Anticipatory Risk Assessment and Mitigation for Water Distribution Infrastructures in Coastal Communities Subject to Sea-Level Rise

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Abstract: As climate change leads to increasing sea levels, coastal communities are experiencing increased flooding. In the coming years, these effects are expected to lead to movements in coastal populations, with implications for utilities providers, who will face impacts on their distribution network components and changes in demand over time. This study takes an anticipatory approach to infrastructure risk assessment and mitigation. It presents a methodology to characterize the future implications of sea-level rise-induced flooding and population movements for drinking water utility managers, as well as mitigation recommendations to prepare these systems for continued operations under these changing conditions. This study assesses and creates a new understanding of the implications of sea-level rise-induced population displacement on demand to water utilities. The method includes novel integration of sea-level rise modeling, climate-change-induced population shifts, and infrastructure risk analysis to create an anticipatory risk assessment approach for water distribution infrastructure operations and management for the coming decades. Additionally, an emphasis is placed on proposing mitigation recommendations at various points throughout the study. High-resolution building datasets are used in combination with sea-level rise projections to estimate the magnitude and timeline of the change in demand to the drinking water supply. The methodology combines quantitative and qualitative analyses to provide detailed component-specific risk assessment and mitigation measures while considering the urgency with which these mitigation measures may be needed. The methodology is applied to two study areas in Chatham County, GA, on the eastern coast of the United States. Qualitative assessment over a range of study area conditions leads to findings of specific patterns in future types of flooding on a neighborhood scale, which are presented with corresponding mitigation recommendations. A pipe prioritization score combines several physical and operational factors across space and time to quantitatively and systematically highlight pipes that are particularly likely to require intervention to prepare for future changes from sea-level rise in coastal communities. **DOI: 10.1061/JITSE4.ISENG-2778**. *© 2026 American Society of Civil Engineers.*

Practical Applications: Climate change is leading to shifts in where people are living along the coast. This work investigates the impacts of these population movements on changes in demand on drinking water infrastructure systems. It looks decades into the future to predict future population shifts, providing risk mitigation recommendations to prepare these critical systems for continued operations under changing future conditions. A new risk assessment methodology is proposed that integrates readily available datasets to provide a detailed, high-resolution, component-specific risk assessment of water distribution systems. The results provide specific risk mitigation actions to take and enable utility owners and operators to take a proactive rather than reactive approach to managing their systems to better prepare these systems for the realities of the future.

Introduction

All US states are expected to be affected to some extent by sea-level rise (SLR) in the coming years (Hauer 2017). Even if they are not along the coast and not directly affected by shifting coastlines, rising sea levels will result in population shifts throughout the country. Coastal cities are expected to experience population decreases as residents affected by coastal flooding move further inland. Conversely, inland cities are expected to see a net increase in migrants of more than 250,000 by 2100 (Hauer 2017).

These changes to cities have implications for the utilities that supply their inhabitants. Utility providers must anticipate these population movements to appropriately accommodate for shifting populations, whether it is decreased demand on infrastructure, increased demand, or simply geographical shifts. The further ahead these changes can be planned for, the more cost-efficient their implementation can be. Projecting future changes and implementing anticipatory risk mitigation measures can also lower future potential negative impacts on populations as changes in utility services occur.

This paper focuses on drinking water distribution systems in coastal communities, proposing a methodology to conduct anticipatory risk assessment and mitigation for these systems. The methodology provides a new way to assess the current and future performance of these networks and mitigate risks from sea-level rise. Using both quantitative and qualitative methods, it presents a study of how the drinking water distribution network will be affected by sea-level rise in the next 125 years until the year 2150. It considers the buildings and populations serviced by individual water distribution network pipes. Based on the analyses, it computes

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a quantitative score for each pipe and establishes several distinct categories of affected neighborhoods for which risk mitigation recommendations (e.g., increase pipe capacity, decrease pipe capacity, plan to shut down pipes, service pipes before flooding reduces pipe access) are provided. Compared to prior work, it presents a novel integration of sea-level rise modeling, climate-change-induced population movement, and infrastructure risk analysis to assess the impacts of sea-level rise-induced population shifts on utilities that service coastal communities. This work also takes a step further than risk assessment by presenting actionable mitigation recommendations at several points throughout the analysis.

The rest of the paper is organized as follows: the next section provides background and related works in the areas of sea-level rise modeling, predicting population shifts, and coastal infrastructure risk assessment. Next, the proposed infrastructure risk assessment methodology is presented, including data inputs, processing steps, and analysis outputs. The methodology is then applied to two test study areas in Chatham County, GA, located on the eastern coast of the US Specific values for sea-level rise, building footprint information, and water distribution infrastructure data in these areas are used to demonstrate the methodology. Risk mitigation recommendations are provided based on the results, and the generalizability of the methodology and outcomes to other coastal communities impacted by sea-level rise is discussed.

Background and Related Works

While it is known that climate change is leading to population shifts and that infrastructure systems are critical to support human populations wherever they are, there has been little work rigorously integrating information across these areas to conduct anticipatory risk assessment of infrastructure looking into the future under conditions of climate change. This work fills a research gap by integrating ideas from three main areas: sea-level rise modeling and projections, population shifts over time, and water infrastructure system risk assessment and mitigation to create a novel anticipatory risk assessment and mitigation methodology. With a focus on coastal communities, the outcome of the methodology is to be able to provide detailed component-level risk assessment and risk mitigation recommendations for water distribution system infrastructure to serve changing population needs over time under sea-level rise.

Researchers and stakeholders recognize that SLR will impact water infrastructure and are taking steps to understand this risk and the timeline on which SLR will impact their communities (Nazarnia et al. 2020). Various SLR models have been developed to predict SLR trends over the course of the 21st century (Nieves et al. 2021; Naren et al. 2025; Tebaldi et al. 2021). Notably, the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) presents global SLR projections under five shared socioeconomic pathways (SSPs) representing various levels of climate action (Fox-Kemper et al. 2021; Kopp et al. 2023; Garner et al. 2021). These projections are vital for preparing for changing conditions if they are used to assess specific impacts on infrastructure networks, as this study aims to do. Various works summarize potential risks that SLR poses directly to critical water infrastructure, including saltwater intrusion into drinking water and wastewater and drainage infrastructure (Nazarnia et al. 2020; Sangsefidi et al. 2023). Shen et al. (2023) focused instead on modeling the changes in water supply quality caused by saltwater intrusion, presenting a resilience index indicating wells and water treatment plants that are expected to be disrupted by the increased salinity in the water supply. A systematic review of literature on the effects of climate change on water infrastructure highlights research identifying changes in water demand patterns (e.g., due to increasing temperatures) and supply interruptions due to damage from extreme weather events that place stress on already aging infrastructure (Żywiec et al. 2024). Zhou and Hawken (2023) also include projections of future conditions and use a scenario-based methodology to assess the effectiveness of four different approaches (business as usual, retreat, defense, and accommodation) to reduce identified SLR risk to wastewater treatment plants. For infrastructure risk mitigation, the US Environmental Protection Agency has identified a list of general recommendations for utility providers to prepare for the effects of climate change including elevating water treatment plants and pump stations (USEPA 2023). While these recommendations guide utility managers on how to prepare water infrastructure for changing conditions, they do not identify specific locations nor a timeline on which these adaptation measures will be needed.

Azevedo de Almeida and Mostafavi (2016) identify four major ways in which SLR impacts coastal infrastructure—flooding, erosion, land subsidence, and saltwater intrusion—and present a corresponding list of adaptation measures that can be implemented to address these impacts. Allen et al. (2019) found that SLR threatens coastal residents' reliable access to hospitals, power, clean water, and other critical services. However, a detailed assessment and timeline of the evolving conditions that the network will be faced with over time, as presented in this study, is still needed to provide utility managers with the ability to better plan and implement resilience measures. A prior study has assessed the resilience of water distribution infrastructure, defined as the ability to meet water demand as components (wells and water treatment plants) are contaminated by saltwater intrusion. However, while recognizing that populations in areas affected by SLR may change, this study proceeds assuming that population remains constant (Shen et al. 2024). While Azevedo de Almeida and Mostafavi (2016) and Shen et al. (2024) investigated the risk of damage due to SLR to water system components, they did not assess the consequences of dependent infrastructure (i.e., residential and commercial buildings) on this network. Even if no system components are damaged, the system must adapt to changes in demand as users are displaced from buildings. In the studies included in this paragraph, the relationship between water distribution infrastructure and the specific buildings and populations it serves is not thoroughly considered. A higher resolution assessment of shifts in demand is needed to reveal opportunities for more specific interventions in a neighborhood or on the pipe-by-pipe scale as in this work.

Previous works have taken several approaches to estimating SLR-induced displacement using SLR projections. SLR poses both acute (e.g., storm surge) and chronic flooding risk to populations in coastal areas, with the impacts of more gradual flooding on population shifts being less well understood (Curtis and Bergmans 2018). Curtis and Bergmans (2018) gave an overview of how various works model population displacement from climate change, while highlighting the need to better understand populations' behavior in the face of changing environmental conditions. Population displacement models such as the one developed by Hauer (2017) estimate climate-change-induced population changes for US states, counties, and some major cities. Seeteram et al. (2023) modeled the effects of SLR on resident mobility by assessing Miami-Dade, FL, residents' ability and willingness to relocate. The study combines a flood model with social vulnerability to estimate residents' exposure to flooding and ability to relocate in various SLR scenarios. Wrathall et al. (2019) discussed the need to update these models over time, with many factors influencing residents' decisions to stay or leave in the face of severe natural hazard risk, including varying perceived risk, a cultural connection to the location, socioeconomic status, the presence of flood adaptation measures and climate awareness in the community, as well as reliable access to necessary resources such as food and income (Hino et al. 2017; Daraz et al. 2024; Davis et al. 2018; Heslin et al. 2019; Nourali et al. 2024). While SLR-related population shifts are complex and difficult to predict accurately, it is important for coastal communities to use the best possible estimates to prepare their infrastructure for future migration trends so that these systems are able to continue to provide essential services to their communities in the near and distant future. Gomaa (2022) assessed the effect of SLR-induced population displacement on traffic patterns, including the effects of flooded roads and loss/relocation of regular destinations such as office buildings. Koks et al. (2022) investigated the potential economic damage to European coastal critical infrastructure in various flooding scenarios, including possible population increases in coastal cities driven by projected economic development, but did not include population displacement in their assessments. Pickard et al. (2017) examined how four climate scenarios and subsequent population shifts may affect water demand in counties nationwide. The authors focused on identifying counties where increases in population may cause stress to the drinking water supply. However, while the impacts of climate-change-related population shifts on water utilities are acknowledged to various extents in existing literature, there is a lack of a thorough assessment of how coastal communities will accommodate their decreased demand as customers are displaced by SLR.

