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EDITED BY
Amanda Tritinger,
Engineer Research and Development Center (ERDC), United States

REVIEWED BY
Linda Jane Walters,
University of Central Florida, United States
Erfan Amini,
Columbia University, United States

*CORRESPONDENCE
Stephanie M. Patch
spatch@southalabama.edu

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Adaptation pathways identify effective strategies for mitigating damage on a developed barrier island as sea levels rise

Stephanie M. Patch[1]*, Renee C. Collini[2], Bailey R. Delaney[3], Kaylyn Bellais[4], Mikaela Heming[5] and Peyton Caraway[6]

[1]Department of Civil, Coastal, and Environmental Engineering, University of South Alabama, Mobile, AL, United States, [2]Community Resilience Center, The Water Institute, Baton Rouge, LA, United States, [3]Great Lakes Dredge & Dock Company, Houston, TX, United States, [4]Anchor QEA, Ocean Springs, MS, United States, [5]passivhausMAINE, Freeport, ME, United States, [6]Moffatt & Nichol, Mobile, AL, United States

Adaptation pathways are responsive planning tools intended to help decision-makers incorporate uncertainty of a future scenario while optimizing the use of their resources. In this project, an adaptation pathway was generated for a developed barrier island community, Dauphin Island, Alabama, USA. The project period was October 2019 to April 2022, with community engagement beginning in January 2020. Initial meetings were held with the community to identify vulnerable locations and co-develop adaptation strategies that were evaluated throughout the project. The effectiveness of adaptation strategies to reduce damage was estimated with a process-based numerical model, XBeach, which simulated inundation and morphological change due to Hurricane Nate (2017) and several sea-level rise scenarios. Depending on the Dauphin Island priority area, "damage" was defined as saltwater contamination in a freshwater lake, sand deposits on Dauphin Island's main through route, or decreased sediment volume. When damage was sustained for a given strategy and sea-level rise scenario, a "tipping point" was reached and triggered the implementation of another strategy. Adaptation pathways were generated for two focus locations, with one location having two tipping points resulting in two pathways. This project revealed adaptation pathways are dependent on definitions of tipping points and location even within the same community. Community engagement revealed vulnerable locations that were previously unrealized and identified 'reasonable' or 'unreasonable' adaptation strategies based on community needs and desires. While the pathways produced for Dauphin Island are likely not transferrable to other locations, both findings are key to effective application of the adaptation pathways approach and generating a pathway accepted by the community.

KEYWORDS

XBeach, inundation, morphological change, community engagement, Dauphin Island, Hurricane Nate

1 Introduction

In the last decade, adaptation pathways have continued to gain recognition as an effective and responsive planning tool for decision-makers to use for optimizing resources in an uncertain future climate. Haasnoot et al. (2013) coined the phrase "Dynamic Adaptive Policy Pathways," a method for decision-making comprised of policymaking and action sequencing for dynamic adaptation. Wise et al. (2014) summarized the state of adaptive planning at that time and identified five shortcomings of adaptation pathways as an all-inclusive climate adaptation tool. Those shortcomings produced five suggestions for improving adaptive planning: 1. Climate adaptation should consider societal responses to change; 2. Responses should be coordinated when spatial scales, sectors, or jurisdictional boundaries are crossed; 3. Temporal responses should be considered to prevent path dependency and lock-in; 4. The system's current and future condition should be evaluated and monitored; and, 5. Adaptation should understand and overcome prevailing societal norms and power relations. Wise et al. (2014) concluded by reimagining adaptation pathways with more flexibility to uncertainty and identifying the need for theoretical research and case studies to inform and further develop the adaptation pathways concept. Since then, numerous studies have been conducted using several adaptive planning methodologies by researchers across a multitude of disciplines within climate adaptation, producing adaptation pathways that vary in complexity and application (e.g. Barnett et al., 2014; Desai et al., 2021; Lawrence et al., 2018; Sánchez-Arcilla et al., 2024; Smallegan et al., 2017; Werners et al., 2021).

This study focuses on the generation of simple adaptation pathways intended to serve as planning tools for a developed barrier island vulnerable to sea-level rise (SLR). Barrier islands are estimated to make up about 10% of coastlines worldwide, with the United States (USA) containing the highest proportion of barrier island area at 25% (Stutz and Pilkey, 2011). These dynamic, ecologically important coastal landforms respond to changes in sea level by migrating landward through overwash processes and inlet dynamics (Donnelly et al., 2006; Leatherman, 1979a, b). As humans construct infrastructure on these dynamic systems, an island's position becomes fixed, disrupting its natural landward migration, increasing vulnerability to SLR, and likely accelerating barrier island drowning (Anarde et al., 2024; Miselis and Lorenzo-Trueba, 2017). Uncertainties in relative SLR rates, coastal population growth, and storm impacts cause the future of barrier islands to be largely unpredictable. Due to these factors, barrier island loss rates on the USA Atlantic and Gulf coasts vary from a few meters to tens of meters of landward retreat per year (Morton and Sallenger, 2003; Stutz and Pilkey, 2011), with recent studies showing greater than 50% barrier island losses (Mariotti and Hein, 2022; Thomas et al., 2024) to 100% barrier island losses due to complete drowning of the barrier island (Koen et al., 2023; Portos-Amill et al., 2023). Adaptation pathways address this unpredictability by identifying effective adaptation strategies for mitigating damage due to storms and SLR. Pathways also inform coastal decision-makers when to plan for the next strategy based on observed conditions rather than uncertain long-term predictions.

Adaptation methods employed on developed barrier islands have shifted from engineering against nature (e.g., shoreline hardening with massive seawalls) to engineering with nature (e.g., implementation of natural and nature-based features (NNBF; National Research Council, 2014; Van Der Meulen et al., 2023). The appropriate type of NNBF for a given location depends on several factors, including the wave climate, level of protection sought from the adaptation strategy, available resources, and property right-of-way required for project construction (Seddon, 2022; Van Der Meulen et al., 2023). Beach nourishment is commonly employed as a NNBF along sandy coastlines exposed to ocean or gulf waves and water levels. The added sediment serves as a sacrificial feature during storms thereby mitigating wave impact and inundation to landward regions. Numerous examples of beach nourishment projects exist, with the placement of sand as a shore protection method beginning in the USA nearly a century ago. Beaches in more than 475 communities have been restored through nourishment (Elko et al., 2021). In New Jersey during Hurricane Sandy (2012), areas with beach nourishment sustained substantially less damage than areas without nourishment, saving an estimated $1.3 billion in avoided damages (Houston, 2022). Areas that are sheltered or located in areas with lower wave energy often include NNBF, such as marsh fill or breakwaters constructed of naturally-derived materials. NNBF in these environments dissipate waves prior to reaching the shoreline and provide habitat and other ecological benefits (National Research Council, 2014). For example, junior mangroves in Florida (FL), USA, have been observed to defend shorelines against waves, and physical model testing estimates mangroves reduce wave energy by up to 60% resulting in up to a 70% decrease in shoreline erosion while providing ecological benefit (Weaver and Stehno, 2024).

Adaptation strategy effectiveness is based on its impacts to biodiversity and people in addition to reducing shoreline erosion and retreat in a changing climate (Seddon et al., 2021). Sustainable and successful adaptation strategies should maintain or enhance biodiversity, thereby maintaining or enhancing diverse coastal ecosystems. From the onset of this project and throughout its duration, strong focus is placed on the engagement of people to guide adaptation pathway development. Adaptation pathways provide a sequence of actions for the community; therefore, early and consistent involvement is key to local buy-in, ownership, maintenance, and monitoring of any implemented strategy (Seddon et al., 2021). As such, an "effective" adaptation strategy is defined herein as one that mitigates physical damage caused by storms and SLR to a developed barrier island while also being accepted by the community that the strategy serves.

2 Site description

Dauphin Island, Alabama, USA served as the example barrier island for adaptation pathway development. Dauphin Island was selected for two main reasons: 1) Pre- and post- storm datasets were available for calibrating the numerical model used in this study and 2) Pre-established relationships with Dauphin Island officials and community members allowed for more effective engagement.

Dauphin Island is a unique microtidal barrier island with a robust 'East End' region and a vulnerable 'West End' region (Figure 1). The East End and approximately 5.5 kilometers (km) of the West End are developed. In 2020, Dauphin Island sustained more than 1,700 permanent residents and 3,100 seasonal residents (U.S. Census Bureau, 2020). The island supports a diverse marine ecology, including endangered and protected species, and offers recreational activities (e.g., boating, bird watching, fishing). The East End consists of a maritime forest and dunes up to 15 meters (m) in height. A freshwater lake and aquifer on the East End provides freshwater from the water-table. A hydrogeological study revealed the water-table is recharged mainly by rainwater and is the only source of drinking water (Kidd, 1988). The water-table's shallow depth makes the aquifer vulnerable to saltwater contamination. The West End has elevations around 2 m above mean sea level (MSL) and an average width of nearly 300 m. A public beach parking lot delineates the developed West End from the 12.5 km undeveloped westernmost region of the island.

Bienville Boulevard connects to the West End public beach parking lot and extends east along the length of the developed portion of Dauphin Island. During minor storm or flooding events, relatively large volumes of sand deposit onto Bienville Boulevard, which limits and sometimes prevents access to or from nearly 200 residences. As such, the Town of Dauphin Island spends a substantial amount of their annual operating budget to mechanically remove sand from Bienville Boulevard and restore access after coastal storms. For example, in 2021, the Town spent $2.5 million of their approximately $4 million budget on removing sand from roads on the West End (King et al., 2022).

Tide gauge measurements began on Dauphin Island in 1966 and measured 0.26 m of SLR with a present rate of 4.43 mm/yr (NOAA, 2025b). In that time, 46 tropical cyclones have transited within 150 km of Dauphin Island (NOAA, 2025a). Hurricanes Ivan (2004) and Katrina (2005) were the most catastrophic of those 46 storms, causing breaches on the undeveloped West End and severe damage to infrastructure from wind, waves, surge, and erosion (Froede, 2006, 2008). Since the adaptation strategies developed in this study were for long-term planning purposes as opposed to emergency responses to catastrophic events, Hurricanes Ivan and Katrina were not appropriate to consider as the storm of interest. Additionally, the pre- and post- storm data required for model calibration are lacking for Hurricanes Ivan and Katrina. Therefore, Hurricane Nate (2017) served as the storm of interest in this study.

