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Towards collaborative smart cities: a participatory framework to co-develop an environmental monitoring dashboard along the Texas Coast

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ABSTRACT

Cities in coastal regions are particularly prone to experiencing environmental impacts arising from both natural and human causes. Additionally, Climate Change imposes stressors on communities along shorelines. Smart city concepts can assist communities in informed decision-making, building on technology-based approaches to measure and evaluate various aspects of everyday life in cities. While smart city concepts have gained significant momentum over past decades, this study presents an approach to integrate the human factor from the early stages of developing smart cities. The active engagement of residents underscores the pursuit of data accessibility and equity within urban governance. This study outlines a comprehensive participatory framework integrating local knowledge and stakeholder engagement into designing and implementing an environmental monitoring data dashboard for coastal communities. By leveraging insights from multiple disciplines – including urban design & planning, civil engineering, computer science, and public policy – this research seeks to create a sociotechnical network that effectively addresses the complex interplay between technology and human factors. To do so, this study follows the Participatory Action Research paradigm, deploying a mixed-methods approach for developing a data dashboard tailored to the specific needs of communities and their environmental challenges. The Texas Coastal Bend Region serves as a case-study to demonstrate the development and application of a six-step participatory framework, developing a sociotechnical monitoring network on flooding, air quality, and water quality. The outcomes of this study serve as a guide for engaged scholars and designers in developing participatory frameworks for designing data dashboards addressing academic and non-academic constituents, residents seeking informed insights, and decision-makers entrusted with the stewardship of urban development in a vulnerable context.

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Highlights

- Participatory framework for environmental monitoring in coastal cities.
- Multidisciplinary approach integrates local knowledge and stakeholder input into dashboard development.
- Sociotechnical network addresses flooding, air quality, and water quality challenges.

1. Introduction

1.1. Background

As the effects of climate change intensify, coastal cities are increasingly vulnerable to rising sea levels, extreme weather events, and their associated consequences, such as flooding, erosion, and infrastructure damage. In addition, industrial activities keep polluting water and air in proximity to human settlements (Jenewein & Hummel, 2021). Among the various environmental hazards impacting coastal communities, flooding, water pollution, and air pollution are among the most critical hazards threatening cities and shorelines worldwide (Koop & van Leeuwen, 2017; Mayer, 1999; Vitousek et al., 2017). However, the lack of comprehensive environmental monitoring data and data accessibility are significant factors in enabling or preventing effective decision-making processes (Hajibabaei et al., 2024; Jiao et al., 2016; Wong et al., 2018).

In recent years, smart cities have gained prominence as an approach to urban sustainability, incorporating technology-based solutions and sensor networks to collect quantitative data (Anthopoulos, 2015; Obringer & Nateghi, 2021; Su, Li, & Fu, 2011). The integration of information and communication technology (ICT) and the Internet of Things (IoT) have become cornerstones of the smart city paradigm (Kopackova & Libalova, 2017; Meijer & Thaens, 2018; Papa, Gargiulo, & Galderisi, 2013). On the pathway to creating smart cities and regions, bridging data gaps is essential to enable data-driven decision-making processes (Bacco et al., 2017; Cvitanovic, McDonald, & Hobday, 2016; World Health Organization, 1987). However, smart city concepts must go beyond technology-based approaches and include human actors in their development (Nilssen, 2019). Therefore, the activation of local knowledge through engagement of stakeholders who inhabit and influence the urban environment is recognized as a critical component in the design and development of smart cities, combining three essential factors: (1) people, (2) technologies, and (3) institutions (Cardullo & Kitchin, 2019; Papa et al., 2013). Engaging communities and public and private stakeholders acknowledges ‘smart citizens’ as a crucial component in the process of designing and maintaining smart city concepts (Breuer, Walravens, & Ballon, 2014). The construction of sociotechnical networks, actively engaging a diverse array of stakeholders, allows these actors to become indispensable contributors to the formulation and execution of future strategies and actions (Dameri, 2013; Mao et al., 2020).

Incorporating the principles of Participatory Action Research (PAR), this study adopts a grassroots approach to create a sociotechnical framework that communicates environmental threats to residents (Baum, MacDougall, & Smith, 2006; Lewin, 1946; McIntyre, 2007; Ozanne & Saatcioglu, 2008; Walker, 1993). PAR is a research approach that actively involves the community or stakeholders in the research process (Jenewein & Hummel, 2022). It aims to address real-world issues collaboratively, empowering participants to identify problems, devise solutions, and affect positive change (Lewin, 1946). It promotes social justice and community engagement by merging research and action for meaningful impact (Reason & Bradbury, 2001). Three central objectives guide PAR. Firstly, it facilitates taking tangible actions on the research topic at hand. Secondly, it fosters a balanced distribution of power between researchers and community partners. Thirdly, it actively involves participants as essential contributors in the research process. This approach summarizes applied research, characterized by the collaborative development of research questions with the community's active participation, aiming toward the production of actionable outcomes that are directly beneficial to the engaged constituents and decision-makers (Binet et al., 2019; Jenewein et al., 2023; Ozanne & Saatcioglu, 2008). The development of an environmental monitoring data dashboard is utilized to demonstrate practical applications for the proposed participatory framework. This participatory process utilizes the small coastal town of Ingleside on the Bay (IOB), Texas, to develop a pilot project as a scalable blueprint to engage and build a regional-scale sociotechnical network. In essence, this research aspires to foster academic-civic relationships, bring technology-based approaches closer to communities, and provide data for informed decision-making. By engaging local stakeholders and activating their knowledge with low-cost sensor technology, this initiative seeks to equip residents of coastal Texas with the necessary data in their journey toward becoming a smart and resilient region capable of addressing its environmental challenges.

1.2. Research gap

While existing literature underscores the significance of involving stakeholders in the development of smart city initiatives, there remains a need for frameworks that effectively integrate sociotechnical perspectives across multiple disciplines (Anttiroiko, 2016). Current models often focus on either the technical infrastructure or the social dimensions in isolation, neglecting the complex interplay between technology and human factors (Meijer & Bolívar, 2016; Nam & Pardo, 2011). Moreover, the fragmentation of disciplines such as urban design, civil engineering, computer science, and public policy has hindered the development of truly interdisciplinary solutions.

To address this gap, this paper employs a participatory mixed-methods methodology to construct a sociotechnical framework linking urban design and planning, civil engineering, computer science, and public policy. This study proposes a participatory framework, utilizing the development of an environmental monitoring data dashboard applied to the selected case study as an example. One key facet of this approach is the acknowledgment of local knowledge as a valuable resource. Therefore, local insights and expertise are leveraged as a fundamental source of information that informs the technical aspects of the network. Consequently, the sociotechnical network being constructed aims to integrate human and technical dimensions, transcending the conventional boundaries that often separate community knowledge from advanced technological solutions.