At the intersection of population shift modeling and water infrastructure management are works conceptually discussing the challenges that utilities face in shrinking cities (for reasons not specific to climate change) in addition to works on meeting the demand on utilities in growing cities (Grundel and Magnusson 2023). It has been recognized that the spatial distribution of water demand makes it difficult to keep water operation costs reasonably low for cities facing population decline (e.g., maintaining a branch of the distribution system operational despite that area being very sparsely populated can drive up costs for all customers) (Faust and Kaminsky 2018). The unique challenges of shrinking demands on water utilities can also be seen in studies conducted following the coronavirus pandemic. Quarantine and sudden drops in use of many office and commercial buildings caused changes in demand patterns to which drinking water utilities had to quickly adjust. Berglund et al. (2022) found that the increased residence time of water in parts of the distribution network with less demand negatively affected water quality by allowing bacterial growth. Bostic et al. (2021) found that small water distribution systems (servicing fewer than 10,000 people) were especially vulnerable to decreases in revenue. These studies highlight the risk of being unprepared for future shifts in demand to drinking water infrastructure. Lessons from prior unpredictable events such as the pandemic can be used to motivate water utility managers to assess longer term changes in demand they can expect in coming decades as proposed in this work and take steps to better prepare. A table summarizing the goals, methods, tools, and relevant limitations of the works presented in this section is provided as Fig. S1.

The proposed methodology combines SLR projections and population displacement estimates to understand how SLR may affect the drinking water distribution system and offer recommendations to prepare the drinking water distribution system for these changes from now through the next 125 years. Emphasis is placed on creating an anticipatory risk assessment and mitigation approach, rather than simply reacting to conditions after they occur (Tien 2022). Understanding SLR-induced population displacement trends years, if not decades, in advance gives utility providers time to increase pipe capacity, plan to shut down pipes, or take other actions as needed. This work advances upon the existing relevant research presented in this Background and Related Works section by providing high-resolution results from the building level, i.e., identifying buildings expected to become uninhabitable over time due to coastal flooding. The analysis considers the implications of this population displacement on the drinking water distribution system that services the area by identifying regions that will face a decrease in water demand and others that may experience an increase in water demand as the county's population shifts inland. This building-level resolution of expected changes in water demand allows for planning on a city scale, and the SLR estimates until 2150 provide a timeline of evolving conditions and a sense of the amount of time available before action must be taken in different parts of the network. Resulting pipe-specific risk assessments and mitigation recommendations provide actionable adaptation recommendations for multiple future scenarios for coastal communities in which the water network is impacted by SLR.

Methodology

The proposed risk assessment methodology for drinking water distribution systems in coastal communities is shown in Fig. 1. The methodology includes several data inputs, processing steps, and outputs. Each of these is described in more detail in the following sections. Specific application of the methodology to the study area of Chatham County, GA, is provided in the following section to demonstrate use of the methodology and resulting findings and mitigation recommendations.

Projecting Sea-Level Rise over Time in Study Area

The first step of the analysis is to estimate how quickly sea levels will rise in the chosen study area. While there is no standard way of doing this, tide gauge data, global SLR scenario estimates, and local SLR scenario estimates can be used in combination to estimate a plausible timeline for SLR for the future time period of interest. The specific data sources available for this depend on the selected study area, though some, such as the NASA sea-level projection tool, provide estimates at various locations globally based on the IPCC AR6 global projections (Fox-Kemper et al. 2021; Kopp et al. 2023; Garner et al. 2021). Global SLR estimates such as the IPCC AR6 global estimates provide a starting point for regional estimates. The reader is referred to the related works section of this paper for additional available models. If available, site-specific regional data, such as tide gauge data, can be used to adjust predictions and compared with projection data to confirm that the projection is reasonable (i.e., the actual measured tide gauge data fall within the range of possible future scenarios). If this is not the case and there is no evidence of error in the tide gauge data, a more regional projection may be necessary to increase accuracy of the site-specific results.

Determining Parts of Study Area Expected to Flood at Various Levels of Sea-Level Rise

The next step is to estimate the parts of the study area that are projected to flood under varying future scenarios of SLR. The National Oceanographic and Atmospheric Administration (NOAA) Office for Coastal Management provides map layers containing estimates for 0.30–2.44 m (1–8 ft) flooding scenarios at 0.30 m (1 ft) intervals above mean higher high water. As projections of climate-change impacts can be subject to high degrees of

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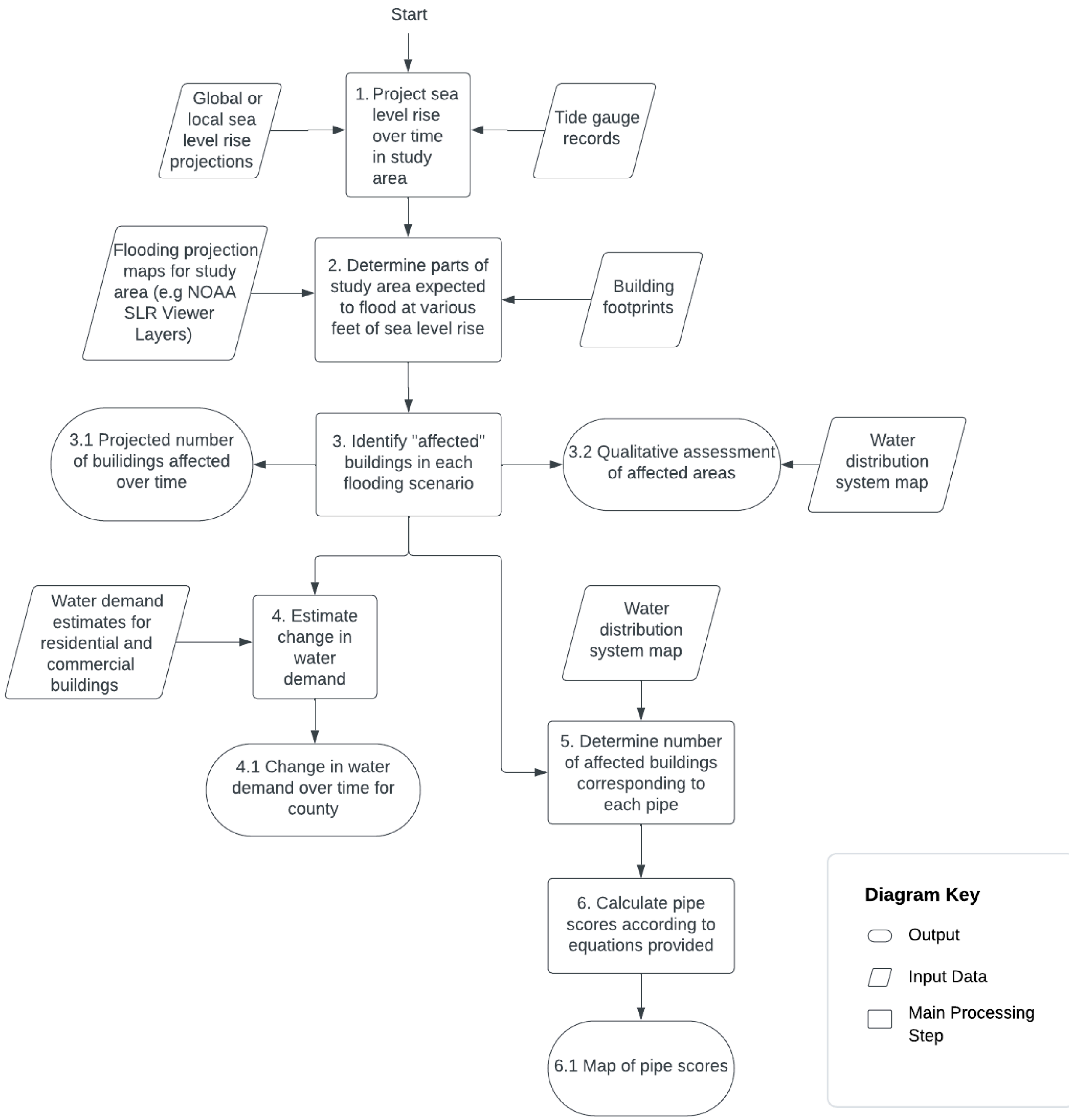

Fig. 1. Workflow summarizing proposed risk assessment methodology for drinking water distribution system in coastal communities subject to sea-level rise.

uncertainty, it is recommended that uncertainty be accounted for in the analysis at this step by including uncertainty in identifying these flooded areas. The NOAA map layers each consist of "high confidence" flooded areas, indicating areas expected to be flooded with an 80% degree of confidence, meaning that these areas can be expected to be correctly labeled as "flooded" more than 80% of the time, and "low confidence" flooded areas including areas expected to be flooded less than 80% of the time (NOAA Office for Coastal Management 2024). These datasets are available for the entire US excluding Alaska. Notably, the NOAA SLR datasets do not include subsidence, erosion, or human-made interventions such as dredging or culverts. Levees are included where data are available. Similar flood maps are available for international study areas, such as the Extreme Coastal Flood Maps for Aotearoa New Zealand (Paulik et al. 2023). Note that these map layers typically show areas expected to be flooded with a baseline of 0 m SLR in 2000. If the baseline level (i.e., year 2000) for the data of the study area is the same as the baseline for the SLR projections, no adjustments need to be made. If the baseline year is different, the SLR between the projection baseline year and the NOAA SLR scenario map baseline should be found and added to the NOAA SLR scenario map [e.g., the 0.61 m (2 ft) SLR map may actually be a 0.70 m (2.3 ft) SLR map once adjustments are made]. It is recognized that the identification of flooded areas in this step does not include the impact of drainage infrastructure on water levels or outputs from more complex hydrodynamic models showing detailed flood levels across a study area. If such data and projections are available for the desired study area, these can be used to improve the accuracy of the analysis at this step. The NOAA map layers are used in the study area application in this paper to demonstrate use of the methodology with widely available datasets.