Hurricane Nate represents a 10-year storm event that caused relatively minor damage on Dauphin Island. Gulf and sound water levels and wave characteristics were measured during Hurricane Nate and surveys were collected immediately before and after storm landfall (Coogan et al., 2019). These data were critical for calibrating the numerical model. Model calibration is described in Patch and Caraway (2025) and summarized in the following section. Hurricane Nate produced water levels up to 3.1 m MSL on the East End and greater than 2.5 m MSL on the West End (Beven and Berg, 2018;

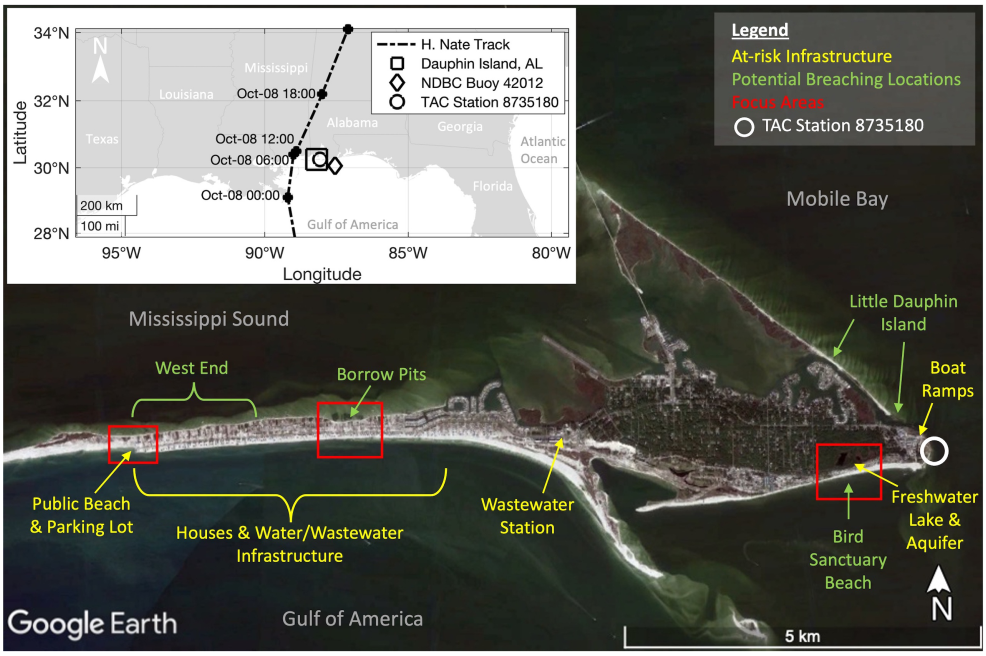

FIGURE 1
Regional map (inset) shows Hurricane Nate track (black dashed line; times reference UTC), Dauphin Island, AL (square), NDBC wave buoy 42012 (diamond), and TAC tide gauge station 8735180 (circle). Satellite image shows vulnerable locations identified by Dauphin Island leadership at a meeting held on January 23, 2020 at the onset of this project (Collini, 2020). Infrastructure identified as "at risk" of damage during storms or from SLR are marked in yellow, locations where the island has historically or may potentially breach are marked in green, and areas of focus for this project are represented by red boxes. Satellite image was obtained from Google Earth (earth.google.com).

Coogan et al., 2019). While structural damage from Hurricane Nate was minimal, substantial morphological changes were observed. Dune crest heights were reduced up to 2.3 m along survey transects, sand deposits up to 1.5 m deep were deposited on Bienville Boulevard, and 66% of the island experienced some degree of overwash (Coogan et al., 2019).

Dauphin Island's morphology was also affected by the Deepwater Horizon oil spill disaster in 2010. As an emergency response to the man-made disaster, sand was excavated from Dauphin Island's back barrier region and placed on its gulf-side to prevent oil from washing over the island and causing further ecological catastrophe (Webb et al., 2011). The excavation changed Dauphin Island's morphology by creating large 'borrow pits' along the northern West End. Many of the borrow pits have naturally filled in or are enclosed on the island as swales and wet ponds; however, some did not recover and localized areas of island narrowing still exist today. The island width decreases approximately 50 m from 300 m to 250 m at some borrow pits, and elevations are relatively low at 2 m above MSL. Breaches can occur when storm magnitude exceeds barrier profile dimensions (Sallenger, 2000). As such, the barrier profile dimensions at the borrow pits are smaller than most other parts of the island and may be exceeded during a coastal storm leading to a potential breach. A breach at this location would sever the West End's only evacuation route and destroy access to more than 170 residences on the West End.

3 Methodology

Community engagement and morphodynamic modeling methods were coupled to generate community-informed and scientifically-based adaptation pathways for Dauphin Island. The project began in late October 2019 and concluded in April 2022. Community engagement was intentional, began early in the project, continued throughout the project's duration, and leveraged long-established relationships. Community members' feedback informed which locations and adaptation strategies were simulated by the numerical model. Results from the numerical model were then analyzed to generate adaptation pathways. As shown in Figure 2, community engagement and modeling efforts were employed concurrently and cannot be truly separated; however, they are described below in their respective sections for improved readability.

3.1 Engaging the community through in-person and virtual meetings

Community engagement was expected to occur through a series of in-person meetings throughout the project; however, the COVID-19 pandemic began shortly after project onset and required a substantial pivot in the proposed engagement plan. As such, only one in-person meeting was held, and the remaining six meetings were conducted virtually.

Regardless of how the meeting was held, all meetings followed a similar process agenda that included introductions, project background presentations, a mapping activity to identify vulnerable areas and infrastructure, a brainstorming session for adaptation strategies, an activity aimed at identifying planning perspectives in terms of SLR, and discussions regarding the next steps of the project. SLR scenarios were presented to attendees in terms of likelihood of occurrence instead of quantity of rise, which helped determine individual risk thresholds. The exceedance

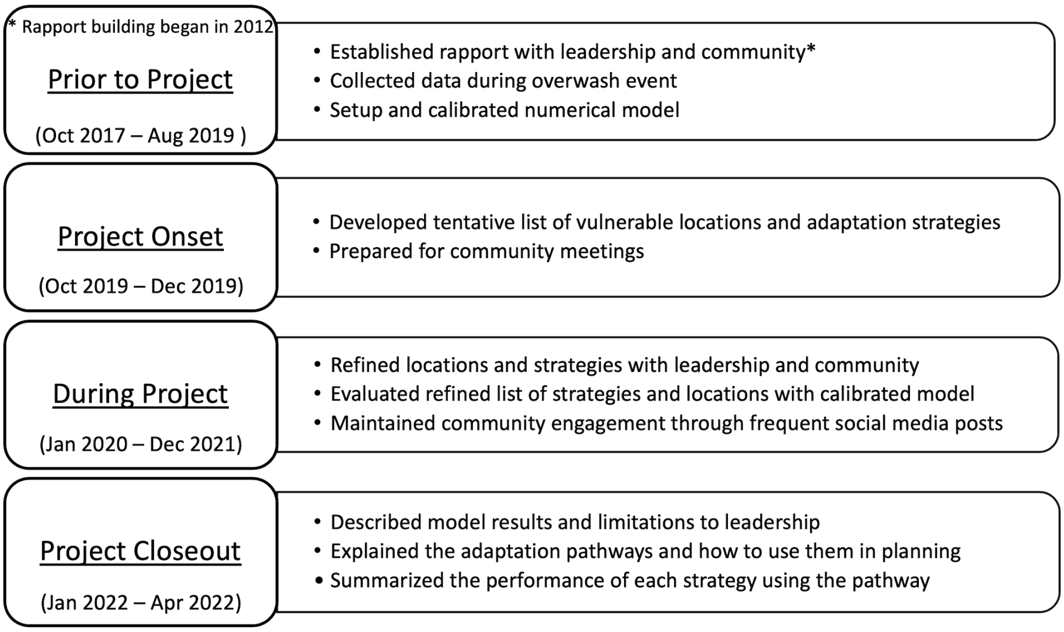

FIGURE 2
Timeline of the methods employed to generate science-based and community-informed adaptation pathways.

probabilities were based on relative SLR projections from Sweet et al. (2017) corresponding to Representative Concentration Pathway (RCP) 8.5 occurring by 2100. This RCP most closely aligned with SLR observations presented in Terando et al. (2020). For RCP 8.5, probabilities ranged from the Low scenario corresponding to more than a 99% likelihood of occurrence to the Extreme scenario corresponding to a 0.1% likelihood of occurrence by the end of this century. Intermediate-low, Intermediate, Intermediate-high, and High SLR scenarios were also presented in terms of their exceedance probabilities.

3.1.1 In-person leadership meeting

On January 23, 2020, a two-hour in-person meeting with five invited leadership officials was held on Dauphin Island. The Mayor of Dauphin Island and representatives from the Dauphin Island Planning Commission, Dauphin Island Water & Sewer Board, and Alabama Power attended the leadership meeting. These officials were invited due to their direct roles in adaptation planning for the island and active engagement in projects ongoing at that time. At the meeting, each official identified vulnerable locations to damage by storms and SLR, at-risk infrastructure, and potential breaching locations on a printed Google Earth aerial image of Dauphin Island (earth.google.com). The officials suggested several adaptation strategies at each vulnerable location for consideration as part of this project (Table 1). Strategies were categorized based on their location of implementation, which were "gulf-side", "sound-side", or "other" in the case neither gulf- nor sound- side location applied.