1.3. Research aims & questions

This study seeks to create a participatory framework that incorporates local knowledge and stakeholder involvement in the design and implementation of an environmental monitoring data dashboard for coastal communities. By drawing on insights from various disciplines, including urban design and planning, civil engineering, computer science, and public policy, this research aims to establish a sociotechnical network that effectively integrates the relationship between technology and human factors. The following research questions guide this study:

(1) How can local knowledge and stakeholder engagement be effectively integrated into designing and implementing an environmental monitoring data dashboard for coastal communities?
(2) What are the key factors that influence the successful deployment and maintenance of low-cost sensor technology in vulnerable coastal areas, and how can these factors be addressed through a participatory framework?
(3) How can stakeholder input be utilized to determine dashboard functionality and design?

By integrating local knowledge and stakeholder involvement within the framework of this study, we not only aim to enhance the design and implementation of an environmental monitoring data dashboard for coastal communities but also to promote the principles of citizen science, which empower communities to actively participate in the stewardship of their environment and foster a deeper connection between technology and the human experience.

2. Materials & methods

2.1. Research framework

The research framework emphasizes active user involvement in developing a sociotechnical approach for reporting environmental monitoring data through a community

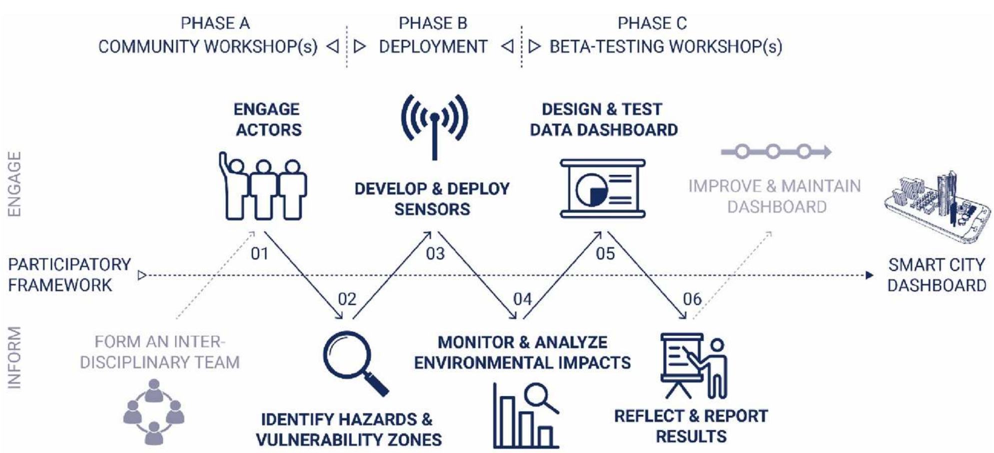


Figure 1. This participatory framework shows the six major steps in developing the dashboard across three phases of engagement, highlighting the sociotechnical interplay of this study.

dashboard. This bottom-up process serves as a foundational step in creating a smart city framework, structured into Phases A through C, with each phase including distinct steps to engage the community to co-create the sociotechnical network (Figure 1). Throughout these three phases, six steps structure the engaged process: (1) Engage actors: Engage residents and stakeholders through a community-based process to gain deeper insight into the neighbourhood and involve individuals who contribute to the development of the sensor network. (2) Identify hazards & vulnerability zones: Identify areas within the case study particularly susceptible to environmental hazards, whether with natural origin or from human activities. (3) Develop & deploy sensors: Develop and deploy a low-cost sensor network to measure selected environmental hazards working with community members. (4) Monitor & analyze environmental impacts: Monitor and analyze data related to comprehensively understand the selected environmental conditions. (5) Design & test data dashboard: Facilitate beta-testing workshops and present the collected data through a user-friendly data dashboard, thereby equipping both community members and decision-makers with valuable insights. (6) Reflect & report results: Analyze and reflect upon findings to inform residents and, decision-makers, on the next steps for establishing a comprehensive regional framework.

Key engagement events are part of all three phases: Phase A – Community Workshop involves focus group sessions that gather initial input from residents and stakeholders while recruiting volunteers for the next phase. This phase aims to identify assets, challenges, strategies, and actions, locate vulnerability zones, recruit volunteers for sensor placement, and engage beta-testers. Phase B – Deployment engages these volunteers in sensor placement and maintenance, ensuring continuous data collection and fostering community involvement. This phase focuses on deploying and maintaining sensors to support ongoing data collection and community participation. Phase C – Beta-Testing Workshop refines the dashboard based on feedback from the community. This phase aims to provide an overview of dashboard functions and gather feedback on its design (see Table 1). These steps are essential as they build upon one another, linking the components of the engagement workshops throughout the study. Each phase contributes to a comprehensive understanding of the project's objectives, timeline, and projected outcomes, ultimately enhancing community participation and the overall effectiveness of the study.

In this study, Phases A-C were conducted over nine months. Phase A involved conducting a community workshop in month 1 to gather initial input from residents and stakeholders, during which volunteers were also recruited for the subsequent phase. Phase B spanned months 2–6, during which these volunteers assisted in sensor placement and maintenance, ensuring continuous data collection and fostering ongoing community

Table 1. Overview of community workshops, methods, and aims applied in this study.

		Methods	Aims
PHASE A	Community Workshop	Focus groups Group discussions & reflections	(1) Identify assets, challenges, strategies & actions (2) Locate vulnerability zones (3) Recruit volunteers for sensor placement (4) Engage beta-testers
PHASE B	Deployment	Quality Assurance Project Plan (QAPP)	(5) Deploy & maintain sensors
PHASE C	Beta Testing Workshop	Tutorial Online survey	(6) Provide an overview of dashboard functions (7) Gain feedback on dashboard design

involvement. This phase continues as the project grows, allowing for further adaptation and engagement. Finally, Phase C included a beta-testing workshop in month 7, aimed at refining the dashboard based on feedback collected from the community.

2.2. Study area

While the Texas Coastal Bend Region stretches across nine counties along the South Texas Coast and its hinterlands, this study focuses mainly on Nueces, San Patricio, and Aransas counties, three coastal counties located adjacent to Corpus Christi Bay (Figure 2). With a total population of just over 445,000 residents in these three counties (Nueces: 353,178; San Patricio: 68,755; Aransas: 23,830), the City of Corpus Christi (population: 317,863) is by far the largest city, housing over 70 percent of residents in the three counties combined (Census Bureau, 2022). All three counties see median household incomes below the state average, with Aransas County ranking significantly lower (Median Texas: $67,321, Nueces: $59,477; San Patricio: $59,532; Aransas: $51,509) than the more populated San Patricio and Nueces counties (Census Bureau, 2022).