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Identifying "Affected" Buildings in Each Flooding Scenario

To provide a high-resolution analysis of the study area, building footprint data are input and used in this step. For the area of interest, buildings are determined to be "affected" in a flooding scenario if they are within the regions expected to be flooded in the NOAA flooding scenarios described in the previous section. This is determined based on geographic locations of buildings. For example, using a mapping program such as ArcGIS, the intersection tool can be used to identify the buildings that fall within the polygons representing flooded areas, noting whether buildings fall within the high confidence or low confidence flooded areas. In the proposed methodology, if any part of a building is within the NOAA SLR polygon, then it is counted as affected and the full water demand for the building is considered to be eliminated under the future SLR scenario. This is because it is expected that even if only a portion of a building is permanently flooded, the occupants will be encouraged to move elsewhere because of the severe flood risk in such close proximity to underwater areas and the threat of a coastline that is slowly moving closer.

Qualitative Assessment of Affected Areas

The aforementioned analysis presents a quantitative estimate of the scale on which buildings in the community will be flooded in the coming decades. However, it alone does not give the information needed for planning mitigation efforts. A qualitative assessment of the types of flooding impacting the affected areas reveals common types of flooding scenarios. Mitigation recommendations can then be provided that correspond to the specifics of the scenario.

Using the proposed methodology and looking across the study areas with the NOAA sea-level scenario layers combined with the water distribution system map reveals similarities in the patterns of flooding across neighborhoods and roads. We categorize these into distinct "types" of flooding at the neighborhood scale (e.g., all buildings in a neighborhood are flooded, flooded areas are completely surrounding but not directly overlapping with a cluster of buildings, etc.). For each identified flooding "type," we make several actionable recommendations to be considered to address the situation. Utility managers may choose one or multiple proposed recommendations depending on the funding and time available. Conducting an assessment such as this several years in advance allows utility managers to plan more cost-effective interventions rather than needing an emergency intervention later in time. The specific risk mitigation recommendations are presented in the study area application section, although these flooding situations are anticipated to be found in different study areas, and the corresponding mitigation recommendations are also applied.

Projected Number of Buildings Affected Over Time

By finding the number of buildings affected in each of the flooding scenarios [0.30 m (1 ft), 0.61 m (2 ft), etc.] and using the sea-level projection to estimate the year in which each of the flooding scenarios may occur, a quantitative estimate of the number of buildings affected over time can be found. Each flooding scenario will have a high confidence and a low confidence affected building count, with the low confidence count including the buildings in the high confidence affected building count. The outcome provides a timeline of SLR-induced impacts, which can be visualized by plotting the changing number of affected buildings over time as a function of the corresponding year of SLR.

Estimating Change in Water Demand across Building Types

To estimate the change in water demand due to population shifts from future flooding, high-resolution building footprint information is combined with water usage data. Demand is dependent on a variety of factors, including building use, number of occupants, and building size. A variety of sources can be used to estimate water usage. In this study, a combination of data sources was used, including data from the Savannah Area Geographic Information System (SAGIS) categorizing buildings as commercial or residential, the Environmental Protection Agency (EPA) estimates of residential water use per person per day (WaterSense 2017), and industrial water usage estimates obtained from the Industrial Water Demand Forecast for the state of Georgia (CDM Smith 2022), which provides the county-wide industrial water usage for Chatham County. Assumptions about average household size were made combined with analysis of building code information. If more detailed data about the number of residential units in each building or number of occupants per household are available for a selected study area, they can be used to further refine water usage estimates at this step.

Mapping Affected Buildings to Affected Pipes

Next, to connect affected buildings with specific water distribution infrastructure assets for which planning or risk mitigation efforts can be made, we determine which buildings are serviced by which pipe, so that affected (e.g., flooded) buildings can be mapped to their corresponding pipe. In lieu of specific building-level information on service lines, this is done by assigning each building to the pipe nearest to it. The result is the number and locations of buildings serviced by each pipe and, for the "affected" buildings, the number of affected serviced buildings for each pipe.

Estimating Change in Water Demand over Time for County

Using the estimated number of buildings affected over time, building type codes to differentiate between residential and commercial buildings, and the estimated water demand per building, the change in water demand over time is estimated. This is done by multiplying each affected building by its corresponding estimated water use under each of the SLR scenarios. Values over time can be found for the maximum and minimum SLR scenarios and high and low confidence flooding to obtain a plausible range of future SLR impacts in the community.

Calculating Pipe Prioritization Scores

Looking across the many assets comprising a water distribution system and the typically limited resources to address potential risks, it is important to identify the critical components to prioritize system interventions. In this step, we define a pipe prioritization score considering the multiple factors that contribute to a pipe being more severely affected in a future scenario or a pipe needing attention more urgently than another. The components of the pipe prioritization score are shown in Table 1. Each of the components contributes to an overall pipe score to prioritize pipes for intervention and enables us to systematically prioritize pipes for resilience efforts. Pipes serving more buildings and larger pipes are prioritized. In the absence of flow rate data, pipe diameters and edge betweenness centrality—a measure of how often a network edge (i.e., pipe) lies along the shortest path

Table 1. Components of pipe prioritization score

Component	Details	Variable	Quantification
Amount of buildings serviced by the pipe	Captures how many residents rely on the pipe	C_{serviced}	$\frac{\text{Number of serviced buildngs}}{\text{Number of bildings in study area}}$
Pipe importance	Captures how important the pipe is to the system, in terms of both pipe capacity and pipe centrality	$C_{\text{importance}}$	$\frac{\text{Pipe diameter}}{\text{Max pipe diameter in system}}$ + Pipe betweenness centrality
Amount of affected buildings serviced by the pipe	Captures how many of the buildings serviced by a pipe are flooded in a given flooding scenario	C_{affected}	For each flooding scenario: $\frac{\text{Number of affected serviced uildings}}{\text{Number of serviced buildings}}$
Urgency	Captures how soon the pipe will be affected		Weighting of each flooding scenario's affected serviced building component: Scenario weight 0 ft: 1 1 ft: 0.8 2 ft: 0.6 3 ft: 0.4 4 ft: 0.2

between any two points in the network—are used to identify pipes that are most important in distributing water throughout the network. This component assigns higher priorities to arterial water mains compared to pipes with smaller diameters further along the edges of the system. Pipes serving more buildings that are affected in SLR scenarios expected to occur sooner (i.e., more urgent scenarios) are prioritized. Given the time-dependent nature of the amount of buildings affected and urgency based on future SLR scenarios between 0 and 1.22 m (4 ft), the bottom two components presented in Table 1 are combined to calculate a single variable C_{affected} based on Eq. (1)

$$C_{\text{affected}} = \frac{\text{0 ft number of affected serviced builidings}}{\text{number ofserviced buildings}} \times 1 + \frac{\text{1 ft number of affected serviced builidings}}{\text{number of serviced buildings}} \times 0.8 + \frac{\text{2 ft number of affected serviced builidings}}{\text{number of serviced buildings}} \times 0.6 + \frac{\text{3 ft number of affected serviced builidings}}{\text{number of serviced buildings}} \times 0.4 + \frac{\text{4 ft number of affected serviced builidings}}{\text{number of serviced buildings}} \times 0.2 \quad (1)$$

Within the C_{affected} component, alternative weights can also be assigned to the scenarios. For the results presented in this paper, the weights presented in the bottom row of Table 1 decrease linearly to give flooding scenarios expected to occur sooner greater importance compared to scenarios expected to occur at a later time. Nonlinear weights can also be assigned to capture the nonlinear rate of SLR for a particular scenario or location that is of interest or for any other reason specific to a study area.

To combine the three component variables into a single score for each pipe, C_{serviced} and C_{affected} scores are normalized and standardized. Normalization by their corresponding maximum scores results in C_{serviced}, $C_{\text{importance}}$, and C_{affected} scores ranging from 0 to 1; subtracting the mean for each component from each value sets each component mean at 0. Lastly, all three components for each pipe are added together to give a single score for each pipe. This can be simply summarized as shown in Eq. (2)

$$C_{\text{composite}} = C_{\text{serviced}} + C_{\text{importance}} + C_{\text{affected}} \quad (2)$$

Care has been taken to normalize all components on the right-hand side of Eq. (2) to prevent one component from having a greater influence on the composite score than the others. However, if utility managers consider one component to be of higher importance than others, weighting of components can also be done as desired prior to summing the three components into a combined composite score. A sensitivity analysis showing the effect of varying component weights is shown in the study area application results.

Map of Pipe Scores

To visualize pipe prioritization scores and facilitate infrastructure management decisions across a neighborhood or community, resulting scores are mapped over the study area. In the study area application, scores are split by quartile and mapped with four colors (one quartile of the results for each color), where the darker red pipes (highest quartile of scores) are considered highest priority for an intervention.

