landward and inland runoff moving gulfward.

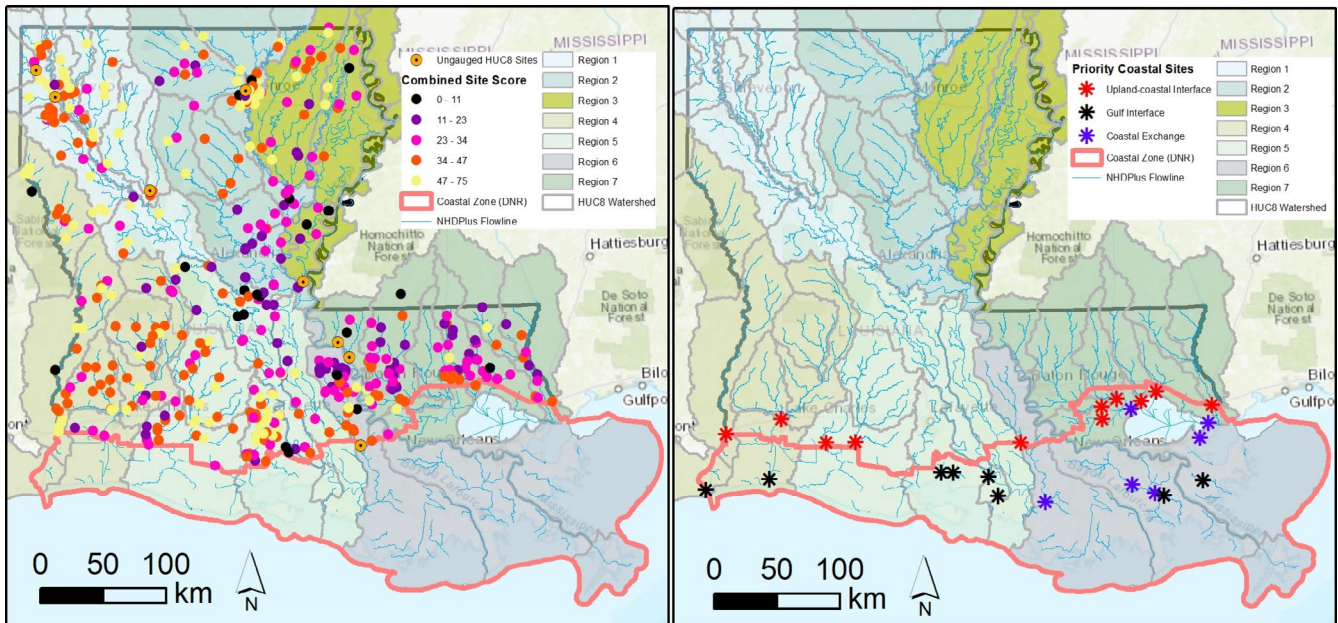
### 3 | Results

#### 3.1 | Gage Selections in Unmonitored HUC 8 Watersheds

Figure 4 illustrates the spatial distribution of all Louisiana HUC 8 watersheds. The state has organized these HUC 8 watersheds into seven provisional watershed management regions to support the development of hydrodynamic models and the deployment of monitoring gages. Eight HUC 8 watersheds not currently monitored by any gages within their domain were assigned gages at their respective outlets, referred to as Tier 1 (Figure 4). However, if stakeholders, USGS, or NWS suggested a location near the same HUC 8 outlet, that location was used instead of the HUC 8 outlet.

#### 3.2 | Automated Gage Scoring of Inland Gages

The results of automated gage site scoring are displayed in Figure 4. Automated gage scores were classified into five ranks (1 through 5) using Jenks natural breaks (Jenks 1967) that minimize variance within classes and maximize variance between classes. There are 40 gages with the highest ranking, rank 1, with gage scores between 47 and 75; 19 of these are gages suggested by stakeholders, 14 are post-1970 discontinued USGS gages, three are from USGS statistical analysis, and four are from NWS-suggested gages. Rank 2 (score between 34 and 47), rank 3 (score between 23 and 34), rank 4 (score between 11 and



**FIGURE 4** | Left panel: Results of the criteria-based gage site score for inland sites and ungauged HUC8s. Right panel: Coastal gauges identified using the three-category criteria.

23), and rank 5 (score below 11) included 107, 153, 115, and 47 potential gage sites, respectively.

### 3.3 | Gage Selections in the Coastal Region

In total, 34 coastal gage sites were selected (Figure 4) using the three prioritization criteria described earlier. The 34 sites include (a) 10 sites capturing the upland-coastal interface, (b) 18 sites capturing the gulf interface, and (c) 6 sites capturing critical flux exchange between surge and inland runoff.