3.1.2 Virtual community meetings

Community meetings were planned to commence in-person beginning in March 2020. Instead, these meetings were delayed while in-person activities were adapted for virtual engagement. On May 12, 2020, the project team established a virtual presence through a Facebook project page published with approval from the U.S. Coastal Research Program supporting the project. The Facebook page was linked to pre-existing Facebook groups for the Town of Dauphin Island and its residents. Project information and upcoming virtual community engagement meetings were announced through a digital flyer posted on Facebook on May 18, 2020. Realizing not all Dauphin Island community members engage with social media, paper flyers were mailed to 200 residences. Mailing flyers was a result of the pivot from in-person engagement to virtual engagement, so project funds were not available to mail the flyer to every residence. As such, West End residents were prioritized since that area was more vulnerable than the East End and had a greater likelihood of being selected as a site to implement an adaptation strategy to reduce its vulnerability. Flyers were mailed to all 170 residences on the West End, and 30 flyers were mailed to randomly selected residences on other parts of the island. While no data are available on the receipt of the mailed flyers, Facebook statistics show the digital flyer reached 1,897 accounts, resulted in 150 engagements ("likes" or comments), and 12 shares within the first two weeks of its posting (Heming, 2020). Of the six virtual meetings, two were "Live" events on Facebook, two were videoconferences on Zoom, and two were call-ins over telephone. Call-ins were included to reduce accessibility bias of residents who did not use social media.

Feedback from virtual-meeting attendees was obtained through emailed or mailed surveys. The 12-question survey collected responses on adaptation strategies and SLR scenarios to consider for this project. Relevant demographic data were also collected, such as residency status, where on the island respondents live or own property, and their level of participation in virtual engagement sessions. In total, 23 attendees of the community meetings were sent a survey, and 19 surveys were completed and received by the project team (82.6% response rate). Survey questions may be found in Supplementary Materials.

3.1.3 Outcomes of community engagement

Leadership meeting attendees identified a freshwater pond and aquifer on the East End and a borrow pits site on the West End as vulnerable locations (Figure 1). If compromised during a storm, either of these two sites could severely reduce Dauphin Island's ability to respond and recover. When surveyed, community members almost unanimously agreed with the leadership's risk evaluation and classifications of these two sites (Heming, 2020). Therefore, the "aquifer" and "borrow pits" sites were included in numerical modeling.

Leadership also developed a list of possible adaptation strategies, and community members expressed their level of interest in each strategy through the surveys. From the 19 completed surveys, four adaptation strategies received interest

TABLE 1 Community members' interest levels for adaptation strategies co-developed with Dauphin Island leadership.

Gulf-side adaptation strategies	% interested	Sound-side adaptation strategies	% interested	Other adaptation strategies	% interested
Raise Driveways	**63.2%**	**Fill Borrow Pits**	**68.4%**	Close End of Bienville Blvd	26.3%
Maintenance Beach Nourishment	**57.9%**	Construct Breakwaters	26.3%	Keep Sand on Bienville Blvd	21.1%
Restoration Beach Nourishment	**52.6%**	Add Bulkheads	15.8%	Raise Island Elevation	10.5%
Raise Dune Crests	42.1%	Elevate Existing Bulkheads	10.5%	Other	31.6%
Fortify Dunes	26.3%	Other	21.1%		
Other	26.3%				

Four strategies (bold font) were included in this project.

greater than 50% from the community (Table 1). Of the gulf-side strategies, 'raise driveways' had 63% interest, 'maintain present-day beach width and elevation through nourishment' had 58% interest, and 'restore beach width and elevation to a historical profile through more nourishment' had 53% interest. Only one sound-side strategy, 'fill borrow pits on the north side of the island' received a response above 50% interest by community members. These four adaptation strategies were implemented in numerical modeling as described in the next section. Other adaptation strategies that received fewer votes included adding structures to the island, such as a seawall buried beneath dunes or a breakwater on the sound-side to mitigate wave impacts, allowing sediment to accumulate on Bienville Boulevard during overwash events to raise road elevations, and intentionally raising the island's elevation (Collini, 2020; Heming, 2020). These strategies were not included in numerical modeling.

Meeting attendees were asked to vote for their top two out of six SLR scenarios they believed to be most appropriate for planning purposes on Dauphin Island. In general, leadership voted for more extreme SLR scenarios compared to community members for adaptation planning (Table 2). The top two highest-voted scenarios from leadership were Intermediate and Intermediate-high, whereas the top two-highest voted from community members were Intermediate-low and Intermediate. These outcomes indicate the leadership group was more risk-averse than community members, voting for more severe SLR scenarios with lower likelihoods of occurrence by 2100 (Collini, 2020). The discrepancy between leadership and community members' opinions on appropriate SLR scenarios for planning likely stems from a difference in planning horizons. Leadership discussions were mostly focused on critical infrastructure with life cycles greater than 50 years (e.g., the water treatment plant servicing Dauphin Island), and their votes for Intermediate and Intermediate-high SLR scenarios reflect their longer planning perspectives (Collini, 2020). However, community members expressed concerns of infrastructure with shorter life cycles (e.g., 30-year home mortgage) and voted for Intermediate-low and Intermediate scenarios (Heming, 2020). Several SLR scenarios were considerd in numerical modeling, including the top-voted Intermediate-low, Intermediate, and Intermediate-high scenarios.

TABLE 2 Leadership and community members' votes for sea-level rise (SLR) scenarios most appropriate for planning on Dauphin Island.

SLR scenario by 2100	Exceedance probability	Leadership votes (%)	Community votes (%)
Low	99%	0.0%	14%
Intermediate-low	**96%**	20.%	**39%**
Intermediate	**17%**	**40.%**	**44%**
Intermediate-high	**1.3%**	**30.%**	2.8%
High	0.3%	10.%	0.0%
Extreme	0.1%	0.0%	0.0%

Exceedance probabilities reference SLR projections from Sweet et al. (2017) corresponding to RCP 8.5 occurring by 2100. The two top-voted responses from leadership and community groups are in bold font.

Nearly 70% of survey respondents participated in a virtual community meeting and, as such, had some level of prior knowledge about the project before completing the survey. All but one survey respondent owned property on Dauphin Island and the majority lived or had property on the West End. Of the property owners, 56% were part-time residents and 28% were full-time residents, roughly corresponding to the 65% seasonal and 35% permanent residents occupying Dauphin Island at that time. The remaining 16% classified their residency as "other". While the representation of seasonal versus permanent residents seems proportionate in survey responses, potential selection bias due to other factors, such as overrepresentation of entrenched interests or misrepresentation of other groups such as economically vulnerable populations, was not evaluated and is a limitation to this study.

3.2 Numerical modeling with XBeach

XBeach, a process-based two-dimensional depth-averaged (2DH) model, was employed due to its ability to estimate wave transformations, sediment transport, and bed level changes on the barrier island scale while considering hydrodynamic forces acting on an island's seaward and landward sides (Roelvink et al., 2009). Applied in its *surfbeat* mode, XBeach estimates wave action by resolving short wave groups as opposed to individual waves, saving computational time but limiting the model's applicability to conditions when wave groups dominate the energy spectra such as during storm conditions (Masselink and Heteren, 2014). The model can also simulate flow and sediment transport in the presence of structures. XBeach requires, at a minimum, model grid files, hydrodynamic forcing files, and a control file specifying user-defined parameters.

3.2.1 Model calibration and setup

Prior to project onset, XBeach was calibrated using data collected from Hurricane Nate near the "public beach & parking lot" on the West End (Figure 1). The model calibration process followed the methodology of numerous other studies (e.g. Simmons et al., 2019; Smallegan et al., 2016) and included tests on the grid resolution and several XBeach parameters. The reader is referred to Patch and Caraway (2025) for information on model calibration, which is summarized here. Coogan et al. (2019) contains information on the field data collection during Hurricane Nate.

The model grid employed in the final calibration utilized spatially-varying cell sizes to reduce computational time without sacrificing accuracy of simulated results. A 1 m cell size was applied from the 1 m depth contour on the gulf side to the 0.5 m depth contour on the sound side. A 10 m grid spacing extended from the 1 m depth contour to the 8 m depth contour on the gulf side and from the 0.5 m depth contour to the north end of the model domain on the sound side. A 30 m cell size was applied at the offshore and lateral boundaries. Elevation data were obtained from lidar data collected prior to Hurricane Nate landfall and a digital elevation

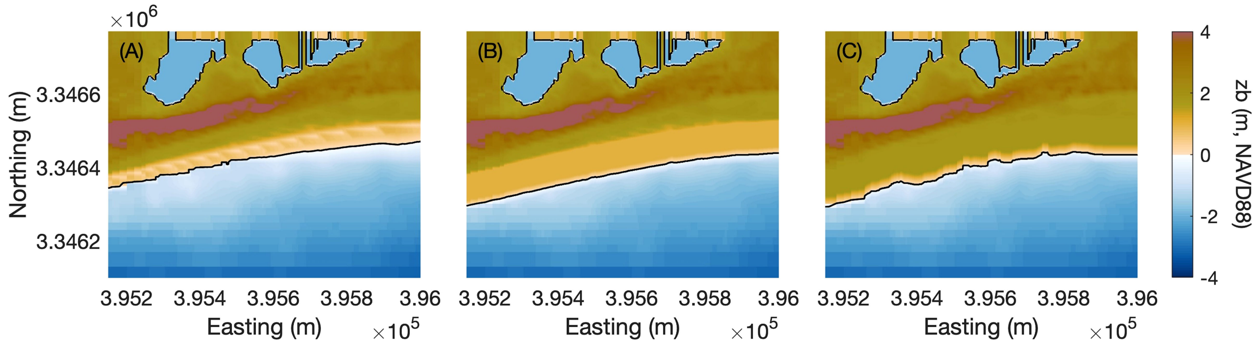

FIGURE 3
Elevations, *zb*, in the initial pre-storm **(A)** AQ grid were obtained from topobathymetry at the aquifer site. The **(B)** AQW and **(C)** AQWR strategies were applied by altering *zb* in the AQ grid. Elevations reference NAVD88 where positive values are represented by shades of brown and negative values are represented by shades of blue. The 0 m MSL (-0.016 m NAVD88) contour is shown by the black line in each grid.

model (DEM) produced for the Mobile Bay, AL region (Danielson et al., 2013; NCEI, 2016). The lidar data has a 0.35 m grid spacing with 10 centimeters (cm) vertical accuracy and 100 cm horizontal accuracy, whereas the DEM has approximately a 3 m resolution with accuracy ranging from 6 to 20 cm root mean squared errors (RMSE) depending on the original source. The lidar and DEM datasets were merged and interpolated onto the spatially-varying model grid using Matlab. Spatially-varying friction factors were specified for each cell as Manning *n* coefficients based on land cover type within the grid (Passeri et al., 2018).