Assumptions

The major assumptions for this methodology can be summarized as follows:

1. All buildings are assumed to be single-family homes. This is a reasonable assumption for the study area by examination of building code information. However, if additional data on number of residents per building are available, these can be incorporated into the water demand estimates per building (Step 4).
2. If any part of a building falls within the flooded areas defined by the NOAA SLR layers, it is assumed to be uninhabitable.
3. All buildings falling outside of the NOAA SLR layers are assumed to remain fully in use.
4. Displaced residents are assumed to leave the county.

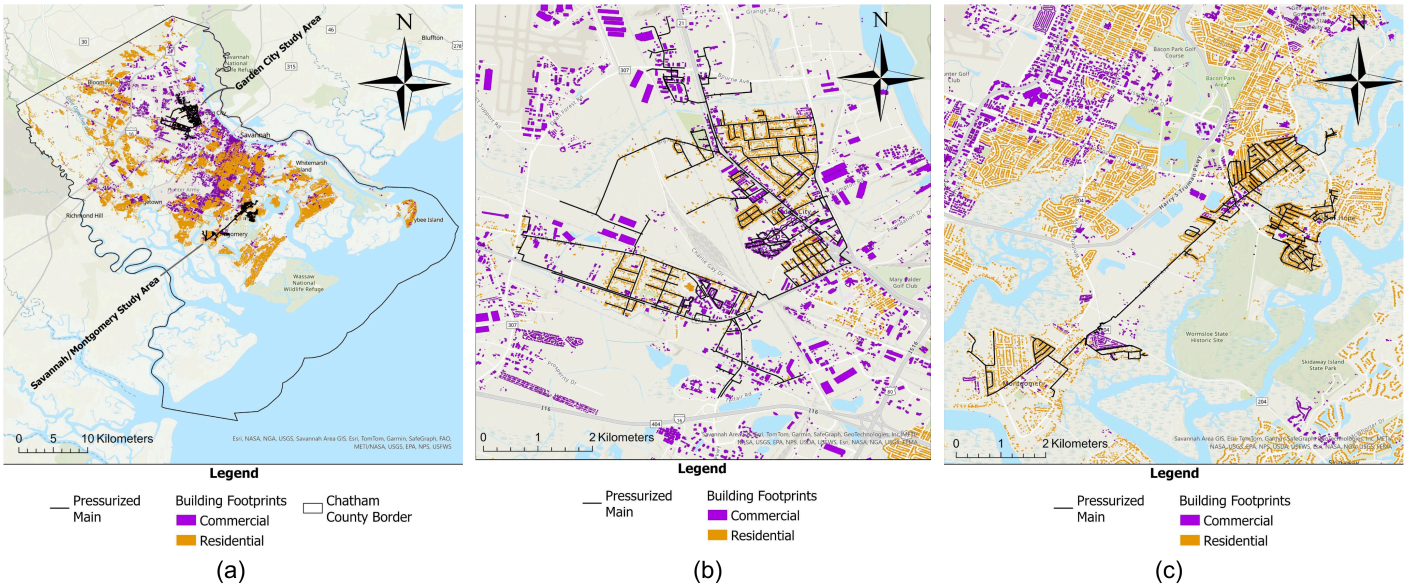

Fig. 2. (a) Map showing two study areas within Chatham County, GA; (b) zoomed-in view of the Garden City study area showing buildings and pressurized mains; and (c) zoomed-in view of the Savannah/Montgomery study area showing buildings and pressurized mains. [Sources (a) from Esri, NASA, NGA, USGS, Savannah Area GIS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS; sources (b and c) from Savannah Area GIS, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA, USFWS, Esri, NASA, NGA, USGS, FEMA.]

Table 2. Estimated meters of global SLR relative to baseline sea level from 1995 to 2014 global mean sea levels

SLR scenario name	2030	2050	2090	2100	2150
Max SSP5-8.5	0.10 (0.09–0.12)	0.23 (0.20–0.29)	0.63 (0.52–0.83)	0.77 (0.63–1.01)	1.32 (0.98–1.88)
Intermediate SSP2-4.5	0.09 (0.08–0.12)	0.20 (0.17–0.26)	0.48 (0.38–0.65)	0.56 (0.43–0.76)	0.92 (0.66–1.33)
Min SSP1-1.9	0.09 (0.08–0.12)	0.18 (0.15–0.23)	0.35 (0.26–0.49)	0.38 (0.28–0.55)	0.57 (0.37–0.85)

Note: Median values with likely ranges in parentheses (17th to 83rd percentiles) from IPCC AR6 (Fox-Kemper et al. 2021; Kopp et al. 2023; Garner et al. 2021).

5. No new development nor internal migration is assumed in the inland portion of the county. If information about migration within the county is available, whether from displaced coastal residents moving inland or other inland migration, these can be incorporated into the calculations of water demand across the county (Step 4).

Study Area Application

The following section shows the results of applying the proposed methodology in Chatham County on the coast of Georgia. Given the component-level analysis and resulting detailed risk assessments at the individual pipe level, two specific areas of Chatham County, GA, are analyzed. These include Garden City, a more inland community just west of Savannah, GA; and an area spanning Montgomery, GA, and Savannah, GA, closer to the coast on the eastern edge of Chatham County. An overview of the county and the two specific study areas is shown in Fig. 2.

The county contains seven incorporated cities and several unincorporated cities and towns. The northern portion of the coastline, including beach tourist destination Tybee Island, is well populated, while the southern portion consists of unpopulated wetlands. Closer toward the coast, the majority of buildings are residential, including in the Savannah/Montgomery study area, while the northern part of the county around the Garden City study area has a larger proportion of commercial buildings. Both the Garden City and Savannah/Montgomery water distribution networks are roughly split into two sections connected by, in the case of Garden City, two pipes and, in the case of the Savannah/Montgomery study area, one pipe spanning a sparsely populated area. Upon first inspection, this suggests a need to maintain the resilience of these critical pipes that allow water to flow to the densely populated parts of the networks.

Projecting Sea-Level Rise over Time in Study Area

To estimate SLR over time for the study area, three global estimate scenarios representing a range of shared SSPs, or levels of climate action, are used. The IPCC AR6 global projections are used to estimate SLR in the years 2030, 2050, 2090, 2100, and 2150, all relative to the year 2000 (Fox-Kemper et al. 2021; Kopp et al. 2023; Garner et al. 2021). These global estimates are presented in Table 2.

Next, the study area includes a tide gauge that can be used to adjust and compare SLR projections. Fort Pulaski (located within Chatham County, GA) monthly tide gauge data are used to compare the monthly tide gauge readings with the global projections. Monthly tide gauge data from February 1945 to January 2022 are plotted relative to the 10-year-average from February 1945 to February 1955 (Smart Sea Level Sensors 2024). Tide gauge data and interpolations based on IPCC AR6 data are presented in Fig. 3.

In Fig. 3, the IPCC AR6 data points (black points) and error bars serve as estimates of a minimum SLR scenario (SSP1-1.9),

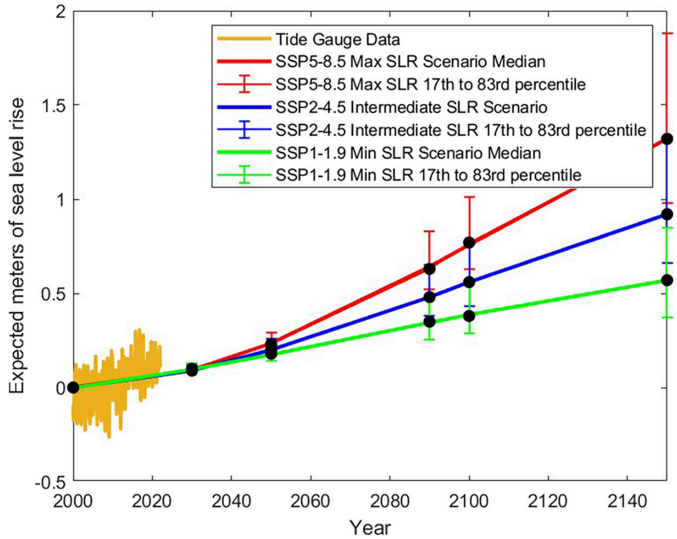

Fig. 3. Sea-level rise projections interpolated from IPCC AR6 data and Fort Pulaski, GA, tide gauge data.

intermediate SLR scenario (SSP2-4.5), and maximum SLR scenario (SSP5-8.5). A spline interpolation is used to connect the data points, resulting in a range of possible future outcomes, from minimum (bottom line) to maximum (top line) SLR projection scenarios. The tide gauge data are plotted to compare the site-specific historical to the projections. The tide gauge data are reasonably close to the projections, though with a slightly steeper slope, supporting the global projections as reasonable for Chatham County with a trend toward the maximum SLR scenario.

Determining Parts of Study Area Expected to Flood at Various Levels of Sea-Level Rise

Based on the values shown in Fig. 3, the NOAA SLR layers can be used to estimate which parts of Chatham County will be flooded at various levels of SLR. The NOAA 0.30 m (1 ft) flooding scenario is expected to occur in 2079 in the minimum SLR scenario, in 2065 in the intermediate SLR scenario, and in 2058 in the maximum SLR scenario. The 0.61 m (2 ft), 0.91 m (3 ft), and 1.22 m (4 ft) flooding scenarios are expected to occur in 2088, 2113, and 2140, respectively, in the maximum SLR scenario. For all three scenarios, uncertainty ranges are larger for the scenarios further in the future.

Identifying "Affected" Buildings in Each Flooding Scenario

To determine "affected" buildings in each flooding scenario, building footprint data obtained from the SAGIS are used. Combining this with the 0 m, 0.30 m (1 ft), 0.61 m (2 ft), 0.91 m (3 ft), and 1.22 m (4 ft) flooding scenarios, the intersections between the building footprints and maps for each of the flooding scenarios are found. Building footprints falling within the high confidence and low confidence flood polygons are marked as "affected." All buildings in the high confidence flood areas are compared with and included in the low confidence affected building dataset to avoid double counting buildings in both scenarios. The resulting maps of affected buildings for 0–1.22 m (0–4 ft) of SLR are presented in Fig. 4.