The coastal location along Corpus Christi Bay has enabled significant industrial development along the shoreline. Over the past century, the maritime infrastructure of the Gulf Intercoastal Waterway (GIWW), the Corpus Christi and La Quinta Ship Channels, and the dredging of the Aransas Pass channel enabled the development of Port Corpus Christi (PCC), the third largest port by annual tonnage and number one port by revenue tonnage in the nation (U.S. Department of Transportation, 2023). PCC is a major petrochemical hub, operating within a logistical network of rails, pipelines, and waterways to process and distribute raw and refined materials (Port of Corpus Christi Authority, 2023). With a wide range of petrochemical plants, the region faces several environmental

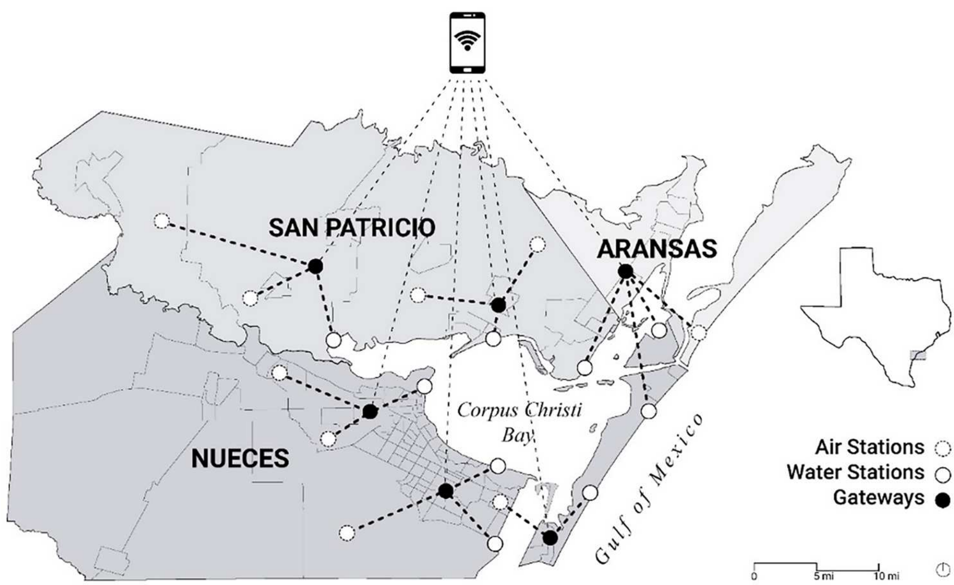


Figure 2. Overview of Nueces, San Patricio, and Aransas counties.

impacts due to air and water pollution (McGaughey et al., 2009). In addition, a series of planned desalination plants around Corpus Christi Bay demands thorough environmental monitoring of the impact on the marine and urban ecosystems in the adjacent cities (Port of Corpus Christi Authority, 2020). Presently, environmental conditions in the Coastal Bend area are being monitored with limited spatial detail by various local, state, and federal agencies and private entities, including the Texas Commission for Environmental Quality (TCEQ), National Oceanic & Atmospheric Administration (NOAA), and the City of Corpus Christi. However, the resulting data are either not shared with the public or are scattered across different websites with varying reporting methods and access protocols. Consequently, these data are not easily accessible to community members who wish to stay informed about conditions in their own neighbourhoods. Given the environmental impacts arising from the local industry and natural forces along the coast, the air quality nodes measure CO_2, $PM_{2.5}$, PM_{10}, SO_2, NO_2, humidity, and temperature, while the water quality nodes focus on salinity, dissolved oxygen, water temperature, and water level.

This study uses the small coastal town of IOB, approx. 700 residents (Census Bureau, 2022), to pilot an approach to the environmental monitoring dashboard, utilizing the development process as a blueprint for the regional application to the three described counties along Corpus Christi Bay (Figure 3). In 2020, 73 percent of the IOB population are white and 26 percent Hispanic, with an average age of 51. The per capita income is $39,159, and the median household income is $85,469, significantly higher than the state median of $66,963. Additionally, only 3.5 percent of the population live below the poverty line, compared to the state average of 14.3 percent (US Census, 2020).

Moreover, it is noteworthy that this study is an extension of a prior participatory research endeavour undertaken by Jenewein & Hummel, 2021, which was initiated in response to residents' expressed interest in environmental monitoring (Jenewein et al., 2023; Jenewein & Hummel, 2022). Consequently, the research team had already forged relationships and established formal collaboration agreements with community-based organizations (CBOs) in the region. These pre-existing relationships with local organizations serve as a cornerstone for fostering a broad and cohesive coalition, encompassing residents, civic leaders, and government officials, thereby amplifying the impact and reach of the research endeavour.

2.3. Participatory framework

2.3.1. Engage actors

The engagement process begins with the research team forming strategic alliances with various stakeholders within the respective city. Such conversations are often informal, targeting CBOs, elected officials, and business and industry representatives as a network of stakeholders who advertise the respective workshops to their constituents (Cunliffe & Scaratti, 2017; Holliman & Warren, 2017). The scale of the respective city or region determines whether neighbourhoods, cities, or communities should be identified as individual entities when dividing the case study area into appropriate parcels for engagement. A major challenge is the appropriate representation of minority groups in participatory processes, as elite groups tend to be disproportionally represented (Cuthill, 2004; Huggins, 2012). Therefore, it is crucial not to generalize findings and outcomes to

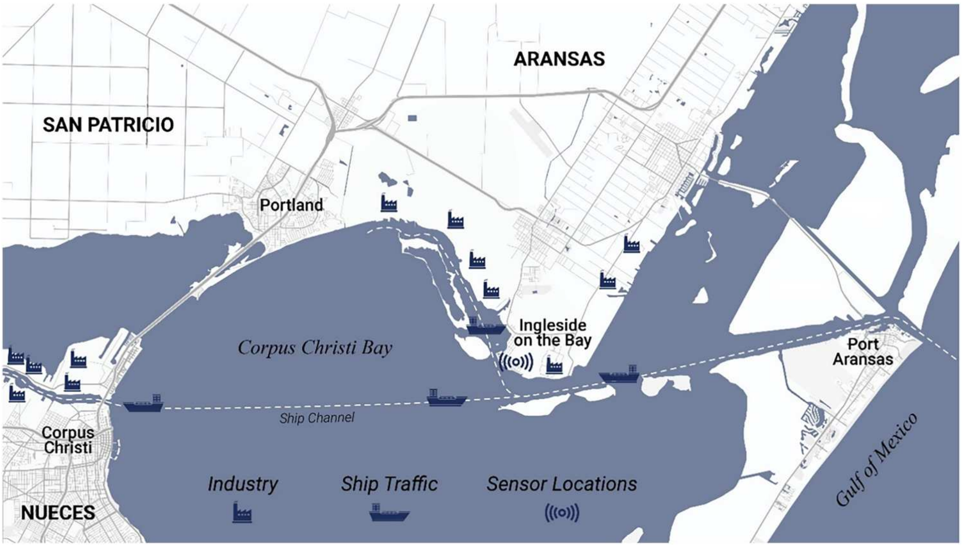


Figure 3. Location of IOB within Corpus Christi Bay, at the intersection of the Corpus Christi and La Quinta Ship Channels, and several industrial facilities. This map underlines the significant location of this pilot project, which serves as a blueprint for other cities around the bay.