### 3.4 | Combined Gage Selections

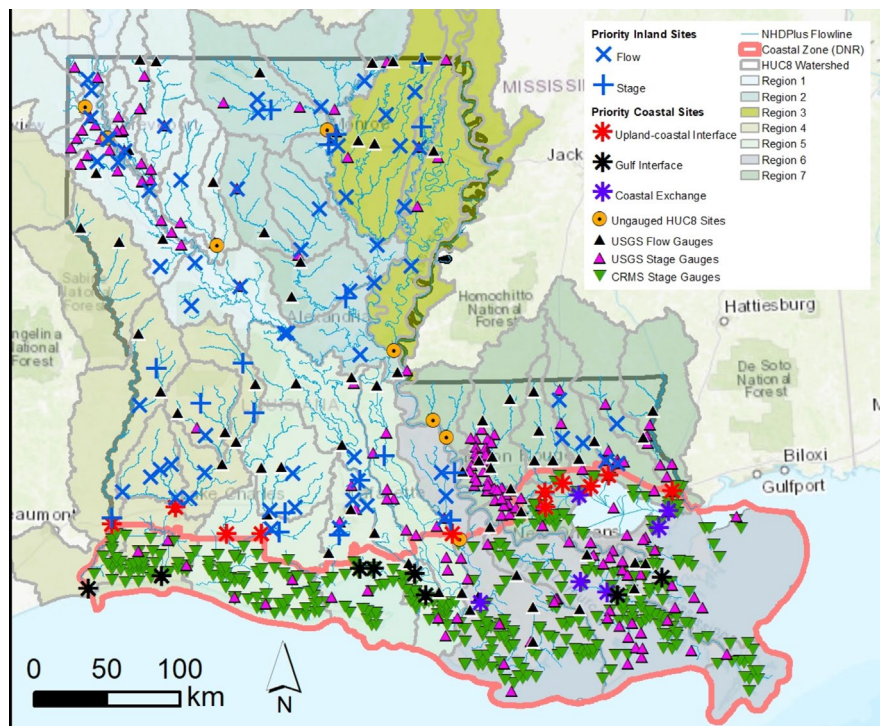
This section presents the combined results of gage selection using the abovementioned process. The goal of the analysis is to produce a network with approximately 100 new gages across the state to match the available budget. However, for practical reasons, it was desirable to identify more than 100 gages in the network design, given the likelihood that some proposed gage sites may prove to be infeasible due to logistical or site constraints. As such, 123 sites are included in the final set of gage selections. These sites were comprised of (1) eight locations that were identified in ungauged HUC 8 watersheds; (2) 81 locations identified in the automated site scoring analysis for inland flow gages; and (3) 34 locations identified as priority sites for coastal flow gages. Besides the automated scoring, a manual expert-based quality assurance and validation analysis was conducted to revise the selections. This expert-based analysis was limited to eliminating stakeholder input errors based on the description they provided about their needs or removing locations that are not feasible for gage installation (e.g., no nearby structure). This resulted in removing some of the Rank 1 locations and

promoting some Rank 2 and 3 locations, resulting in the final 123 sites shown in Figure 5. For reference purposes, the existing USGS streamflow and stage gages, as well as CRMS stage-only monitoring stations, are also shown in Figure 5. An interactive ArcGIS Online Map showing the selected gages for the final network design and their scores is provided in the Data Availability section.

While the new gaging sites are designed to monitor both stage and flow rate, the sponsoring agency requested that, due to potential resource constraints, only 80 of these monitor flow rates and 20 monitor stage only. To meet these requirements, a manual analysis was conducted to identify sites where stage-only measurements could be adequate from a hydrological perspective. This was done by examining factors such as proximity to active USGS streamflow gages, the potential ability to infer flow from a combination of nearby active or proposed streamflow gages, and the potential ability to infer flow from reservoir/spillway rating curves. The specific locations of the sites identified for stage-only gages are shown in Figure 5. Re-ranking of the 123 gages is possible as needed if different weights are to be assigned to each prioritization criterion described earlier.