Fig. 4 gives a sense of the scale and geographical distribution of affected buildings. The figure shows that flooding impacts the most densely populated area of the county on three sides. It should be noted that the NOAA map layers indicating underwater areas in varying flooding scenarios include offshore areas and waterways within the county as well. The Savannah River runs along the northern edge of the county. Fig. 4(a) shows that high confidence flooded areas do not extend very far outside of waterways, though many buildings are affected along these waterways toward the center of the study area. The low confidence flooded area extends far beyond the high confidence areas, largely covering the southeastern half of the county, though much of this area consists of unpopulated wetlands. While the northern half of the coastline is heavily populated, building density slowly decreases as the distance from the coast increases. Tybee Island, on the northeastern point of the county, is affected in all five scenarios, though there is a large increase in the number of affected buildings from the 0.91 m (3 ft) SLR scenario to the 1.22 m (4 ft) SLR scenario. The single road that connects Tybee Island to the rest of the county begins to flood in the 0.61 m (2 ft) SLR scenario and is mostly underwater by the 0.91 m (3 ft) scenario.

The distribution of affected buildings remains consistent as the flooded areas encroach on the central densely populated part of the county. Identifying distinct clusters of affected buildings at this stage in the analysis would be valuable, as this would indicate substantial population displacement and a corresponding concentrated drop in water demand to specific water distribution networks. A cluster of affected buildings appears on Tybee Island early on and grows as the sea level rises. Though more gradual, a cluster begins to appear around the Savannah/Montgomery region, indicating that this network will also face a decreasing customer base due to SLR. The Garden City study area is less affected than the Savannah/Montgomery study area, though clusters begin to form by the 0.91 m (3 ft) and 1.22 m (4 ft) SLR scenarios. Conversely, the unaffected areas in the northwest of the county suggest areas where populations are not expected to be displaced and may even be the destination of displaced residents that choose to relocate within Chatham County—resulting in an increase in water demand. Census population projections or future land use maps can be incorporated at this stage if available to better identify areas where demand may increase. If available, including natural and human-made factors that may impact flooding (e.g., erosion, subsidence, and stormwater drainage infrastructure) at this stage can improve the precision of the flood projections and consequently the estimates of affected buildings.

Projected Number of Buildings Affected over Time

Using the values shown in Fig. 3 estimating the time at which NOAA SLR scenarios will occur and the counts of affected buildings in each SLR scenario shown in Fig. 4, we can estimate the number of affected buildings over time for the three SLR scenarios. These results, as percentages of the Chatham County's buildings affected, are presented in Fig. 5.

Fig. 5 shows that in the maximum SLR scenario (red) and intermediate SLR scenario (blue), the number of affected buildings grows at an increasing rate. Until about the year 2060, the number of affected buildings increases at a relatively slow rate, and it quickly grows in the years following. By 2150 in the maximum SLR scenario, 3.7% (5,160 buildings) of the county's 138,283 buildings are affected with high confidence while 8.4% (11,574 buildings) are flooded with low confidence. Similarly, in the intermediate scenario, 1.3% (1,808 buildings) are affected by 2150 with high confidence and 4.2% (5,748) with low confidence. While there are large differences between the low and high confidence estimates, these values provide a sense of the range and magnitude of future impacts in the community from SLR. In the minimum SLR scenario, the number of buildings affected increases at a slower

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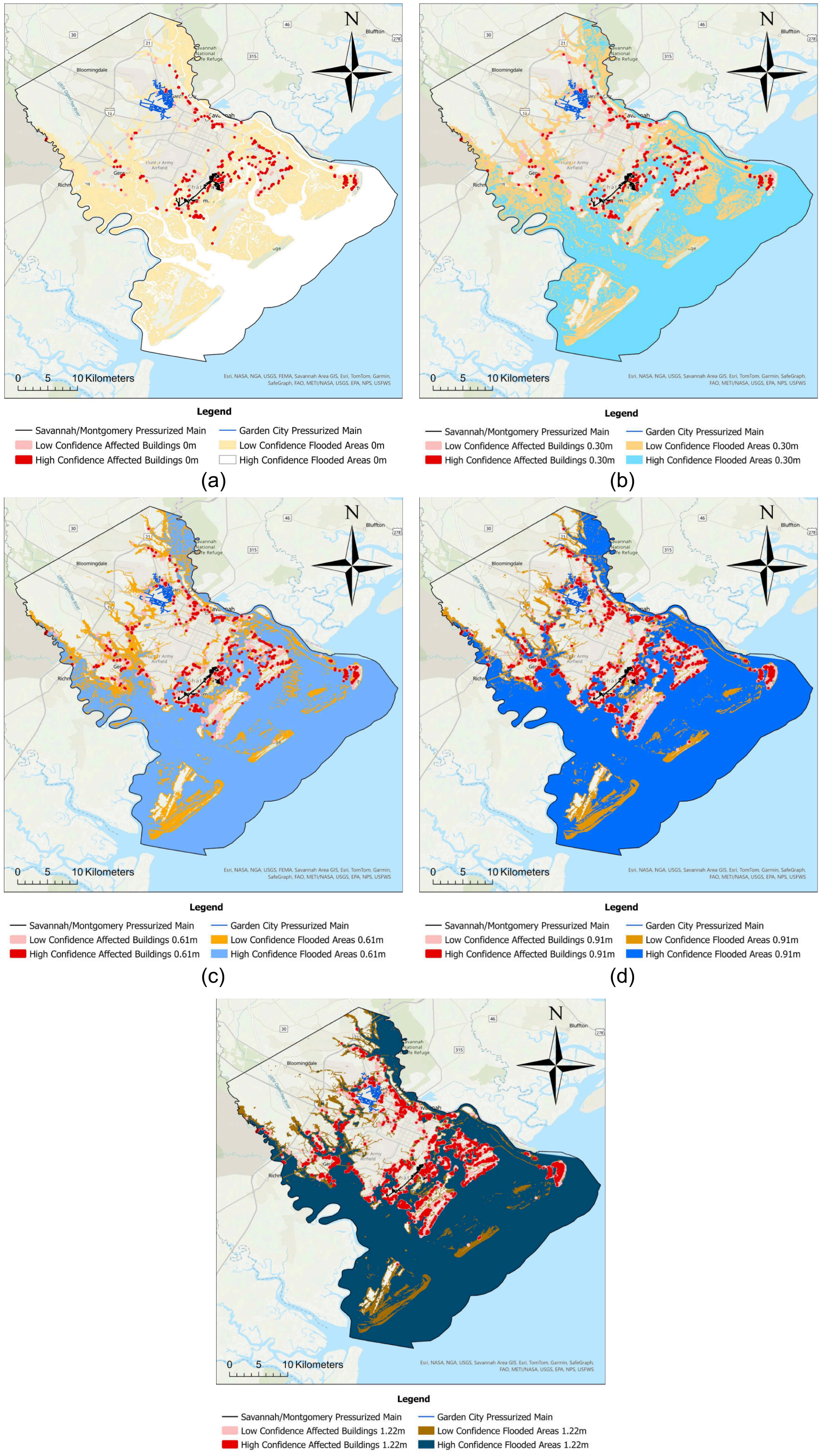

Fig. 4. Buildings affected in flooding scenarios for (a) 0 m SLR; (b) 0.30 m (1 ft) SLR; (c) 0.61 m (2 ft) SLR; (d) 0.91 m (3 ft) SLR; and (e) 1.22 m (4 ft) SLR. (Sources: Esri, NASA, NGA, USGS, FEMA, Savannah Area GIS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS.)

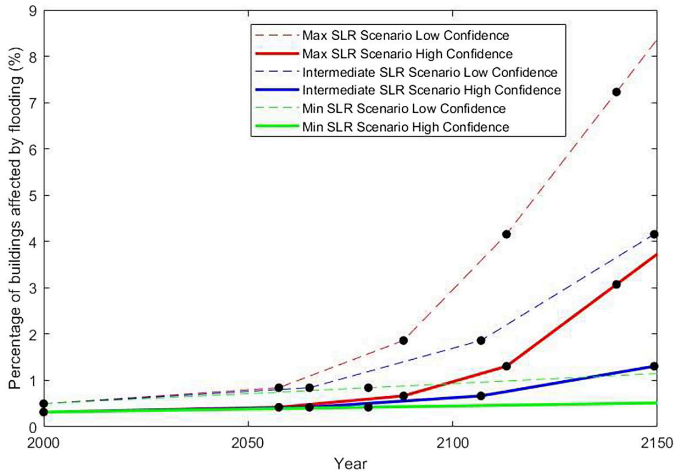

Fig. 5. Percentage of buildings affected by flooding over time in minimum, intermediate, and maximum SLR scenarios.

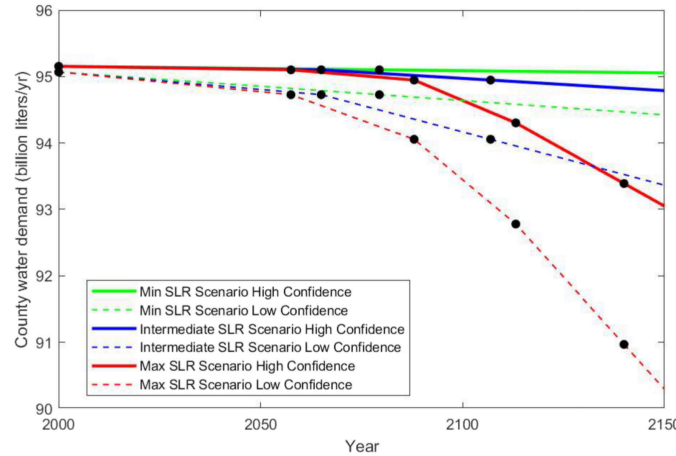

Fig. 6. Water demand (billion liters per year) over time (year) in minimum, intermediate, and maximum SLR scenarios.

and more constant rate. Still, there are more than 700 buildings expected to be permanently flooded by 2150 (0.5% with high confidence up to 1.5% of the county's total buildings in the low confidence projection).