represent the community as a whole but rather the respective workshop participants in case a representative distribution of stakeholders, including vulnerable groups, cannot be identified.

The initial community workshop marked a significant step in the engaged research journey. During this event, a broad spectrum of topics was explored utilizing three focus groups of 6–10 people (Morgan, 1996; Powell & Single, 1996). These focus groups, with a total of 25 participants, introduced the primary research topics of flooding, air quality, and water quality and served as the first point of contact between the research team. The workshop adopted an approach summarizing 'Assets-Challenges-Strategies-Actions' (ACSA) to structure the discussions and outcomes (Jenewein et al., 2023).

(1) *Assets*: Participants are encouraged to identify and highlight the existing assets and strengths within the community that could be leveraged for the smart city framework.
(2) *Challenges*: The workshop examines challenges and obstacles the community faces concerning flooding, air quality, and water quality. These discussions aim to pinpoint areas that require attention and improvement.
(3) *Strategies*: The community brainstorms strategies and approaches to tackle the identified challenges effectively. This step fosters innovative thinking and problem-solving among participants.
(4) *Actions*: Building on the strategies, the workshop culminates in the development of concrete actions. These steps form the basis for addressing issues related to flooding, air quality, and water quality in the community.

Depending on the number of participants, the workshop can be divided into an appropriate number of focus groups discussing the predefined topics. Discussion facilitators used a list of interview questions to guide participants through the discussion (Table 2). To ensure an equal distribution of discussion topics, participants rotated among the tables, allowing the topics to be thoroughly explored within the overall workshop timeframe. Through this approach, the PAR framework aimed to align valuable insights and priorities identified by the participants during the workshop with the subsequent sensor data collection efforts.

The ACSA framework focuses on predefined topics and serves as the procedural model for content analysis by applying a category system (Mayring, 2014). The comments were collected on sticky notes, then transcribed, and put into a Microsoft Excel table to categorize and count (Microsoft, 2024). Each comment was assigned to a category, applying equal weight to the number of mentions per comment to establish the frequency analysis (Lindsey, 1995). This approach to content analysis as a data analysis method was applied to quantify qualitative data. The frequency analysis showcased what topics were mentioned and how often participants brought specific topics up. Since the number of participants did not exceed 25 and the topics overlapped substantially, no coding software was necessary in the case of this study as the complexity remained low.

During the discussions, participants point out assets, challenges, strategies, and actions on a map to create a spatial correlation between the respective topic and where people think this is occurring in the neighbourhood. To do so, physical maps are provided, allowing participants to pin locations associated with their comments.

Table 2. Discussion questions for community workshop discussions appropriated from (Jenewein et al., 2023). Total number of participants = 25.

What are the assets?		
ASSETS	(1)	What are some of your community assets?
	(2)	Why do you consider them to be assets?
	(3)	Is there something about where they are located that makes them an asset?
What are the challenges?		
CHALLENGES	(1)	Thinking about [air quality, water quality, flooding], what are the major challenges related to health, safety, and quality of life in [your city/neighbourhood]?
	(2)	How concerned are you about the [air quality, water quality, flooding issues] in and around [your city/neighbourhood]?
	(3)	What do you think are the main sources/causes of [air pollution, water pollution, flooding] in [your city/neighbourhood]?
	(4)	What parts of the community and which members of the community are likely to experience the greatest impacts due to these challenges?
What are the strategies to overcome these challenges?		
STRATEGIES	(1)	What ideas do you have to address [air pollution, water pollution, flooding] in [your city/neighbourhood]?
	(2)	How might efforts to address [air quality, water quality, flooding issues] impact jobs, property values, or economic prosperity?
	(3)	How well are local, state, and/or federal government officials and agencies (like TCEQ and Port of Corpus Christi) keeping the [air, water, land] healthy, safe, and conducive for a high quality of life?
	(4)	Which specific [contaminants, flood impacts] do you think are most important to measure and monitor, if any?
What are the actions needed to implement the strategies?		
ACTIONS	(1)	How can some of the strategies on [air pollution, water pollution, flooding] in [your city/neighbourhood] be implemented?
	(2)	Who are the specific actors to address pathways of implementation with?

During the community workshop, environmental hazards need to be identified and linked to potential sites. This process encourages participants to actively engage by volunteering their properties for sensor deployment. This approach underscores the fundamental importance of CBOs and community members as key stakeholders in the development of a sociotechnical network. By involving the community in deploying sensors on their properties, this study harnessed local knowledge and expertise and fostered a sense of ownership and empowerment within the community. This collaborative effort was integral to the successful implementation of the sociotechnical network, as it ensured that the technology was tailored to the specific needs and contexts of the community. Furthermore, the workshop was a platform for participants to self-identify as volunteers for beta-testing. This act of volunteering goes beyond just offering physical space for sensor deployment. It signified a commitment to actively participate in the ongoing development and maintenance of the network. The level of community involvement strengthened the bonds between CBOs, community members, and the research team, creating a more resilient and responsive sociotechnical system. In summary, this workshop facilitated the collection of community input and emphasized the collaborative and participatory nature of the sociotechnical network development process, with community volunteers and CBOs at its core. This holistic approach ensured that the resulting network was not just a technological infrastructure but a reflection of the community's values and aspirations.

2.3.2. Identify hazards & vulnerability zones

This section discusses how to utilize local knowledge in the process of identifying hazards and vulnerability zones within the community, which is essential for effective sensor deployment. The community workshop aims to identify vulnerability zones and recruit volunteers for sensor placement, among other goals. These two particular aims are integral to deploying sensors in relevant geographic locations. Throughout the focus group discussions, participants pinpointed locations within the community that are particularly prone to the presented problems of flooding and air and water quality. In the closing discussion of the community workshop, consensus is built on what zones are most vulnerable according to the project scope. Simultationously, participants have the opportunity to volunteer their properties as potential sites for sensor placement. After the community workshop, potential deployment sites within the respective vulnerability zones were identified for sensor placement.