As a result of the calibration tests, only three parameters improved agreement between simulated and measured post-storm elevations: *facua* governing wave skewness, and *D50* and *D90* specifying grain size distribution. Otherwise, parameters were kept at their default values. Wave skewness parameter *facua* was set to 0.01 (default is 0.1) in the calibrated model setup. Some researchers have noted that steep beaches with slopes above ~5% are more sensitive to *facua* with higher *facua* values producing results with greater skill and the default value of *facua* falling outside of reasonable values (e.g. Simmons et al., 2019; Vousdoukas et al., 2012). However, Dauphin Island is a mildly sloping (~1%) dissipative beach and *facua*=0.01 produced nearly identical results to the default value. Brier Skill Scores (BSS) for results with *facua* set to 0.01 were 0.02 higher on average than the results with the default value. As such, *facua* was set to 0.01, and the calibrated model setup was used in simulations at the aquifer and borrow pits sites.

Grain size distribution parameters *D50* and *D90* were set to 0.22 mm and 0.35 mm, respectively. Grain sizes were obtained from sieve analysis performed on sediment samples collected on Dauphin Island after Hurricane Nate. BSS were used to quantify agreement between measured and modeled morphological change, with a BSS of 1.0 indicating perfect agreement (van Rijn et al., 2003). The calibrated model setup produced BSS ranging from 0.84 to 0.96, which indicates good agreement between post-storm surveys and simulated post-storm elevations and demonstrates the calibrated model's capability to skillfully reproduce storm-induced morphological change.

3.2.2 Aquifer site model setup

The aquifer grid (AQ) was generated by interpolating the merged pre-Nate lidar and DEM data onto a model domain extending from UTM Zone 16N 3343230 m northing (N) 395000 m easting (E) to 334700 m N 396140 m E (Figure 3A). Adaptation strategies were implemented into the AQ grid by altering bed elevations using Matlab. The 'widen beach' adaptation strategy grid (AQW) applied a beach nourishment template that widened the beach by 70 m at a constant 1 m elevation to match the average beach elevation in the AQ grid (Figure 3B). The 'widen and raise beach' adaptation strategy grid (AQWR) implemented a beach nourishment template that widened the beach by 70 m and raised beach elevations to approximately 1.8 m to match berm elevations on the island (Figure 3C). Both beach nourishment templates apply an approximate 1:15 beach slope from the nourished beach seaward until intersecting the existing bathymetry. Mannings n values were also updated to represent any changes in land cover, such as from water to unconsolidated sandy shore (Bellais, 2022). Table 3 lists the aquifer grid descriptions and their acronyms used in the following sections.

3.2.3 Borrow pits site model setup

The borrow pits grid (BP) was generated by interpolating the merged pre-Nate lidar and DEM data onto a model domain extending from UTM Zone 16N 3344254 m N 387200 m E to 3347680 m N 389690 m E (Figure 4A). Adaptation strategies were

TABLE 3 Acronyms for grids at the aquifer and borrow pit sites and their adaptation strategies.

Aquifer site		Borrow pits site	
No Strategy	AQ	No Strategy	BP
Widen Beach	AQW	Widen Beach	BPW
Widen Beach + Raise Elevations	AQWR	Raise Driveways	BPRD
		Fill Borrow Pits	BPFP

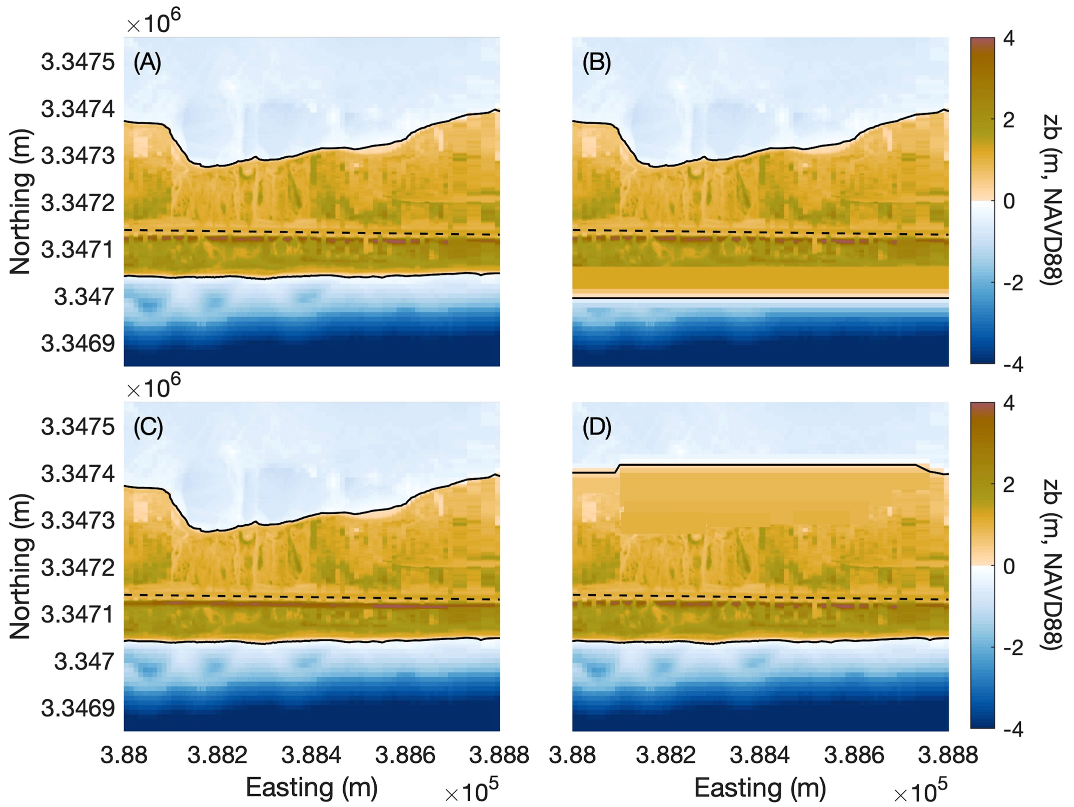

FIGURE 4
Elevations, *zb*, in the initial, pre-storm **(A)** BP grid were obtained from topobathymetry at the borrow pits site. The **(B)** BPW, **(C)** BPRD, and **(D)** BPFP strategies were applied by altering *zb* in the BP grid. Elevations reference NAVD88 where positive values are represented by shades of brown and negative values are represented by shades of blue. The 0 m MSL contour (-0.016 m NAVD88) is represented by the black solid line, and the location of Bienville Boulevard is represented by the black dashed line.

implemented in the BP grid by altering bed elevations using Matlab. Strategies at this site included widen the beach through beach nourishment, raise driveway elevations, and fill borrow pits (Figure 4). The beach nourishment grid (BPW) included widening the beach by 50 m at 1 m elevation to restore the island to its 1997 width determined from historical satellite imagery (Figure 4B). The 'raise driveways' grid (BPRD) closed breaks in the dunes caused by driveways for gulf-front houses by increasing driveway elevations to approximately the surrounding dune crest elevations, creating a relatively longshore continuous dune system (Figure 4C). The 'fill pits' grid (BPFP) was applied by increasing elevations in the borrow pits to approximately 1.5 m to create a continuous elevation and width on the back barrier region (Figure 4D). The seaward side of the BPW grid and sound side of the BPFP grid apply an approximate 1:15 beach slope from the added sediment until the profile intersects existing bathymetry. Mannings n values were also updated to represent any changes in land cover (Delaney, 2022). Table 3 lists the borrow pits grid descriptions and their acronyms used in the following sections.

3.2.4 Wave and water level model forcing

In all simulations including the calibration setup, Hurricane Nate was simulated as a 20-hour storm in XBeach with waves and water levels input hourly. Wave spectra were measured by National Data Buoy Center (NDBC) buoy 42012 located southeast of Dauphin Island at the 25 m depth contour (NDBC, 2025). Wave heights reached approximately 5 m with an average peak period of 10 s, and waves approached from the south-southeast. Gulf water levels were obtained from the Dauphin Island tide gauge and reached 1.2 m MSL (NOAA, 2025b). Mississippi Sound water levels were measured by Coogan et al. (2019) and reached 1.7 m MSL. SLR was superimposed on the gulf and sound water levels for values of 0.53 m, 0.66 m, 0.75 m, 1.0 m, 1.26 m, and 1.93 m.

3.2.5 Definitions of damage and tipping points

The effectiveness of adaptation strategies to mitigate damage on Dauphin Island was evaluated using results from 49 XBeach simulations, with 21 model runs completed at the aquifer site and 28 model runs completed at the borrow pits site. At the aquifer site, damage was defined as saltwater overtopping the dunes and contaminating the freshwater lakes supplying the aquifer. A tipping point was reached when hydraulic connectivity was established between the salty gulf and the freshwater lakes in numerical model simulations.

At the borrow pits site, damage was originally defined as breaching. However, none of the model simulations produced a breach at this location for the storm and SLR scenarios considered. Therefore, the definition of damage on the West End was re-

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evaluated through conversations with the community and redefined as Bienville Boulevard is impassable after a storm and the backbarrier region drowns due to sediment starvation. Two tipping points resulted from this definition of damage: 1) sand was deposited on Bienville Boulevard by the end of model simulations and 2) the amount of sediment volume remaining on the island was reduced when an adaptation strategy was applied.