Estimating Change in Water Demand across Building Types

To estimate how the number and locations of affected buildings are used to assess impacts of SLR on the water distribution system, first commercial water usage estimates are obtained from the Industrial Water Demand Forecast for Georgia (CDM Smith 2022). This report states that the industrial water demand for 2020 in Chatham County was 155.7 million L (41.14 million gal) per day. To estimate industrial water use per building, this total was divided by the building area of all nonresidential buildings in Chatham County. This water use per square foot was multiplied by the area of each building to find its estimated water use. The estimates for residential buildings used in this study are obtained from the EPA estimate of 378.5 L (100 gal) of water use per person per day (WaterSense 2017). Building codes from the SAGIS data identify buildings as commercial or residential buildings. Chatham County largely consists of residential buildings, though the building codes do not differentiate between single-family homes and multifamily homes. For this study, all homes were assumed to be single-family homes with a household of 2.43 people—the average household size for Chatham County between 2017 and 2021 (US Census Bureau 2022). Additional analysis of the available building codes for this dataset shows that 96.7% of the residential buildings in the study area have building code R3, indicating residential buildings that contain no more than two residential units.

Estimating Change in Water Demand over Time for County

Using the average household size and average water usage per person for residential buildings, and the building footprint size and estimate for commercial building water use, we estimate the change in water demand over time due to SLR, as shown in Fig. 6.

In the maximum SLR scenario, water demand is expected to decrease by about 2 billion L/year by 2150 with high confidence and up to 5 billion L/year in the low confidence scenario estimate. The changes in water demand in the intermediate and minimum SLR scenarios are also shown. Note that the scale is in billions of liters, indicating the scale of the anticipated future changes. The ability to analyze over time also shows how the scale of future changes will evolve over the coming decades, enabling utility owners to conduct anticipatory planning and mitigation for future changes.

The analysis shown in Fig. 6 gives insight into the scale of the impact of SLR on water demand across the county. A more detailed analysis at the individual pipe level enables us to have a better idea of how the flooding is affecting specific neighborhoods and how these may be addressed by infrastructure owners and operators with proactive planning, management, and operations decisions at the asset level. Such a detailed analysis requires additional data. Therefore, two smaller study areas within Chatham County, where detailed water distribution system information is available, are studied. The first of these areas is Garden City, a community just west of Savannah, GA. The other spans Montgomery, GA, and Savannah, GA, closer to the coast on the eastern edge of Chatham County.

Qualitative Assessment of Affected Areas

From conducting a detailed assessment of the intersections of affected buildings and water distribution infrastructure and a qualitative categorization, we identify four specific types of future flooding that can be evaluated across locations. The purpose of the qualitative assessment is to find recurring types and patterns of flooding situations and to make mitigation recommendations that may be applied to several areas within the community. Fig. 7 summarizes the findings of the four flooding types across the study areas. For each type, the example figures show water distribution infrastructure as black lines, flooding extent with a white background, other nonflooded parts of the area with a gray background, affected buildings colored red, and nonaffected buildings in the area colored green. Corresponding risk mitigation recommendations for water distribution infrastructure under each flooding type are provided in the third column.

In cases where an entire neighborhood is flooded, all inhabitants are expected to relocate, leaving the buildings vacant. Because storm surge is not considered in this study, a case where a full neighborhood is flooded refers to permanent flooding from SLR. If this were an acute flooding event, not all inhabitants may be expected to relocate. Extensive work has been done to model the decision-making processes of inhabitants affected by flooding events, depending among other factors on socioeconomic status, extent of damage to the home, future threat of flooding events, and

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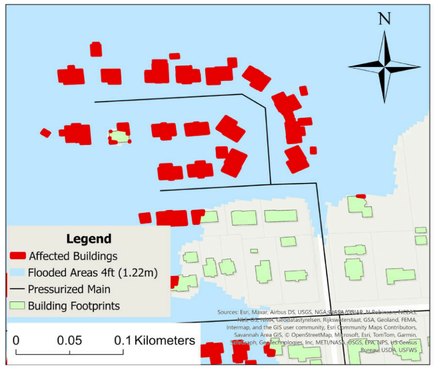
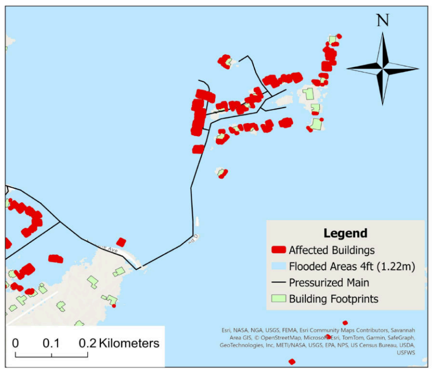
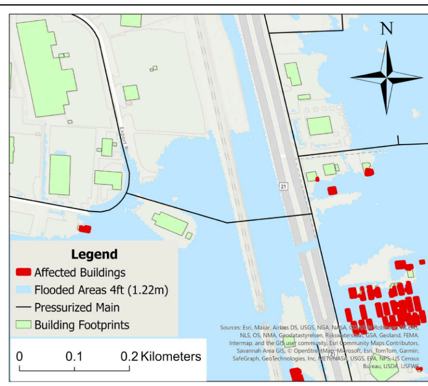
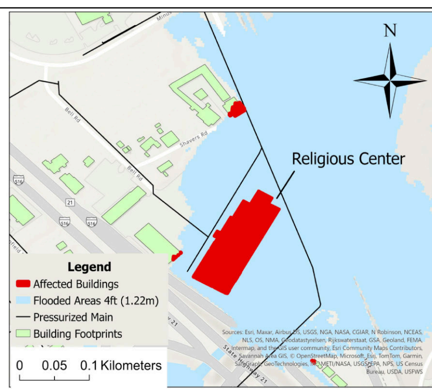
<table>
<tr><th>Future Flooding Type</th><th>Example</th><th>Risk Mitigation Recommendations (in no particular order)</th></tr>
<tr><td>(a) All of neighborhood flooded</td><td>
</td><td>
• Inform community members/other departments of severe risk
• Plan to shut off nearest valve and stop service to section
• Identify any pipes that will have increased loads from shutting of these valves.</td></tr>
<tr><td>(b) Most of neighborhood flooded</td><td>
</td><td>
• Inform community members/other departments of risk
• Conduct surveys to gauge intention to relocate and timeline for relocation
• Install sensors in at-risk areas to more closely monitor flooding
• Consider decreasing pipe size during already planned maintenance to reduce supply</td></tr>
<tr><td>(c) Pipe flooded but no significant number of surrounding buildings</td><td>
</td><td>
• Perform any needed water distribution infrastructure maintenance before flooding makes it more difficult to access pipe</td></tr>
<tr><td>(d) Community building flooded</td><td>
</td><td>
• Communicate with building managers to estimate whether/how long the building will still be in use
• Gather past water usage data to more accurately predict decrease in water demand
• Determine if and where the community building will be relocated to</td></tr>
</table>

Fig. 7. Identified future flooding types and corresponding mitigation recommendations. [Map sources (a, c, and d) from Esri, Maxar, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijklwaterstaat, GSA, Geoland, FEMA, Intermap, and the GIS user community, ESRI Community Maps Contributors, Savannah Area GIS, © OpenStreetMap, Microsoft, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS; map sources (b) from Esri, NASA, NGA, USGS, FEMA, Esri Community Maps Contributors, Savannah Area GIS, © OpenStreetMap, Microsoft, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS.]

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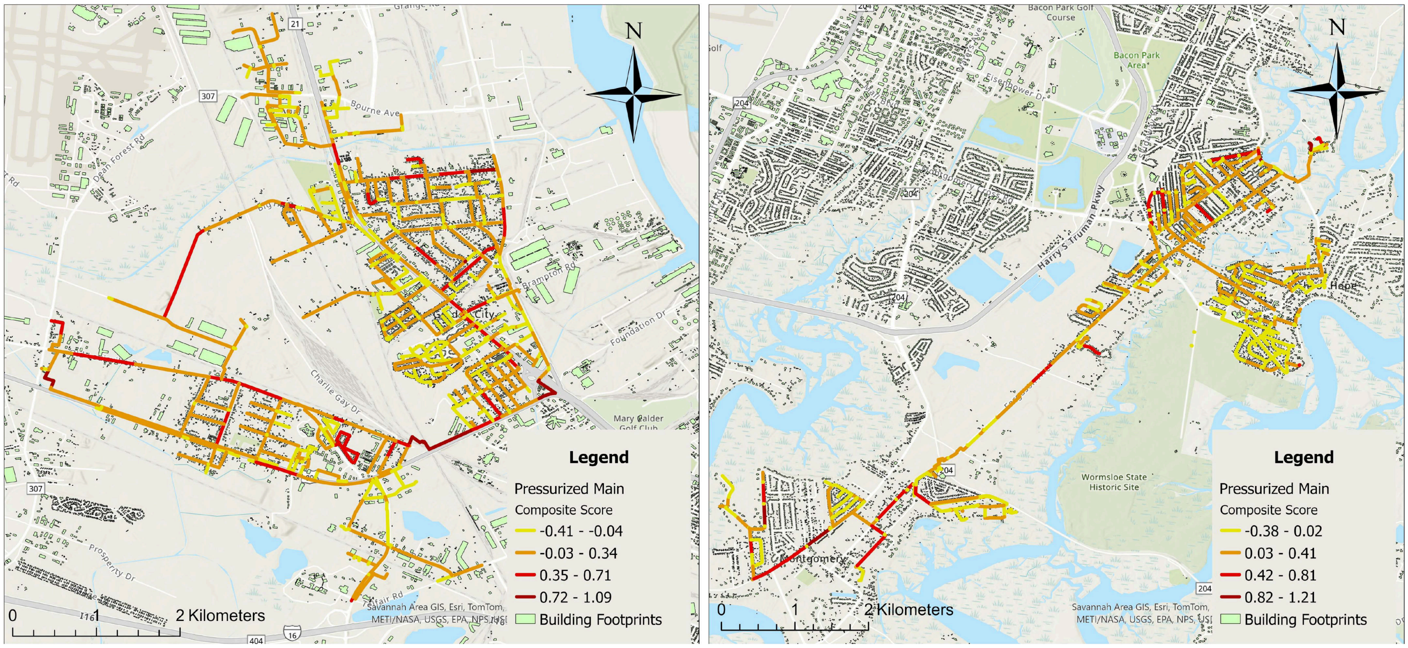