2.3.3. Develop & deploy sensors

This section outlines the development and deployment of a range of sensor nodes aimed at enhancing environmental monitoring within the community. A combination of in-house sensor nodes and off-the-shelf products was deployed to achieve an optimal balance between affordability, reliability, and precision. The air quality nodes were designed to measure key parameters, including CO_2, $PM_{2.5}$, PM_{10}, SO_2, NO_2, humidity, and temperature. Power was supplied via a solar panel to minimize costs for community members who hosted the nodes. Concurrently, the water quality nodes were equipped to assess salinity, dissolved oxygen, water temperature, and water level. Off-the-shelf products were deployed for the water quality and flooding sensors. For air quality monitoring, in-house sensor nodes were developed. The strategic deployment of these advanced sensor nodes occurred at locations identified in collaboration with community members based on local knowledge of pollutant sources, ease of access for maintenance and calibration activities, and the security of each site. Each node is equipped with a Long Range Wide Area Network (LoRaWAN) or cellular communication module for data transmission to a central server, enabling near real-time monitoring of the environmental conditions within the targeted community.

Considerations regarding whether to place sensors on public or private properties, or a combination of both, are crucial, given the site-specific conditions within neighbourhoods in the respective case studies. The liability factors in case of damage, access to private property for sensor repair, and cost to stakeholders for power or Wi-Fi need to be determined. To address these topics, a Quality Assurance Project Plan (QAPP) is needed, following guidance from the Environmental Protection Agency (EPA) (Clements et al., 2022). The QAPP outlines the responsibilities of each party in developing, operating, and maintaining the sensor network and collected data.

2.3.4. Monitor & analyze environmental impacts

In this phase, the focus is on systematically gathering and analyzing data related to environmental conditions within the community. The sensors ideally monitor key indicators such as flooding, air quality, and water quality by deploying a network of low-cost sensors in real-time. This data collection process allows a comprehensive understanding of the community's environmental impacts and vulnerabilities. While advanced analytical techniques are employed to interpret the collected data, it is important to note that the technical analysis of this data is not part of this paper. Instead, the emphasis is on engaging community members in the monitoring process, fostering transparency, and empowering residents to understand and address environmental challenges actively.

2.3.5. Design & test data dashboard

This section details the design and testing process of the data dashboard, which is crucial for effectively communicating environmental monitoring information to the community. By incorporating feedback from community partners and reviewing existing best practices, the research team aims to create a user-friendly dashboard that meets the specific needs of residents and community-based organizations while ensuring accessibility and clarity of critical environmental data.

The design of the data dashboard was informed by input from community partners regarding their desired use cases and information needs. The research team also reviewed existing dashboards for environmental monitoring data to document standards and best practices for data communication. The dashboard draws on design elements from existing dashboards, such as those from the United States Geological Survey (USGS, 2024) and NOAA (NOAA, 2024), but is also designed to meet specific needs identified by community members and CBOs. For example, the dashboard allows for flexible options in plotting and downloading data, which is essential for community partners who want to analyze data or use graphs in their meetings with potential funders or government officials. In addition, the dashboard provides contextual information about each monitoring variable so users can easily understand what is being monitored and how it might impact their health.

A beta-testing workshop was utilized as a participatory method to gain feedback during the development phase of the dashboard. This beta-testing workshop was conducted as an open call for participation, inviting volunteers who would agree to participate in a 90-minute workshop, have access to appropriate hardware, like smartphones or computers, and had participated in the previous workshop. The beta testers enlisted in the study were granted access to the dashboard for usability testing and feedback, and were offered a $25 gift card. Following a predefined time period for testing, feedback was collected through two channels: a beta-testing workshop and an online survey. The beta-testing workshop, comprised of a tutorial on dashboard functionality and exercises asking participants to find air quality data at a specific time and location, aimed to identify potential shortcomings. The workshop concluded with a discussion session to reflect on dashboard experiences. The survey focused on specific aspects of the dashboard and asked for qualitative or quantitative feedback through a point-rating system and open-ended questions. In this study, beta-testers were asked to rate predefined questions on a 5-point scale, including navigation, overall design, design of data displays, the relevance of displayed information, and the comprehensibility of the data presented. This task was followed by an open-ended section for users to provide comments or additional feedback regarding the dashboard.

2.3.6. Reflect & report results

In this phase, the focus shifts to reflecting on the findings gathered throughout the engagement process. This involves a thorough examination of the data collected from community feedback, sensor readings, and dashboard interactions. A key component of this process is the role of CBOs as vital points of contact for keeping constituents engaged. These organizations facilitate communication, ensuring that residents are not only informed about the project's outcomes and implications but also understand the significance of the findings in the context of environmental monitoring and community resilience. By leveraging the connections established through CBOs, stakeholders can synthesize insights effectively, highlighting achievements and lessons learned. Furthermore, this reflection outlines the next steps for establishing a comprehensive regional framework, ensuring that the knowledge gained contributes to future initiatives and fosters ongoing community engagement through sustained collaboration with CBOs.

3. Results & discussion

3.1. Community engagement outcomes

The engagement components of this study included two primary events: the community workshop (Phase A) and the beta-testing workshop (Phase C). Additionally, individuals and organizations who volunteered as beta testers and/or for sensor deployment were frequently engaged through email and site visits throughout the entire phase of this pilot project (Phase B). A total of 25 people participated in the first workshop, 7 of which volunteered as beta testers as well. All participants were residents of IOB. This group included elected officials, the mayor and council members, representatives of San Patricio County, and the CBO Ingleside on the Bay Coastal Watch Association (IOBCWA).

The community workshop's primary objective was to collaboratively pinpoint strategic sensor deployment locations, drawing from the participants' collective knowledge and local insights. Through content analysis of the co-created dataset acquired during this workshop, we were able to discern the frequency with which certain topics were raised. This quantitative analysis shed light on the issues that resonated most profoundly with the community, offering crucial insights into their priorities.

The culmination of this analysis can be found in Tables 3–5, which categorize and rank these topics in order of their prevalence within the community workshop discussions. This ranking served as a valuable reference point, guiding the subsequent research efforts by highlighting the issues of utmost significance to the community, thereby ensuring that the study aligns closely with its needs and concerns (Table 6).