Sediment volume remaining on the island above MSL considering SLR was used to evaluate damage to the backbarrier region through sediment starvation. Remaining sediment volumes were calculated by integrating the final elevations above MSL considering SLR.

$$Volume = \int_{y_1}^{y_2}\int_{x_1}^{x_2} z_{bf+,MSL}\,dx\ dy \quad (1)$$

where $z_{bf+,MSL}$ is the final simulated elevations above MSL, and MSL is dependent on SLR such that

$$MSL = 0.016\ m\ (NAVD88) + SLR \quad (2)$$

and $z_{bf+,MSL}$ is integrated over the model domain from x_1=387200 m E to x_2=389690 m E and y_1=3344254 m N to y_2= 3347680 m N. Datum information was obtained from Dauphin Island tide gauge 8735180 (tidesandcurrents.noaa.gov).

4 Results

XBeach results were output at the end of each hour during the simulations to characterize damage due to storm conditions and SLR. At the aquifer site, maximum water levels (*zs*) identified saltwater contamination by dune overtopping. At the borrow pits site, changes in elevations (*zb*) during the simulations were relevant for identifying sand deposits on Bienville Boulevard and quantifying volume of sediment remaining on the island as sea levels rise.

4.1 Inundation at the aquifer site

Maximum *zs* within the AQ grid is shown in Figure 5 for no SLR and Intermediate-low (0.66 m), Intermediate (1.26 m), and Intermediate-high (1.93 m) SLR scenarios; areas in white were not inundated during the simulation. In Figure 5, the 0 m MSL (-0.016 m NAVD88) contour is based on the 1983–2001 epoch and is not adjusted for SLR scenarios. The point of separation between the seaward inundated areas and the landward non-inundated areas is referred to as the peak shoreline.

In general, inundation extended further inland and maximum *zs* was higher as sea levels rose (Figure 5). Inundation extents were

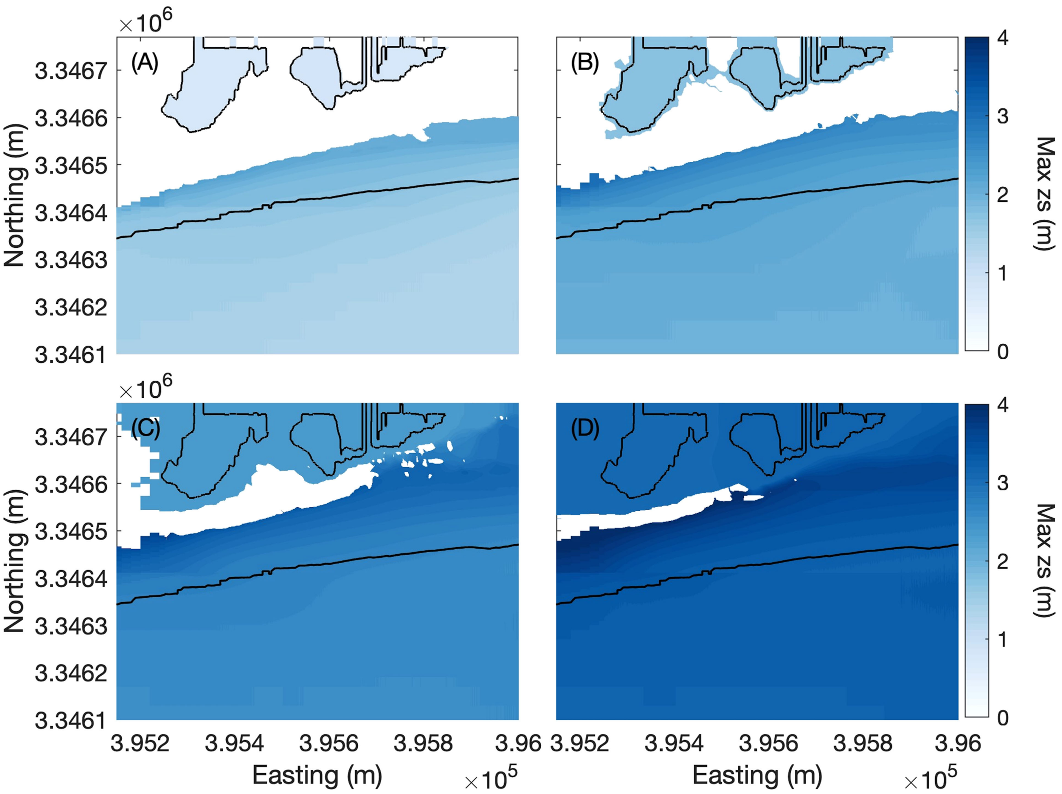

FIGURE 5
XBeach-simulated maximum water levels, *zs*, on AQ for **(A)** no SLR, **(B)** Intermediate-low (0.66 m) scenario, **(C)** Intermediate (1.26 m) scenario, and **(D)** Intermediate-high (1.93 m) scenario. Inundated areas are shown in blue with darker shades representing higher maximum *zs*. Areas that are not inundated during the simulation are shown in white. The 0 m MSL (-0.016 m NAVD88) contour is shown by the black line in each grid.

50 m to 150 m inland from the 0 m MSL contour for no SLR (Figure 5A). For a 0.66 m rise in sea level, inundation extended an additional 50 m compared to no SLR (Figure 5B). Hydraulic connectivity between the freshwater lakes and gulf was observed in simulations for SLR greater than 1.00 m (Figures 5C, D). Peak values of maximum *zs* occurred along the peak shoreline where swash zone processes contributed to the overall water level. Maximum *zs* was also locally higher on top of inundated dunes due to wave setup for SLR greater than 1.00 m (Figures 5C, D). Peak values for maximum *zs* were 2.44 m for SLR=0 m, 3.14 m for SLR=0.66 m, 3.72 m for SLR=1.26 m, and 4.38 m for SLR=1.93 m, corresponding to a linear increase in peak *zs* with SLR.

For SLR up to 0.66 m, the tipping point was not reached because dunes were not overtopped and hydraulic connectivity was not established between the freshwater lakes and the gulf during the simulation in the AQ grid (Figures 5A, B). As SLR approached 1.26 m, a tipping point was reached because storm surge exceeded dune elevations and inundated the freshwater lakes supplying the aquifer (Figure 5C).

To better identify when the aquifer site tipping point occurred, maximum *zs* from SLR simulations between the Intermediate-low and Intermediate scenarios were analyzed and are shown in Figure 6 for the AQ, AQW, and AQWR grids. For SLR=0.75 m, hydraulic connectivity is not established between the freshwater

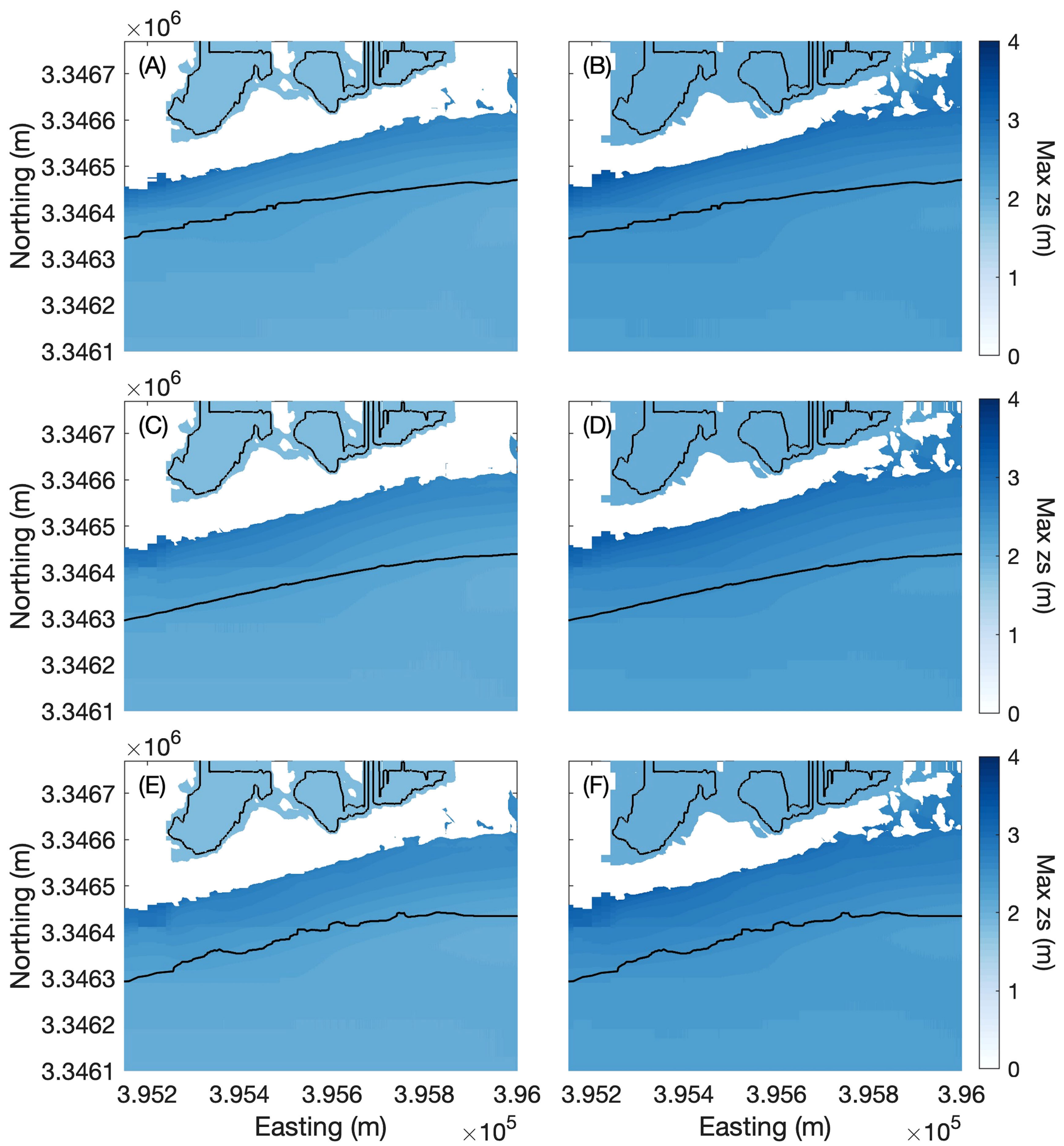

FIGURE 6
XBeach-simulated maximum water levels, *zs*, for the **(A, B)** AQ grid, **(C, D)** AQW grid, and **(E, F)** AQWR grid for SLR of **(A, C, E)** 0.75 m and **(B, D, F)** 1.00 m. Inundated areas are shown in blue with darker shades representing higher maximum *zs*. Areas that are not inundated during the simulation are shown in white. The 0 m MSL (-0.016 m NAVD88) contour is shown by the black line in each grid.

lakes and gulf in the AQ grid or in either adaptation strategy grid (Figures 6A, C, E). The two water bodies remained separated by at least 50 m of dunes that were subaerial during the simulations in the AQ, AQW, and AQWR grids. The widened beach in the AQW grid and the widened and raised beach in AQWR grid was flooded to the same landward extent as the AQ grid. For SLR of 0.75 m, inundation extended about 150 m from the 0 m MSL contour in the AQ grid. Inundation extent increased by 20 m in the AQW and AQWR grids due to the seaward shift of the 0 m MSL contour when the beach was widened. Peak values of maximum *zs* were along the western side of the peak shoreline for AQ, AQW, and AQWR and equaled 3.21 m, 3.14 m, and 3.07 m, respectively.