### 3.5 | Network Implementation

The new gages are currently under installation through collaboration between the USGS and LWI. Implementing the LWI streamflow monitoring network faced challenges at some locations due to factors such as safety hazards, inadequate infrastructure, repetitive debris accumulation, and site accessibility during storm events. Difficulties in measuring discharge were a recurring issue in areas where complex hydraulic conditions rendered accurate discharge measurements impractical due to



**FIGURE 5** | Combined results of gage selection criteria showing: (1) Streamflow gages in ungauged HUC8 watersheds; (2) Priority sites for inland gages; and (3) priority sites for coastal gages. Existing USGS (streamflow and stage) and CRMS stations (stage only) are shown for reference.

the potential for inaccuracies in the rating curve. Additionally, water levels at some of these locations dropped significantly between initial site reconnaissance and installation, indicating that they are unsuitable for velocity measurement for much of the time. Most of these issues often necessitated the relocation or modification of the type (e.g., flow vs. stage only) of the monitoring stations, which was done in consultation with local agencies and stakeholders who suggested the locations, if applicable.

#### 4 | Discussion

The analysis presented here emphasizes the significance of gathering hydrometric data to support regional stormwater management, detect long-term climate change impacts on flood frequency and magnitude, and validate hydraulic and hydrologic predictive and forecasting models. Historically, the selection of gaging sites has been done primarily based on technical analysis, without the explicit inclusion of local knowledge and the participation of stakeholders. The current study offered a balanced approach, combining technical rigor with feedback from various stakeholders and agencies. Incorporating local knowledge increases community buy-in and better reflects the on-the-ground reality of complex flooding patterns. It also captures the impact of urbanization and land-use changes, enhancing the network value in assessing community flood risk.

The design of the gaging network follows a hybrid approach that combines stakeholder input with the results from an automated geospatial scoring system. The automated scoring system relied on objective prioritization factors such as the placement of gages at the outlet of ungauged watersheds, locations with historical records that have been discontinued, impervious areas (proxy of urbanization/population centers), drainage areas, channel slopes, flood zones, proximity to control structures, and coincidence with locations suggested by stakeholders. We do not recommend full reliance on automated scoring systems alone. Rather, we found that additional validation and manual inspection for all scored gages were needed as a critical quality assurance measure. The validation and quality assurance steps were essential in incorporating additional expert-level aspects, such as flood risk to surrounding populations or critical facilities, and the estimated value for model calibration was accounted for. As a result, some highly scored gages were removed from the selection, while other moderately scored gages were prioritized.

Overall, the transparency and clarity of the gage placement methodology and scoring system played a significant role in the level of support and buy-in from the stakeholders and local floodplain administrators, as well as from the various government agencies. While a full assessment of the efficacy of this stakeholder engagement strategy is not a priori to network emplacement, we believe this strategy would pay dividends in regions that contemplate hydrometric networks (new or supplemented) as a key to flood preparedness and post-flood event messaging.

#### 5 | Conclusions and Suggestions for Future Work

Numerous inland and coastal communities are increasingly encountering nuisance and severe flooding from tropical and

non-tropical storms due to climate change and urbanization. The effectiveness of large-scale efforts to mitigate flood risk will depend heavily on the quality of monitoring networks and on predictive and forecasting models. The unique flood hazards that face regions such as Louisiana result from a complex set of factors, including low-gradient topography, proximity of population centers to large water fluxes, coastal effects, and vulnerability to extreme weather phenomena. This diversity of factors leads to a diverse perception of risk and needs from affected communities and stakeholders, which, in turn, poses a challenge to the collaborative design of effective streamflow monitoring.

This study addressed these challenges by offering a balanced approach that effectively integrates stakeholder input into the network design process. The network aimed at supporting the development of a regional flood risk management system and validating predictive and forecasting numerical models. Coupling stakeholders' input with an automated scoring system led to an advanced design that reflected both local knowledge and familiarity with the intricacies of flooding patterns and key features of a given watershed, along with the results from a quantitative scoring system based on measurable watershed attributes.

Despite our comprehensive approach, some limitations remain. Incorporating hydrodynamic modeling results into station selection could enhance network effectiveness, but such models were unavailable and are currently being developed as part of the Louisiana Watershed Initiative. While climate change was not explicitly considered, integrating its anticipated impacts could improve monitoring of flooding frequency and severity. Coastal site selections were based on fluvio-morphological criteria rather than proximity to coastal populations or sensitive ecosystems; future improvements could integrate indices that account for natural hazard risk, resilience, and social vulnerability to better identify necessary site locations. Additionally, we did consider the potential of supplementing traditional gaging networks with cost-effective sensors (e.g., vision-based sensors and citizen-science contribution), which can enhance urban flooding tracking and community awareness. Lastly, the network does not capture flow exchanges near the numerous hydraulic structures within the transition zone, a limitation due more to budget constraints than to lack of importance.