The outcomes of the community workshop, encompassing the concluding discussion, reveal that workshop participants regard water as a valuable asset for the coastal ecosystem and recreational purposes. Nevertheless, it is evident that the workshop participants harbour notable concerns about the associated risks, particularly related to flooding and water quality. The results underscore the impact of a prior drainage study in elevating awareness regarding flood-related issues within the city. Residents are acutely aware of the potential risks posed by flooding, and this concern is prominently featured in their discussions. Furthermore, there is a widespread perception among residents of a discernible link between wind directions and industrial air pollution. Some residents reported detecting odours whenever the wind blew from the east, where an industrial complex is located.

Beyond these concerns, residents are apprehensive about the broader implications of air pollution on respiratory health. The increasing pace of industrial development, ongoing canal dredging activities, and intensified ship traffic collectively contribute to the worries that cut across all three categories of water and air quality, as well as flooding. In response to these concerns, workshop participants suggested various potential strategies and a few actions. These included deploying sensors to monitor and identify different air pollutants, enhancing drainage and stormwater infrastructure to mitigate flood risks, and exploring structural improvements to safeguard against rising waters. These proposed strategies reflect the community's proactive stance

Table 3. Frequency data analysis on assets.

AIR QUALITY	WATER QUALITY	FLOODING
MORE FREQUENT	MORE FREQUENT	MORE FREQUENT
Southeast Wind/Breeze	Water Recreation	Water Recreation
Bird Watching	Wildlife	Drainage Study
Sailing	Water Quality	Bay is almost at Sealevel
Increased Bird Population	Ingleside Cove	McBluff
Cooler Temperatures	Wildlife Sanctuary	Communities Uphill
Air Quality Sensors	Bahia Marina	Efficient Water Drainage
	Berry Island	Permeable Shoreline
	Spoil Island	
	Flat Area	
LESS FREQUENT	LESS FREQUENT	LESS FREQUENT

Table 4. Frequency data analysis on challenges.

AIR QUALITY	WATER QUALITY	FLOODING
MORE FREQUENT	MORE FREQUENT	MORE FREQUENT
Affect on Respiratory Health	Desalination Plant	King Tides
Industry Increasing Emissions	Quality of Drinking Water	Ship Traffic
Increased Ship Traffic	Ship Ballast Water	Dredging
Responsible Parties Deflect	Aging Potable Water Infrastructure	Sea Grass Damage
Regulations aren't Enforced	Smell from Well Water	Noise Pollution
Bad Odors	Drainage System	Road Flooding
Sulfide Fuel	Drainage Check Valves	Standing Water
Fertilizers and Pesticides	Standing Water	Major Storm Events
Decline in Biodiversity	Erosion	Limits Accessibility
Cancer-Causing Pollution	Sea-Level Rise	Infrastructure Damage
Dredging	Large Ship Traffic	
	Silting in Canals	
	Livelihoods/Property Values	
	Government-Industry Collusion	
	Lack of Community Involvement	
	Surrounding Counties Needs	
	Major Storm Events	
	Invasive Species Brought by Ships	
	Permanently Located Boats	
	Lack of Proper Testing/Regulation	
LESS FREQUENT	LESS FREQUENT	LESS FREQUENT

toward addressing these challenges and highlight the importance of a collaborative approach in striving for a more sustainable and healthy environment. Several individuals volunteered to become beta-testers and/or offered their properties for sensor deployment.

Table 5. Frequency data analysis on strategies.

AIR QUALITY	WATER QUALITY	FLOODING
MORE FREQUENT	MORE FREQUENT	MORE FREQUENT
Lower Overall Emissions	Drainage Study	Drainage Study
Recognize PM 2.5 as Pollutant	Recycling Water	Possible Levy
Utilize Air Quality	Replace/Maintain Pipes	Reinforce Existing Properties
Emergency Alert System	Reduce Ship Traffic	Better Drainage Systems
App for Air Quality Alerts	Create a No-Wake Zone	Elevating the Beach Club
Plant More Trees	Place Desalination Plant Off Coast	Increase Infrastructure Funds
Investment in Clean Energy	Increase Resources for Conservation	Reduce Shipping Traffic
Local Checks and Balances	Create a Baseline for Water Quality	Raise Bulkheads
	Proactive Approach to water Quality	Flood Insurance
	Industry Water Pollutant Alert System	Measure Tidal Surges
	Create More Community Awareness	App for Flood Alerts
	Limit MODA Pier From Expanding	Proper Education About Floods
	Removal of Beach Boats	
LESS FREQUENT	LESS FREQUENT	LESS FREQUENT

Table 6. Frequency data analysis on actions.

AIR QUALITY	WATER QUALITY	FLOODING
MORE FREQUENT	MORE FREQUENT	MORE FREQUENT
Deploy Sensors	Deploy Sensors	Deploy Sensors
Monitor Air Quality	Monitor Water Quality	Monitor Flooding
Inform Decision-makers	Inform Decision-makers	Inform Decision-makers
LESS FREQUENT	LESS FREQUENT	LESS FREQUENT

3.2. Deployment & data collection outcomes

In the case of this study, the research team developed and built the sensor nodes, developed calibration and quality assurance algorithms for data quality, maintained the data server and dashboard, and provided technical support as needed. A community-based partner organization, IOBCWA, maintains the nodes and conducts quarterly calibration by co-locating the sensors with a Federal Equivalent Method monitor (EPA, 2024). At the time of this article's publication, all IOB sensors are deployed at private properties (Figure 4).

The sensor network was deployed successfully and has been monitoring the designated community for a test period of three months. However, maintaining these sensors has posed an ongoing challenge due to the harsh coastal environment, especially the presence of seawater, which has led to biofouling on various surfaces.

3.3. Beta-testing outcomes for dashboard design

The PAR approach identified a community-driven demand for readily available, real-time local environmental data presented in an easily understandable format. In response

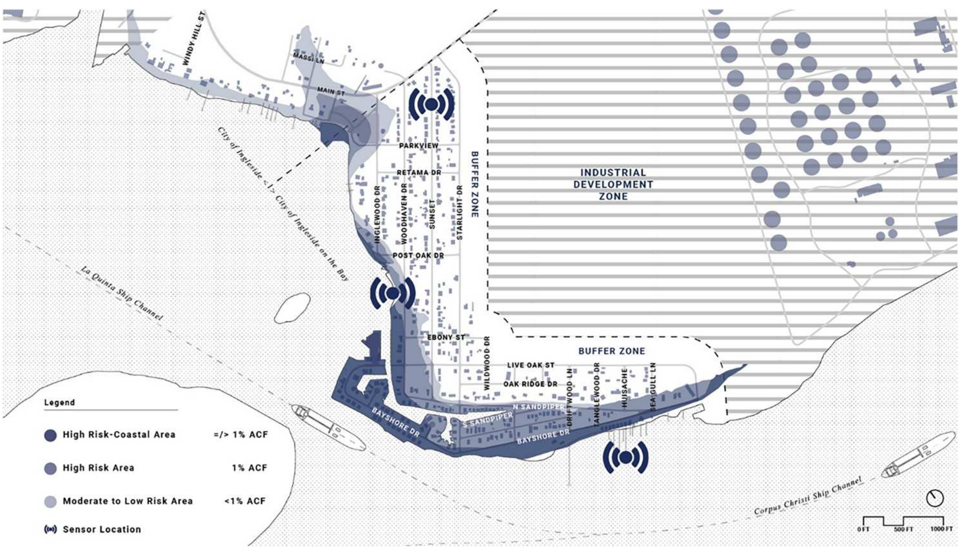


Figure 4. Sensor locations in IOB, adjacent to the Corpus Christi and La Quinta Ship Channels and several industrial facilities.