(a) (b)

Fig. 8. Combined pipe scores for (a) Garden City; and (b) Montgomery/Savannah. (Sources: Savannah Area GIS, Esri, TomTom, METI/NASA, USGS, EPA, NPS, USFWS.)

place attachment (Negri et al. 2025; Seong and Losey 2020). In the permanent flooding from SLR considered in this case, utility services would no longer be needed to that section of the system, and utility managers may plan to close valves to this section of the system and discontinue service to the affected buildings after notifying affected residents and commercial building owners of the severe risk. Closing certain pipes may reroute additional water through other parts of the system, so managers should ensure that the other pipes in the system are equipped to handle these changes. Modeling flow changes after valve shutoff using simulations or other calculations can reveal pipes that may not accommodate the resulting increased flow. Further modeling and simulation of the system and conducting condition assessments of these pipes can identify these potential future problem areas for proactive retrofit or replacement.

If there is severe flooding to a neighborhood, but not all buildings are affected, service cannot simply be discontinued. A first step may be to install sensors in the area to more closely monitor flooding and notify residents and commercial building occupants of the risk. Conducting surveys to gauge occupants' intention to leave a building can also give more actionable details about how the demand will change. Further planning can then address the required water pressure in the pipes to maintain optimal supply and water age, which affects water quality (Kourbasis et al. 2020). If the decrease in demand is known before scheduled replacement of a pipe, utility managers may decide to replace the pipe with one of a smaller diameter.

In the case where a pipe is underwater but none of the buildings in its immediate vicinity are expected to be flooded, then the flooding is expected to have no effect on the water demand supplied by the pipe. However, knowing that a pipe may soon be underwater and be more difficult to access may encourage utility managers to prioritize needed maintenance to the pipe before the flooding occurs.

In cases where flooding impacts a large community building—whether through flooding the building directly or through flooding the area completely surrounding the building—water usage data for the building can be obtained to more accurately predict the decrease in water demand and a time estimate for when that decrease will take place. Lastly, building managers can also provide any plans to relocate the building service so utility managers know where an increase in utility services will be needed and where they can expect an increase in future water demand.

In all cases, it is important to ensure that there are redundancies in the water distribution network, especially in areas most severely affected by flooding, and that pipes are regularly checked for leaks to prevent floodwater from contaminating the drinking water supply. In addition, to complement the qualitative assessment, the pipe prioritization scores described following provide a way to quantitatively and systematically identify pipes that may require an intervention of some sort to meet changing community needs under future conditions.

Mapping Affected Buildings to Affected Pipes

Buildings are matched to their nearest pipe using the process described in the Methodology section. This determines which pipes service which buildings.

Calculating Pipe Prioritization Scores and Map of Pipe Scores

The combined pipe scores summarize the three components of the pipe score into a single pipe prioritization value so that the pipes can easily be compared with each other across a study area as presented in Fig. 8. Scores are split by quartile and mapped by color where darker red pipes (highest quartile of scores) indicate the highest priority for an intervention.

Fig. 8 shows a large range of values for combined scores across both study areas, enabling comparison and prioritization of pipes across the area. In both study areas, the lowest scores correspond largely with shorter pipe segments in well-populated areas in close proximity to several other pipes. These pipes are toward the edges of the network, therefore having lower betweenness centrality scores and, though they are surrounded by many buildings, only serve a fraction of them. Therefore, these segments have lower $C_{\text{importance}}$ and C_{serviced} component scores. Several of the single pipes connecting subsections of the networks have higher scores. This is especially evident in the red pipes in the southeastern corner of Fig. 8(a) as well as the long red pipe segments connecting the two main sides of the area. This highlighting of arterial pipes is especially important because if these connecting pipes fail, water may not be able to flow to a large number of buildings. The inclusion of the urgency of a pipe intervention based on SLR levels means that the high priority pipes are critical based on both spatial and temporal parameters under future SLR scenarios. In Fig. 8(b), one of the dark red pipe segments appears in the southwest corner of the study area. This pipe segment has a high betweenness centrality score because of its location, while also having a high C_{serviced} score because it is near many buildings and near few other pipes. Some of the pipes with high scores (e.g., longer pipe segments connecting the two halves of the network) are consistent with those that intuitively seem of interest. The main value of the composite pipe scores lies in combining many layers of data including the diameter, centrality, proximity to buildings, and exposure to flood risk that would be difficult to interpret all at once. The pipe scores summarize this crucial information into a single map that highlights for utility owners and managers the segments where action may be most needed. Overall, the results from the methodology enable quantitative prioritization of pipes for risk mitigation across the network. With utility networks spread over large areas and composed of many assets with limited resources for SLR risk mitigation across coastal communities, the highest prioritization scores by individual pipe highlight the pipes that should be looked at first and, in more detail, to determine appropriate actions to mitigate risk under the changing conditions of SLR.

Sensitivity Analysis

As described in the methodology section, the results shown in Fig. 8 are calculated using equally weighted components as shown in Eq. (2). However, if utility managers have reason to weight components differently, weights can easily be incorporated into the calculation of the composite score. This section presents three possible reasonings and scenarios for weighting one component higher than the others and discusses how these weights affect the results.

Scenario 1: A small town consists of a few, concentrated residential areas and otherwise more sparsely populated areas where residents typically live semi-off grid. Utility managers are most interested in identifying at-risk sections of the distribution system in the more densely populated areas. The C_{serviced} component is weighted higher than the others as shown in Eq. (3)

$$C_{\text{composite}} = 2 \times C_{\text{serviced}} + C_{\text{importance}} + C_{\text{affected}} \tag{3}$$

Scenario 2: Buildings are fairly evenly distributed throughout the city. Utility managers are aware that their system has minimal redundancy, so they are most concerned with protecting the most central pipes to keep water flowing throughout the network. The $C_{\text{importance}}$ component is weighted higher than the others as shown in Eq. (4)

$$C_{\text{composite}} = C_{\text{serviced}} + 2 \times C_{\text{importance}} + C_{\text{affected}} \tag{4}$$

Scenario 3: A town has already begun to see residents displaced by coastal flooding. They are aware that SLR poses an urgent risk to their community and are mainly interested in understanding which areas will be most affected over the coming decades. The C_{affected} component is weighted higher than the others as shown in Eq. (5)

$$C_{\text{composite}} = C_{\text{serviced}} + C_{\text{importance}} + 2 \times C_{\text{affected}} \tag{5}$$

Fig. 9 summarizes the results for the three scenarios if these weights were applied in the Garden City and Savannah/Montgomery study areas.

Scenario 1

While the distribution of red and dark red pipes is similar in Figs. 8(a) and 9(a), Fig. 9(a) has fewer red pipes throughout. The pipe on the west side in Garden City connecting the two main halves of the network falls from the red category in Fig. 8(a) down to the orange category in the weighted scores in Fig. 9(a) because, though it scores high in the other two components, it has no buildings in its immediate vicinity. Fig. 9(b) highlights many of the same red and dark red pipes as Fig. 8(b), but includes significantly more yellow pipes. This is likely because the areas in red and dark red in the unweighted scores are in the densely populated areas, and the weighting further increases these scores, increasing the separation between the highest scores and the medium to lower scores. For these study areas, weighting the C_{serviced} component does not drastically change the areas of the network highlighted with high pipe scores, but it does reduce the number of pipes highlighted in the network overall.

Scenario 2

While nearly all of the same pipes that are red or dark red in Fig. 8(a) remain red or dark red in Fig. 9(c), additional central pipe segments such as those in the bottom half of the connector between the two sides in Fig. 9(c) are now red. Similarly, Fig. 9(d) highlights most of the same pipes as Fig. 8(b), with the addition of more segments of the pipe running between the northeast and southwest halves of the system and the pipe connecting the northern section to its subsection to the east. Here as well, thin pipe segments along the edge such as those at the northernmost end of the network maintain their high scores. These results indicate that increasing the weight of the $C_{\text{importance}}$ component can lead to the highlighting of additional pipes, while not obscuring the information provided by the other components in the composite scores.

Scenario 3

Here, weighting the C_{affected} component results in the high priority pipes being identified in the same areas as in the unweighted scenario; however, with a reduced number of pipes in these areas, e.g., a subset of the red pipes from Fig. 8(a) remain among the highest scores in Fig. 9(e). While not revealing any new trends, increasing the weight of the C_{affected} component reduces the number of pipes with high scores, highlighting a subset of the high priority pipes. Similarly, Fig. 9(f) highlights a subset of the red and dark red pipes in Fig. 8(b), only far fewer and not in all of the major areas highlighted in Fig. 8(b). The overall number of pipes in yellow (the lowest score category) increases in Fig. 9(f) compared to Fig. 8(b) as well.