As shown in Figures 6B, D, F, the aquifer site tipping point was reached for SLR=1.00 m for the AQ grid and both adaptation strategies due to hydraulic connectivity established between the freshwater lakes and gulf. Dunes on the eastern side of the model domains near UTM Zone 16N 3346670 m N 3958890 m E were overtopped and saltwater to flowed into the flooded freshwater lakes. For SLR of 1.00 m, peak values of maximum *zs* were 3.43 m in the AQ grid, 3.31 m in the AQW grid, and 3.31 m in the AQWR grid and occurred on the western side, although maximum *zs* was also elevated on top of the overtopped dunes. The AQW and AQWR strategies reduced *zs* by up to 5% through energy absorption and dissipation on the widened and raised beach.

4.2 Morphological changes at the borrow pits site

BP grid final elevations, *zb*, are shown in Figure 7 for no SLR and Intermediate-low (0.66 m), Intermediate (1.26 m), and Intermediate-high (1.93 m) SLR scenarios. In Figure 7, the 0 m MSL (-0.016 m NAVD88) contour is based on the 1983–2001 epoch and is not adjusted for SLR scenarios. Bienville Boulevard is shown for reference. Generally, the results show increased dune erosion and profile smoothing as sea levels rise. For no SLR, morphological change in the BP grid was mostly limited to the beach (Figure 7A). Erosion along the beach and berm lowered elevations by 1.50 m between the 0 m MSL contour and the dunes located on the southern side of Bienville Boulevard. Sediment was redistributed mostly to the nearshore region in deposits up to 0.40 m thick decreasing depths along the shore. Relatively small amounts of sediment were transported through breaks in the dune system and deposited Bienville Boulevard with average thicknesses of 0.16 m.

Dune crest elevations in the BP grid were reduced by 3.50 m for SLR=0.66 m, 3.85 m for SLR=1.26 m, and 4.00 m for SLR=1.93 m, where dune sediment was transported to the backbarrier region located north of Bienville Boulevard. Deposit thicknesses along Bienville Boulevard decreased as sea levels increased. For SLR=0.66 m, deposits were 0.80 m, whereas Intermediate and Intermediate-

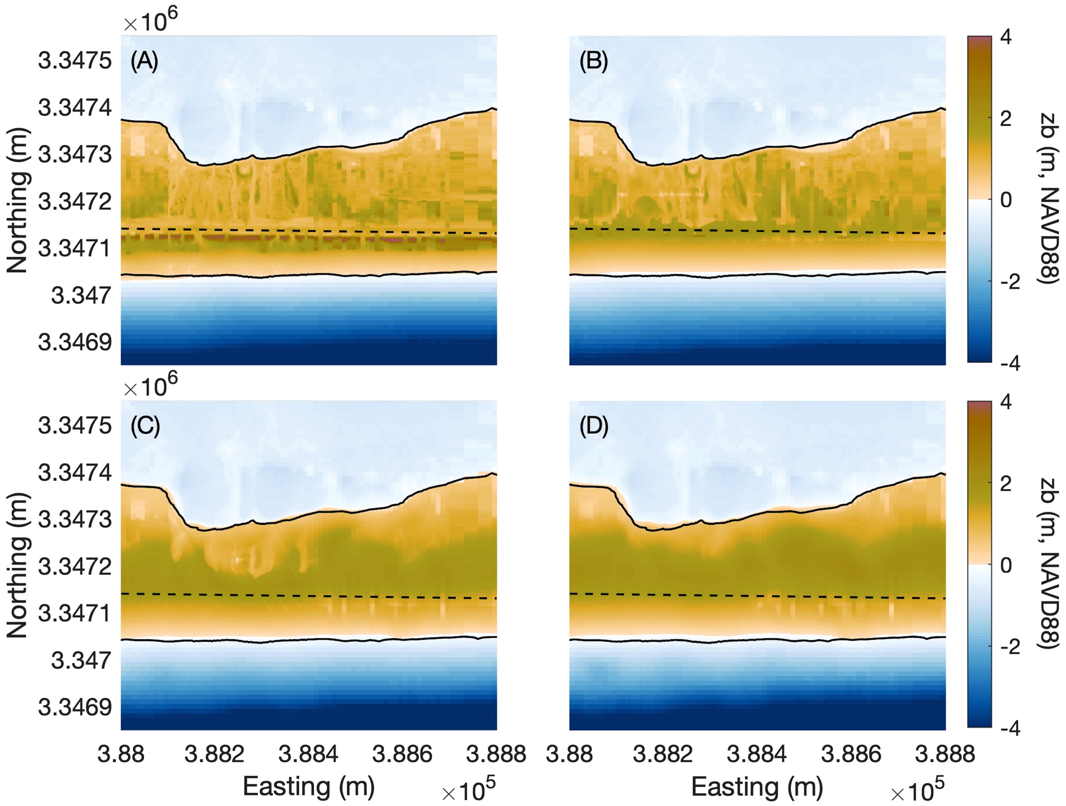

FIGURE 7
XBeach-simulated final elevations, *zb*, of the BP grid for **(A)** no SLR, **(B)** Intermediate-low (0.66 m) scenario, **(C)** Intermediate (1.26 m) scenario, and **(D)** Intermediate-high (1.93 m) scenario. Elevations reference NAVD88 where positive values are represented by shades of brown and negative values are represented by shades of blue. The 0 m MSL (-0.016 m NAVD88) contour is represented by the black solid line, and the location of Bienville Boulevard is represented by the black dashed line.

high SLR scenarios produced deposits 0.66 m and 0.56 m thick. As seas rise, sediment is transported further inland, thereby reducing the amount of deposition on Bienville Boulevard and increasing the amount of deposition on the backbarrier region. Sediment deposits increased backbarrier elevations by 1.33 m on the for SLR=1.26 m and 1.38 m for SLR=1.93 m. Shoreline retreat was relatively small in the BP grid such that maximum retreat equaled 10 m for 1.93 m of SLR. Sediment deposits on the sound side corresponded with the amount of shoreline retreat, and maximum shoreline accretion equaled 10 m for the Intermediate-high SLR scenario.

Figure 8 shows final elevations of the BP, BPW, BPRD, and BPFP grids for no SLR and the Intermediate-low (0.66 m) SLR scenario. Barrier island overwash and profile smoothing were observed in the BPW, BPRD, and BPFP grids for SLR above 0.66 m and were similar to the BP grid results shown in Figures 7C, D.

Final elevations for the BPW grid show the widened beach was eroded with elevations reduced by nearly 1.60 m and about 30 m of shoreline retreat for no SLR and SLR=0.66 m (Figures 8C, D). Negligible dune erosion occurred in the BPW grid for no SLR, but elevated water levels due to the 0.66 m rise in sea level allowed waves to reach and erode the dune toe decreasing dune widths by 10 m. More dunes survived in the BPW grid compared to the BP grid for SLR=0.66 m, indicating the widened beach absorbed and dissipated energy and mitigated dune erosion. The BPRD strategy resulted in negligible dune erosion for no SLR and dune toe erosion was nearly longshore uniform for SLR=0.66 m reducing the dune width by 8 m. No differences between the BP grid and the BPFP strategy were observed on the gulf side, and morphological changes on the sound side were negligible in the simulated results for no SLR and SLR=0.66 m.

Compared to the BP grid, the BPW reduced average sand deposit depths on Bienville Boulevard by 0.05 m for no SLR and 0.17 m for SLR=0.66 m. Maximum sand deposit depths in the BPW grid were 0.4 m and 0.8 m on Bienville Boulevard for no SLR and SLR=0.66 m, respectively. However, the longshore continuous dune in the BPRD grid prevented sand from depositing onto Bienville Boulevard for SLR up to 0.66 m. Sediment deposition on Bienville Boulevard was not affected by filling the borrow pits, and sand depths on Bienville Boulevard were equal in the BP and BPFP grids.

Model results showed the BPRD strategy prevented sand from depositing on Bienville Boulevard. However, the continuous dune also starved the backbarrier region of sediment by preventing sand overwash. Sediment volume was calculated using Equation 1 and adjusted for MSL using Equation 2 such that Figure 9 shows the sediment volume remaining above MSL decreased as sea levels increased. The BPRD grid consistently had the lowest remaining volume even though it performed best at preventing sand deposits on Bienville Boulevard for SLR up to 0.66 m. Remaining sediment volume for the BPRD grid was lower than those for the BP grid by at least 2.82×10^3 m^3 and at most 1.01×10^4 m^3. The BPFP grid had the highest remaining sediment volumes about 1.50×10^4 m^3 above the BPW grid for no SLR and SLR=0.66 m. As sea level rose above 0.66 m, the BPW strategy resulted in more sediment volume above MSL, exceeding BPFP volumes by 1.01×10^4 m^3 and 2.48×10^4 m^3 for SLR=1.26 m and 1.93 m, respectively.