to this community-recognized requirement, the project team crafted an initial web-based data dashboard for displaying real-time sensor data. The design of the initial dashboard was influenced by input gathered during the community workshop.

The initial dashboard design included (1) a navigation map allowing users to view sensor locations spatially and query specific locations and (2) sensor-specific pages displaying time-series graphs of each monitoring variable over the past several weeks. After completing the initial design, feedback from a beta-testing workshop was utilized to further refine the dashboard. This iterative process resulted in substantial updates, including the addition of (1) a plotting page where users can select the location, monitoring variables, and time frame to create dynamic plots showing the requested data, (2) a page for creating dynamic data tables and downloading data in CSV format (comma-separated values) for further analysis, and (3) a page displaying summary statistics for each location and monitoring variable. The dashboard features a landing page displaying a map of the community with markers indicating the locations of available sensors. Users can select a sensor to access another page that provides graphs for each measured parameter. Information about each parameter, its sources, and potential health impacts is also included.

The team developed a data dashboard that presents sensor measurements on a map of the area, enabling real-time visualization (Figure 5). Additionally, we have incorporated relevant data from existing research-grade monitoring stations, including nearby air and water monitoring stations, as well as a recently installed air quality monitor by the community. While the dashboard version presented to users through this study was accessible through web browsers only, future iterations will expand its availability to mobile apps and other platforms, allowing stakeholders and the general public to monitor environmental conditions across the community.

The monitoring data must undergo further validation, analysis, and calibration before being released to the general public. The development process of the sociotechnical network was investigated to fulfill the aim of this study, therefore, the actual findings of the environmental monitoring itself are not fully addressed in this paper. The ultimate goal is to provide community members with a comprehensive overview of environmental monitoring data.

The beta-testing phase uncovered several crucial enhancements that will be integrated into future versions of the dashboard when approaching the regional scale. A primary concern voiced by beta-testers revolved around the difficulty of using certain dashboard features on smartphones. Given that many users are expected to access sensor data through their mobile devices, ensuring seamless compatibility across various platforms, including computers, tablets, and phones, becomes paramount and will be a top priority for our upcoming development endeavours. Additionally, beta-testers expressed challenges faced by non-technical users in distinguishing between normal and ‘high’ or ‘unhealthy’ parameter values. To address this, participants recommended displaying acceptable values and regulatory limits alongside sensor data to provide context, facilitating users in recognizing when action or mitigation measures are necessary.

One notable obstacle encountered during the dashboard evaluation and beta-testing initiative was the limited participation. Seven individuals attended the beta-testing workshop (Table 7). While the gathered feedback provided valuable insights into the

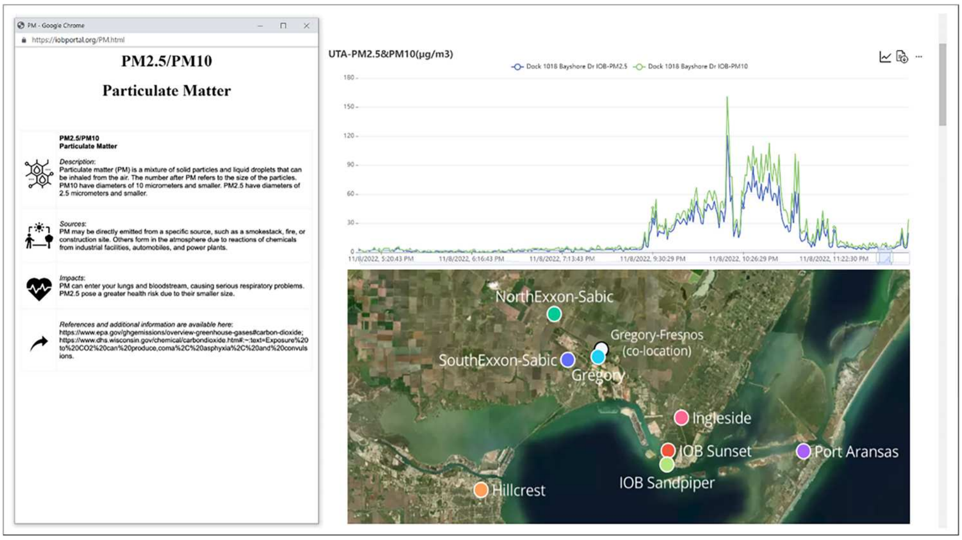


Figure 5. The data dashboard shows the area map and the $PM_{2.5}$/PM_{10} chart, including descriptions for non-academic audiences.

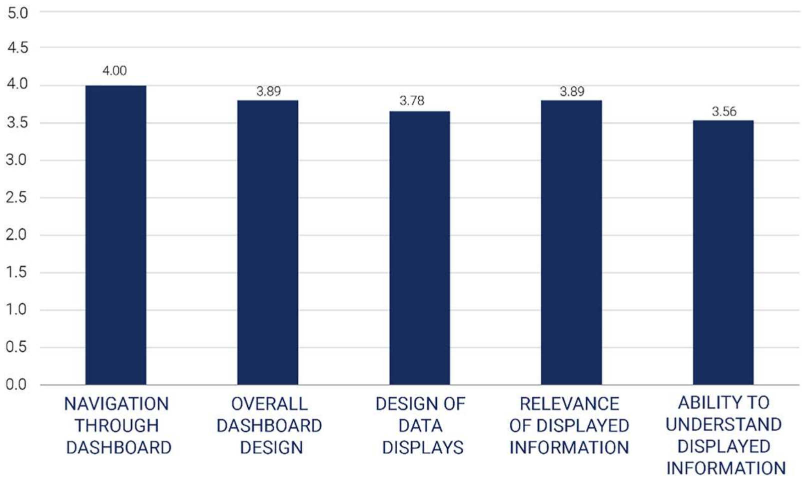
platform's usability, we acknowledge the need to develop strategies to engage more diverse community members in future evaluation efforts.