Another critical area for further research, while less technical, is the implementation of effective funding strategies for maintaining and sustaining large-scale hydrometeorological networks. Continuous maintenance, with periodic updates of site surveys and rating curves, is essential for data quality and representation. Network sustainability is crucial for flood-risk monitoring, as decades of data are needed to capture varying magnitudes of flood events for management and model development. In this regard, flood amnesia (Kunreuther et al. 2018) is one of the factors posing a threat to funding sustainability, highlighting the need for securing stakeholder buy-in and investment as vital elements in resolving the sustainability dilemma.

#### Author Contributions

**Emad Habib:** conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources,

supervision, writing – original draft, writing – review and editing. **Mohamed ElSaadani:** conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, validation, visualization, writing – original draft, writing – review and editing. **Brian Miles:** conceptualization, data curation, formal analysis, investigation, methodology, software, validation, writing – original draft, writing – review and editing. **Robert Miller:** conceptualization, formal analysis, methodology, validation, writing – original draft, writing – review and editing. **Ehab Meselhe:** conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, validation, writing – original draft, writing – review and editing. **Mead Allison:** conceptualization, formal analysis, methodology, validation, writing – original draft, writing – review and editing. **Kelin Hu:** conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft, writing – review and editing.

## Acknowledgments

This work was made possible by the funding support of the State of Louisiana Office of Community Development and the U.S. Department of Housing and Urban Development (CDFA 14.228 Grant B-18-DP-22-001). The authors acknowledge the valuable contributions provided by the USGS Lower Mississippi–Gulf Water Science Center (Todd Baumann, Rodney Knight, Aub Ward, and James Fountain), the NWS Lower Mississippi River Forecasting Center (David Welsh), the LWI state agencies, and the various public and private stakeholders who provided input and feedback on the network design.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The locations of the network gage sites with detailed scoring attributes, along with a data dictionary and downloadable geospatial layers, are publicly accessible at this interactive online map: <http://arcg.is/1G1vyK>. The gages installed by USGS based on the network design are shown at <https://waterdata.usgs.gov/state/louisiana/>. The GIS layers necessary to reproduce the network design analysis of the paper, including a detailed description of each layer, are available in the HydroShare resource: <https://www.hydroshare.org/resource/92f042f61d9f4adca68ac247148391bc/>. The parent data came from the following public sources. The National Hydrography Dataset is available at <https://www.usgs.gov/national-hydrography/> and dataset attributes are available at <https://www.epa.gov/waterdata/nhdplus-national-hydrography-datas-et-plus>. National Land Cover Database (NLCD) on percent impervious is available at: <https://www.mrlc.gov/national-land-cover-database-nlcd-2016>. FEMA flood zones are available at <https://hazards.fema.gov/femaportal/wps/portal/NFHLWMS>. Databases of hydraulic structures are available from the National Bridge Inventory (NBI) (<https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm>). The GCPO Inundation Frequency Mosaic is available at: <https://databasin.org/datasets/>.

## References

Allen, Y. 2016. “Landscape Scale Assessment of Floodplain Inundation Frequency Using Landsat Imagery.” *River Research and Applications* 32, no. 7: 1609–1620.

Bates, P., N. Quinn, C. Sampson, et al. 2021. “Combined Modeling of US Fluvial, Pluvial, and Coastal Flood Hazard Under Current and Future Climates.” *Water Resources Research* 57: e2020WR028673. <https://doi.org/10.1029/2020WR028673>.

Bilskie, M. V., and S. C. Hagen. 2018. “Defining Flood Zone Transitions in Low-Gradient Coastal Regions.” *Geophysical Research Letters* 45, no. 6: 2761–2770.

Eberts, S. M., M. D. Woodside, M. N. Landers, and C. R. Wagner. 2019. *Monitoring the Pulse of Our Nation's Rivers and Streams—The US Geological Survey Streamgaging Network*. US Geological Survey.

FEMA Risk MAP. n.d. “Guidance for Flood Risk Analysis and Mapping.” Retrieved June 8, 2024. [https://www.fema.gov/sites/default/files/documents/Coastal\\_Floodplain\\_Mapping\\_Guidance\\_Nov\\_2019.pdf](https://www.fema.gov/sites/default/files/documents/Coastal_Floodplain_Mapping_Guidance_Nov_2019.pdf).

HCFC. n.d. “Harris County Flood Control District's Flood Warning System.” Retrieved June 8, 2024. <https://www.harriscountyfws.org/>.