Summary of Findings

The salient findings from applying the proposed methodology to the study areas in Chatham County, GA, are summarized as follows:

1. A large number of buildings are expected to be affected by SLR by the year 2150 ranging from a minimum of 713 buildings up to 5,160 buildings in high confidence estimates and 1,590 to 11,574

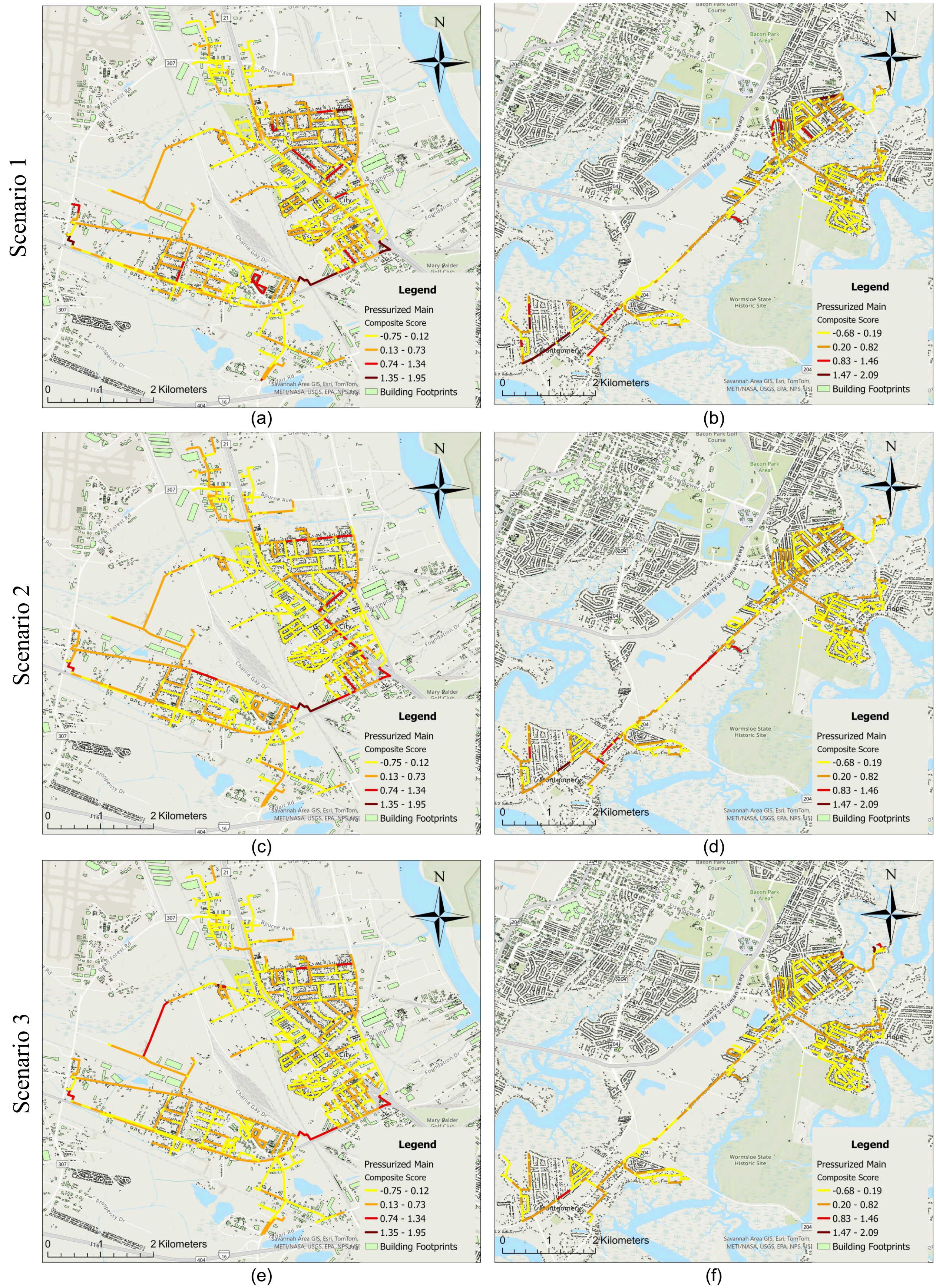

Fig. 9. Composite pipe scores for (a) Garden City under Scenario 1; (b) Savannah/Montgomery under Scenario 1; (c) Garden City under Scenario 2; (d) Savannah/Montgomery under Scenario 2; (e) Garden City under Scenario 3; and (f) Savannah/Montgomery under Scenario 3. (Sources: Savannah Area GIS, Esri, TomTom, METI/NASA, USGS, EPA, NPS, USFWS.)

in lower confidence estimates, out of the 138,283 total buildings in the county.
2. Utility owners and managers can expect a county-wide decrease in water demand of up to 3 billion L/year by 2150, with the rate of decline likely accelerating over time.
3. Four main types of flooding due to SLR that are expected in the coming decades with varying recommendations for risk mitigation are as follows:
   - An entire neighborhood is flooded
   - Most of a neighborhood is flooded but a small subset of buildings is unaffected
   - A pipe is flooded, but no significant number of surrounding buildings are flooded
   - A community building is flooded
4. Pipe prioritization scores highlight sections of the water distribution network that should be investigated in more detail to determine what interventions are necessary and when they should be implemented to mitigate future risks from SLR and population shifts

Generalizability to Coastal Communities Impacted by Sea-Level Rise

The results presented in the prior section are for the methodology applied to the coastal community of Chatham County, GA. However, the methodology is easily generalizable to other coastal communities impacted by SLR. The proposed methodology can be applied to any desired study area to conduct an anticipatory assessment of flood risk and create a mitigation plan using readily available datasets. Various steps in the process shown in Fig. 1 can be adapted to conduct the analysis based on the datasets that are available to a community. For example, more detailed regional SLR models or broader global projections of SLR can be used in Step 1, results from running complex urban flood models or general flood map layers can be used in Step 2, or detailed information from maps showing which buildings are serviced by each pipe in the network or distance-based proxies of service can be integrated in Step 5. The discussion included for each study area shows how results from this methodology can be interpreted and used to reach actionable conclusions to mitigate risk. The identified four types of future flooding shown in Fig. 7 are anticipated to be found across coastal communities, with the risk mitigation recommendations generalizable to those areas based on the applicable flooding type. The pipe prioritization scores are also broadly applicable across distribution networks with a focus on the function, service, location, and urgency of individual pipe components.

Conclusions

The methodology described in this work presents a novel way to conduct anticipatory infrastructure risk assessment and mitigation by integrating SLR projections, building and population information, and water distribution data to anticipate future risks from SLR and recommend actions for risk mitigation for water distribution infrastructure in coastal communities. The proposed methodology includes both quantitative and qualitative analyses to better understand the impact that SLR is expected to have on the drinking water distribution system and implementable actions to mitigate future risks. Projections of the number of affected buildings over time across an area provide a sense of the scale of the impact, showing the urgency of the situation and the importance of planning ahead. The developed pipe prioritization scores include multiple factors across space and time to systematically assess a large network and highlight pipe segments that are of particular concern and should be prioritized for resilience efforts. The qualitative assessment identifies four specific types of future flooding. Identifying these distinct categories of flooding supports generalizable mitigation recommendations to be applied across the study area, and that can be extended to other study areas and locations of interest. The overall system assessment facilitates detailed understanding of the implications of SLR for drinking water distribution infrastructure while providing a timeline for when these impacts are expected to happen. The resolution of the analysis at the individual pipe level makes the results actionable for utility managers, who may choose to implement mitigation recommendations for specific pipes or specific areas depending on the time and budget available. The proposed methodology enables utilities to take an anticipatory approach to risk assessment and mitigation for their distribution infrastructure, anticipating future impacts and mitigating risks of SLR on populations and the infrastructure supporting them.

Study Limitations and Future Work

The main limitation of this work is the lack of inclusion of additional factors that may affect the impact of flooding on populations in an area, e.g., detailed flood modeling information, flood risk from acute events, detailed household data, and population growth in inland parts of a study area. The accuracy and precision of the predictions made in the proposed methodology can be increased by employing more detailed or higher resolution information to expand each of these areas. For example, the methodology can incorporate more detailed flood modeling to account for factors such as drainage infrastructure or retention systems that would reduce areas flooded. Including flood risk from acute events (e.g., heavy rainfall events, storm surge, king tides) and modeling the resulting population displacement would enhance the water demand estimates. Including these effects is expected to increase the number of unoccupiable buildings and amount of people displaced. Incorporating detailed data about the number of households per building or the number of residents per building can lead to more accurate water demand estimates. Future land development maps can also be integrated to predict not only population decline along the coast, but also population growth in inland parts of the study area, as new residents may move to those regions or those along the coast may move farther inland within the county. Additional complexity can be added to better model the destinations of displaced residents along the coast to better capture increases in demand to inland water distribution networks within the county. Though reliable data sources for these data can be challenging to find, they would enhance the results of implementing the proposed methodology in coastal communities. Data describing the population displacement from historical flood events or the impacts of mitigation strategies can also be incorporated to validate the results. A similar analysis can be extended to other components if data are available. While the function of all components in the network (e.g., pumps, valves, etc.) is essential, the focus of this paper is to understand how a drinking water distribution network may adapt to changes in demand over time. With this in mind, additional infrastructure components that would be of particular interest would be water towers, reservoirs, water treatment plants, and other assets relevant to the size and quality of the water supply in a community. The qualitative categorization section of this work can be expanded to include a clustering analysis to more systematically identify recurring patterns of affected buildings. Lastly, the sensitivity analysis can be extended to other inputs (e.g., population displacement models, SLR scenario selection, water demand estimates, etc.) to better understand which inputs have the largest effect on the results.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

Paola Vargas: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft; Writing – review and editing. Iris Tien: Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing – review and editing.

Supplemental Materials

Fig. S1 is available online in the ASCE Library (www.ascelibrary.org).

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