3.4. Discussion

This paper aimed to deliver a participatory framework to develop an environmental monitoring dashboard as an initial step toward a smart city framework. Smart city concepts often emphasize the integration of technical systems and social engagement, and previous studies have highlighted the need for participatory approaches. For example, Hollands (2015) underscores the importance of blending technology with participatory efforts, while Kitchin (2014) critiques the purely technocratic implementations of smart cities that overlook social dimensions. In this context, our study sought to operationalize citizen participation as a core element in creating a sociotechnical framework, thereby extending these theoretical conversations by demonstrating their practical application.

Addressing the research questions, this study shows how local knowledge and stakeholder engagement can be effectively integrated into designing and implementing an environmental monitoring data dashboard for coastal communities. Previous research has identified the gap between expert-driven data platforms and local user engagement, particularly when these platforms are designed without significant community input (Gabrys, 2016; Meijer & Bolívar, 2016; Nam & Pardo, 2011). The methodological approach from the initial community workshop to the beta-testing workshop enabled the research team to form meaningful partnerships with residents, CBOs, and governmental officials. This aligns with the work of Goodspeed (2015), who argues that participatory smart city projects are more successful when they engage local stakeholders throughout the design process.

Table 7. Beta-testing results.



The integration of social and technical components spanned the entire process, from initially seeking community input on what aspects should be monitored and where measurements should be taken to incorporating this feedback into the dashboard design. The dashboard includes explanations of the respective measurements for non-academic audiences, making it easier to understand how certain substances may impact the individual resident. The key factors that influence the successful deployment and maintenance of low-cost sensor technology include liability in case of damage, access to private property for sensor repair, and cost to stakeholders for power or Wi-Fi needs. Discussions with public officials and CBOs suggested placing sensors on private properties as the preferred solution since the sensors are more protected from damage, theft, or vandalism. Furthermore, the individual property owners are all members of the community partner organization, IOBCWA, and therefore, they are already organized through this organization. Stakeholder input was essential in shaping the dashboard's functionality and design. This reflects findings from Barns (2018), who emphasizes the importance of flexibility in data visualization tools in smart city applications. Community feedback resulted in the addition of several features, including a plotting page where users can select the location, monitoring variables, and time frame to generate dynamic plots. Another feature is a page for creating dynamic data tables and downloading data in CSV format for further analysis. Additionally, a page displaying summary statistics for each location and monitoring variable was added. Adding these features underlines how community input led to direct results and changes in the dashboard design.

This pilot project for a participatory framework in developing an environmental monitoring dashboard is a blueprint for other communities and towns in the Texas Coastal Bend Region. The combination of sensors deployed regionally, reporting to one publicly accessible environmental monitoring dashboard, will form the basis for a regional smart city framework moving forward.

4. Conclusion & recommendations

This paper summarizes a participatory approach to deploying an environmental monitoring network that reports data on a community dashboard, presenting residents and decision-makers with a platform for data-driven decision-making. This process was intended to become the first step in enabling a smart city framework, equipping the city with an IoT monitoring network delivering readily available data. To address the aims of this study, this paper developed and applied a six-step framework spanning three phases: Phase A – Community Workshop, Phase B – Deployment, and Phase C – Beta-testing Workshop. These steps included to (1) engage actors, (2) identify vulnerability zones, (3) develop & deploy sensors, (4) monitor & analyze environmental impacts, (5) design & test data dashboard, and (6) reflect and report results. In the growing field of interdisciplinary studies on urban sustainability, this paper adds a practical framework to the existing literature.

The participatory approach enabled the development of the described dashboard and environmental monitoring data. While the dashboard is not yet open for public use, its development integrated community feedback and beta-testing outcomes as fundamental components. The engaged approach established collaborations with CBOs and individual residents, leading to formal agreements between the research team and the stakeholders on sensor placement and maintenance. While the developed data dashboard will not single-handedly transform a city into a smart city, it represents a significant stride towards delivering a data-driven evaluation of environmental impacts. The participatory approach employed in this study, rooted in a bottom-up perspective, has proven itself to be an invaluable tool for constructing a research framework that actively involves stakeholders in the process. This approach has facilitated a deeper level of engagement and collaboration, ensuring that the project aligns closely with the needs and aspirations of the community. Furthermore, the challenge of working across disciplines and applying PAR as an overarching methodology for engagement has been instrumental in securing the targeted community input. Through the series of community and beta-testing workshops, we have harnessed the collective knowledge of residents and stakeholders, allowing them to play a central role in shaping the project's direction. One pivotal achievement has been the identification of sensor locations and the successful deployment of measuring stations on private properties, thanks to the voluntary participation of residents. This grassroots involvement has been essential in establishing a robust and expansive sensor network that covers a wide geographic area.

The data collected through this network will be valuable for informing decision-makers at various levels, from local CBOs to county and state authorities. They will have far-reaching implications, influencing various decisions and initiatives. Once fully accessible to the public, this dashboard will enable residents, CBOs, and governmental officials to better understand data and locations regarding air quality, water quality, and flooding in their community. These data can impact decisions regarding the comprehensive development plan, strategic planning efforts along the waterfront and flood zones, and influence the negotiations with adjacent industries. Moreover, the data generated by this sensor network have the potential to shape decisions at the county and state levels, particularly in terms of future placements of regulatory-grade sensors approved by the EPA. This could create a more extensive and integrated environmental monitoring infrastructure that benefits our community and neighbouring regions. To this end, this study recommends public deployment sites on city- and county-owned properties to ensure easily accessible sensor locations and support from elected officials for environmental monitoring. Support from public entities in both deployment, maintenance, and funding for future sensor nodes is highly recommended to ensure a comprehensive monitoring network.

Looking ahead, the next steps in this endeavour are twofold. First, there is a need to calibrate the sensors to meet regulatory-grade standards, ensuring the accuracy and reliability of the data collected. This step is crucial in maintaining the findings' credibility and relevance for policymakers and researchers. Secondly, the sensor network should be expanded to provide a more comprehensive assessment of environmental impacts, particularly in the Corpus Christi Bay Region. This expansion will encompass a broader range of environmental parameters, including flood impacts, air quality, and water quality. Doing so will deepen the understanding of the region's ecological dynamics and enhance our capacity to address environmental challenges effectively.

Community engagement is a crucial tool for empowering residents to create sustainable urban futures. Integrating human and technical dimensions is an opportunity to combine community knowledge and advanced technology to develop data-based solutions for cities and regions. Smart technologies, leading to smarter cities, will play a pivotal role in this participatory process.

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