Hirsch, R. M., and J. M. Norris. 2001. “National Streamflow Information Program: Implementation plan and progress report (Fact Sheet 005-01).” *US Geological Service Fact Sheet*: 1–5. <https://pubs.usgs.gov/publication/fs00501>.

Homer, C., C. Huang, L. Yang, B. Wylie, and M. Coan. 2004. “Development of a 2001 National Land-Cover Database for the United States.” *Photogrammetric Engineering & Remote Sensing* 70, no. 7: 829–840.

Jenks, G. F. 1967. “The Data Model Concept in Statistical Mapping.” *International Yearbook of Cartography* 7: 186–190.

Jones, K. A., L. S. Niknami, S. G. Buto, and D. Decker. 2022. *Federal standards and procedures for the national Watershed Boundary Dataset (WBD)*. 5th ed, 11–54. U.S. Geological Survey Techniques and Methods. <https://doi.org/10.3133/tm11A3>.

Khojasteh, D., W. Glamore, V. Heimhuber, and S. Felder. 2021. “Sea Level Rise Impacts on Estuarine Dynamics: A Review.” *Science of the Total Environment* 780: 146470.

Konrad, C. P., and S. W. Anderson. 2023. “A General Approach for Evaluating of the Coverage, Resolution, and Representation of Streamflow Monitoring Networks.” *Environmental Monitoring and Assessment* 195, no. 10: 1256.

Kunreuther, H., S. Wachter, C. Kousky, and M. Lacour-Little. 2018. *Flood Risk and the U.S. Housing Market*. Penn Institute for Urban Research and Wharton Risk Management and Decision Processes Center.

LWI. n.d. “Louisiana Watershed Initiative.” Retrieved May 8, 2024. <https://watershed.la.gov/modeling-program>.

McKay, L., T. Bondelid, T. Dewald, J. Johnston, R. Moore, and A. Rea. 2012. *NHDPlus Version 2: User Guide*. Environmental Protection Agency.

Mishra, A., and P. Coulibaly. 2009. “Developments in Hydrometric Network Design: A Review.” *Reviews in Geophysics* 47: RG2001. <https://doi.org/10.1029/2007RG000243>.

National Research Council. 2004. *Assessing the National Streamflow Information Program*. National Academies Press. <https://nap.nationalacademies.org/read/10967/chapter/10>.

Neumann, J. E. 2000. *Sea-Level Rise & Global Climate Change: A Review of Impacts to US Coasts*. Pew Center on Global Climate Change.

Pyrce, R. S. 2004. *Review and Analysis of Stream Gauge Networks for the Ontario Stream Gauge Rehabilitation Project*, 90. Watershed Science Centre (Trent University).

Robinson, A. L., S. C. Worland, and K. D. Rodgers. 2020. “Estimated Daily Mean Streamflows for HUC12 Pour Points in the Southeastern United States, 1950–2009: U.S.” Geological Survey Data Release, ScienceBase.

Saad, H. A., E. H. Habib, and R. L. Miller. 2021. “Effect of Model Setup Complexity on Flood Modeling in Low-Gradient Basins.” *JAWRA Journal of the American Water Resources Association* 57, no. 2: 296–314.

Slade, R. M., T. Howard, and R. Anaya. 2001. *Evaluation of the Streamflow-Gaging Network of Texas and a Proposed Core Network*. US Department of the Interior, US Geological Survey.

Steyer, G. D., C. E. Sasser, J. M. Visser, et al. 2003. "A Proposed Coast-Wide Reference Monitoring System for Evaluating Wetland Restoration Trajectories in Louisiana." *Environmental Monitoring and Assessment* 81, no. 1: 107–117. <https://doi.org/10.1023/A:1021368722681>.

Weber, L. J., M. Muste, A. A. Bradley, et al. 2018. "The Iowa Watersheds Project: Iowa's Prototype for Engaging Communities and Professionals in Watershed Hazard Mitigation." *International Journal of River Basin Management* 16, no. 3: 315–328.

Worland, S. C., S. Steinschneider, W. Farmer, W. Asquith, and R. Knight. 2019. "Copula Theory as a Generalized Framework for Flow-Duration Curve Based Streamflow Estimates in Ungaged and Partially Gaged Catchments." *Water Resources Research* 55: 9378–9397. <https://doi.org/10.1029/2019WR025138>.

Yu, X., L. Luo, P. Hu, X. Tu, X. Chen, and J. Wei. 2022. "Impacts of Sea-Level Rise on Groundwater Inundation and River Floods Under Changing Climate." *Journal of Hydrology* 614: 128554.

### Supporting Information

Additional supporting information can be found online in the Supporting Information section.