4.3 Adaptation pathways for the aquifer and borrow pits sites

At the aquifer site, damage was defined as saltwater inundation caused by overtopping of dunes during a storm event and sea-level rise, and a tipping point was reached when saltwater overtopping was observed in numerical model simulations. Maximum *zs* and inundation extents showed the dunes were overtopped in the AQ, AQW, and AQWR grids and the freshwater lakes were inundated with saltwater as sea-level rose above 1.0 m. Therefore, tipping points for both AQW and AQWR strategies correspond to the tipping point for the AQ grid, resulting in a preferred pathway of maintaining the AQ condition without implementing the AQW or AQWR strategies.

At the borrow pits site, damage was defined as sand deposited on Bienville Boulevard or when the island is starved of sediment. These two definitions resulted in adaptation pathways for the same location on Dauphin Island. Final *zb* showed the BPRD strategy prevented sand deposition on Bienville Boulevard for SLR up to 0.66 m. The BPRD, BPW, and BPFP strategies were ineffective at mitigating damage based on this definition for more extreme SLR. As such, the preferred pathway applies the BPRD strategy adaptation pathway until SLR=0.66 m and points to other adaptation strategies for SLR greater than 0.66 m (Figure 10). Sediment volumes remaining above MSL+SLR were used to identify sediment starvation on the island and showed the BPRD strategy had the lowest remaining volume for all SLR scenarios. The BPFP strategy had the highest sediment volumes remaining for SLR up to 0.66 m, and the BPW strategy volumes were highest for more extreme SLR scenarios. As such, the preferred pathway to mitigate damage due to sediment starvation skips over the BPRD strategy, points to the BPFP strategy for SLR up to 0.66 m when a tipping point is reached, then moves to the BPW strategy for more extreme SLR (Figure 10).

5 Discussion

Adaptation planning in the complex and dynamic coastal environment requires strategies that are site-specific and evaluated within context of its region (National Research Council, 2014). As such, adaptation pathways are unique to their locations and the community they serve, and pathways are not likely translatable to other sites. However, the adaptation pathway approach applied in this study is translatable. This Dauphin Island Adaptation Pathway case study informs the adaptation pathways concept by considering many of the suggestions made by Wise et al. (2014) to develop a more robust climate adaptation tool.

Wise et al. (2014) suggested power relations and prevailing societal norms should be understood and overcome in adaptive planning. As such, Dauphin Island leadership and community members were engaged as separate groups during community engagement phases. The influence of leadership on community

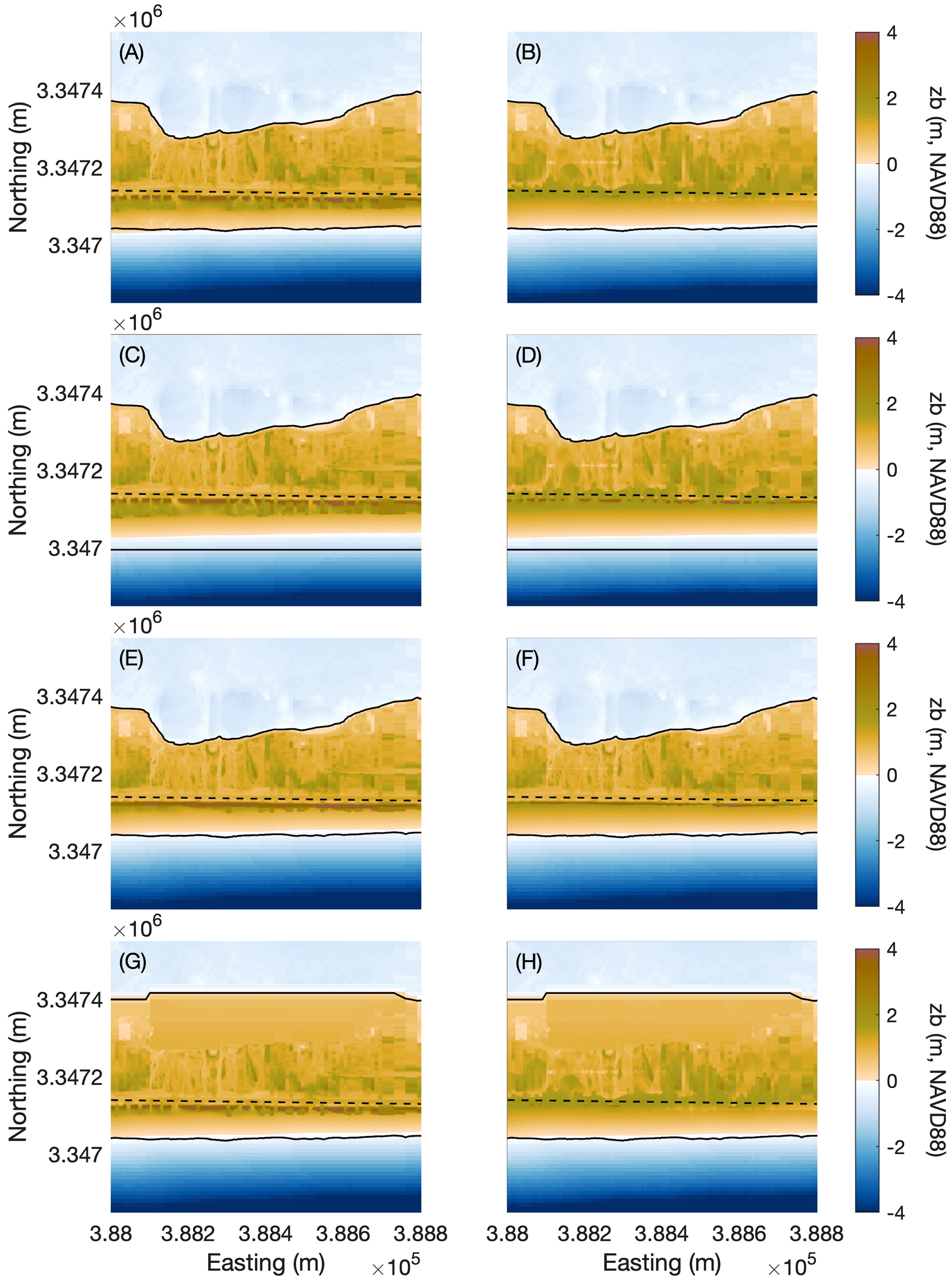

FIGURE 8
XBeach-simulated final elevations, *zb*, of the **(A, B)** BP grid, **(C, D)** BPW grid, **(E, F)**, BPRD grid, and **(G, H)** BPFP grid for **(A, C, E)** no SLR and **(B, D, F)** Intermediate-low (0.66 m) scenario. Elevations reference NAVD88 where positive values are represented by shades of brown and negative values are represented by shades of blue. The 0 m MSL (-0.016 m NAVD88) contour is represented by the black solid line, and the location of Bienville Boulevard is represented by the black dashed line.

member opinions was mitigated by obtaining individual and anonymous responses to adaptation strategies and planning scenarios through surveys. Engaging both leadership and community members led to 'discoveries' that shaped the focus and outcomes of this project. For example, discussions with leadership led to the discovery of the aquifer site and its vulnerability to SLR, and the aquifer site was added to the project because of community interest. At the borrow pits site, the project team suggested a "community driveways" adaptation strategy where a single break in the dune system would serve as a shared driveway

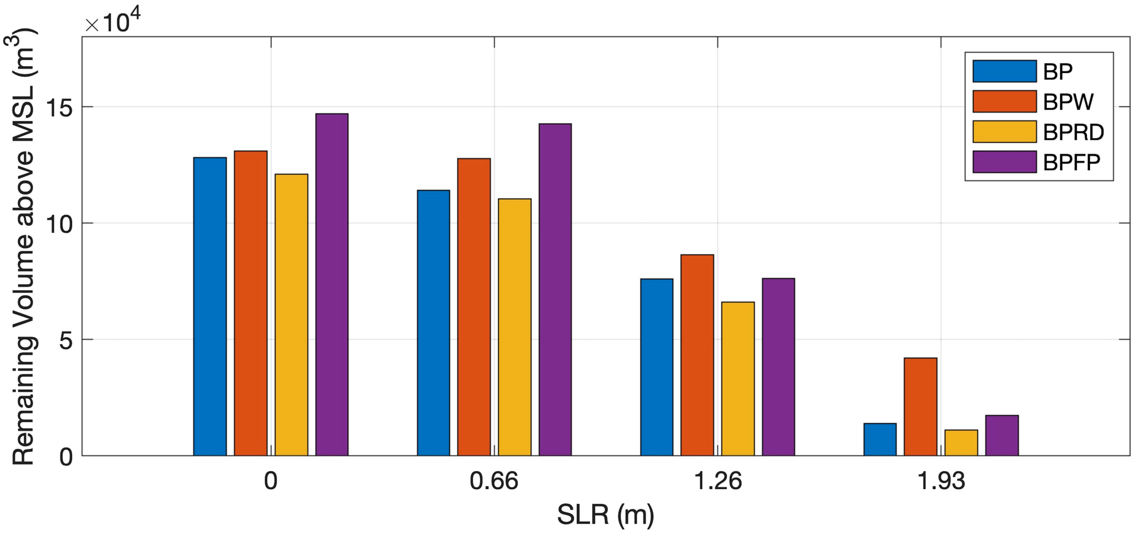

FIGURE 9
Sediment volume remaining above 0 m MSL+SLR grouped by SLR scenario for the BP (blue bars), BPW (red bars), BPRD (yellow bars), and BPFP (purple bars) grids.

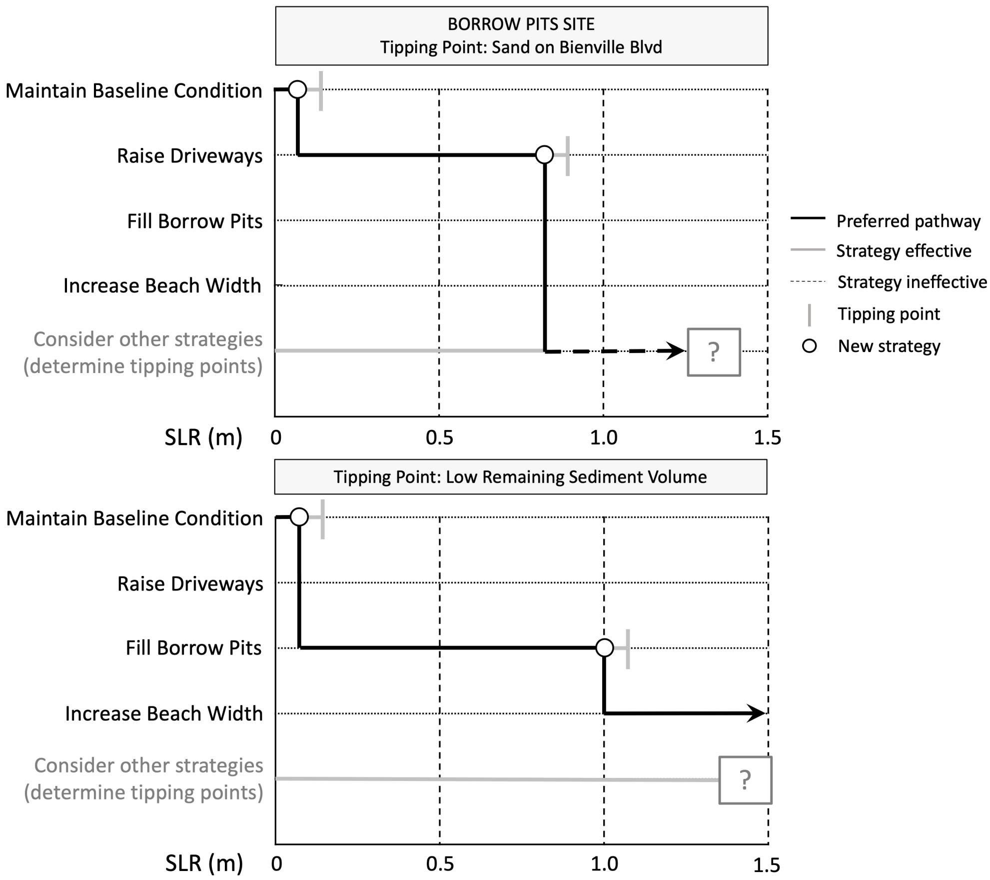

FIGURE 10
The adaptation pathways generated for the borrow pits site define critical tipping points as (top) sand depositing on Bienville Boulevard and (bottom) remaining sediment volume on the island above MSL is relatively low; other adaptation strategies should be considered beyond the identified tipping points.

to groups of gulf-front houses. This strategy was immediately dismissed and substituted with individual raised driveways; thus, the strategy to raise driveways and create a continuous dune feature was discovered and became part of this study. These unexpected responses from community engagement strengthened the outcomes of this project while promoting community buy-in and highlights the importance of engaging with communities early in project planning.

Coordinated adaptation planning was suggested by Wise et al. (2014) and is particularly important to apply at the borrow pits site. The continuous dune created by raising driveways effectively prevented sediment from depositing on Bienville Boulevard in numerical model results. On December 18, 2024, a Town of Dauphin Island ordinance was signed requiring driveways on the West End to be raised (Ordinance No. 108; https://www.townofdauphinisland.org/town-ordinances). Since then, several residents have increased the elevation of their driveways, and elevated driveways have prevented sand deposits on Bienville Boulevard during recent flood events. Figure 11 shows photographs taken from Dauphin Island's backbarrier region facing the gulf after Hurricane Francine (2024) for residences with and without raised driveways. The unelevated driveway created a break in dune crest elevation and allowed sediment transport from the beach and deposit onto Bienville Boulevard (Figure 11A). However, the raised driveway prevented sediment transport from the beach and sand was not deposited on Bienville Boulevard at that residence (Figure 11B). Due to a lack of data collected before, during, or after Hurricane Francine on Dauphin Island, further damage assessments are unable to be provided.

Although raising the driveways successfully prevents sand deposits on Bienville Boulevard, they also starve the backbarrier region of sediment by preventing sediment overwash. Barrier islands respond to rising seas by migrating landward through overwash during storms and preventing this natural process increases its vulnerability (Donnelly et al., 2006; Leatherman, 1979a, b). As such, dune management is a governing factor in the future state of a barrier island (Anarde et al., 2024). Depending on how they are managed, dunes can serve as a sediment source and contribute to building backbarrier elevations during overwash events or they can cause sediment starvation and contribute to barrier island drowning by preventing overwash. Therefore, it is imperative that the Dauphin Island community provide the West End backbarrier region with sediment to replace the reduced supply from regular overwash events prevented by the raised driveways. One such supply could be filling the borrow pits on the northern side of the island in combination with raising the driveways.

In this study, adaptation strategies were evaluated individually and evaluating combinations of adaptation strategies was outside the scope of this project. It is expected that the implementation of an adaptation strategy will affect the effectiveness of other strategies by either increasing or decreasing their ability to reduce damage, and additional numerical analyses are required to estimate those impacts. Implementing more than one strategy at a time or combinations of strategies could produce compound benefits or cascading effects that should be determined. This case study on Dauphin Island's West End demonstrates the importance in coordinating adaptation strategies so that the barrier island is benefited holistically from their implementation.

In another suggestion, Wise et al. (2014) stated that path dependency and lock-in should be prevented by considering temporal responses. This project demonstrated that adaptation pathways were also dependent on the location and definitions of tipping points and lock-in could occur if a holistic planning approach is not taken. For example, the adaptation pathways generated in this study were highly dependent on the spatial vulnerability on Dauphin Island. The aquifer site was vulnerable to a hydrodynamic-focused process (saltwater contamination) compared to the borrow pit site, which was vulnerable to a morphodynamic-focused process (morphological change). The preferred pathways were also governed by the definition of the critical tipping point. Tipping points may be defined in many ways and affect the adaptation pathway as a result. As such, two different adaptation pathways were produced for a single site since the effectiveness of each strategy to reduce damage was dependent on

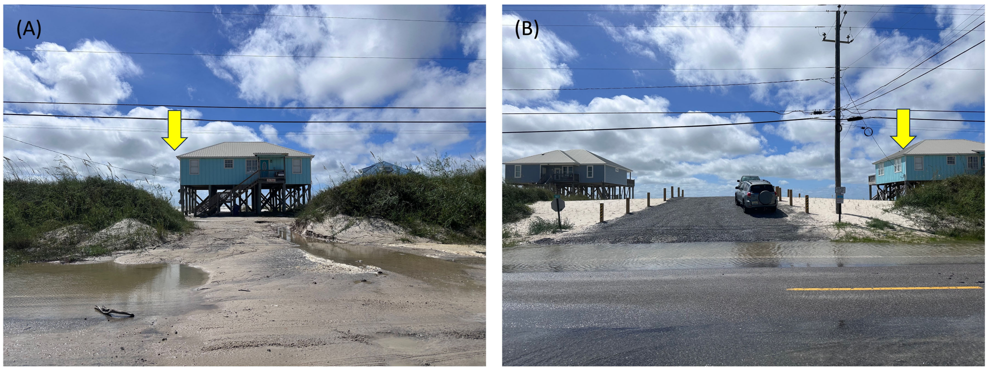

FIGURE 11
Photographs taken after Hurricane Francine show **(A)** sediment deposited on Bienville Boulevard due to sediment transport through an un-elevated driveway located at 30°15′1.37″ north (N), 88°10′15.83″ west (W) and **(B)** a neighboring raised driveway located approximately 25 m east at 30°15′1.37″ N, 88°10′14.86″W prevented sediment transport from the beach. Images are taken facing south towards the Gulf and the yellow arrows indicate the same reference point.

the two different tipping point definitions. By remaining objective and performing rigorous analysis of model results from different perspectives, the impact of raising the driveways on the sediment supply to the backbarrier region was observed. The same set of model results produced a second adaptation pathway at the borrow pits site.

Emphasis was placed on the suggestion by Wise et al. (2014) to evaluate and monitor current and future conditions for improved adaptive planning. The calculated sediment volumes above 0 m MSL for the borrow pits site provides a baseline for the current condition (Figure 9). The sediment volumes calculated for the borrow pits site are on the same order of magnitude as topographic volumes calculated from lidar surveys on Ship Island, Mississippi (MS), an undeveloped barrier island located in the same Mississippi-Alabama barrier island chain as Dauphin Island (Eisemann et al., 2018). As sea-levels rose, the volume of sediment remaining on the island above MSL decreased. However, adding sediment to the island by filling borrow pits or nourishing the beach results in more sediment volume remaining after a hurricane and considering SLR. In general, barrier islands with greater sediment volumes are more resilient to storms and SLR since energy is dissipated as sediment is transported, reducing wave impact and inundation to landward regions (e.g. Eisemann et al., 2018; Houser et al., 2015). Spurgeon et al. (2023) quantified more than a 21% increase in resilience, based on the Coastal Engineering Resilience Index, from beach nourishment at Panama City Beach, FL. Therefore, surveys of vulnerable areas and locations where adaptation strategies are implemented are critical for evaluating current and future conditions.

Community engagement was critical to this project's success, and its continued positive impact is dependent on the leadership's understanding of its content as well as its limitations. Therefore, a final meeting with attendees of the initial leadership meeting was held on June 30, 2022 where results from the numerical model simulations were described, the adaptation pathways generated from those results were discussed, and project "take-aways" were provided in handouts. The meeting attendees were provided guidance on how to evaluate the island's current condition and monitor its state into the future. In-depth discussions included the extent to which raising driveways is likely to affect the backbarrier region and island resilience as a whole, methods to evaluate how much sea-level has risen since a certain baseline, and limitations to look for in any study of their community, including this project. For example, the pathways were generated based on numerical model results, inherent with its own limitations and assumptions, and the model should be further calibrated and validated using data collected from additional areas on the island before, during, and after future storms. Model setup limitations were described as simulations from a single storm, barrier island evolution over time was neglected, SLR was superimposed on storm tide, and definitions of "damage" were based on only physical impacts (e.g., biodiversity assessments or processes affecting water quality of the aquifer were outside the scope of this project). It was also explained that other adaptation strategies and combinations of strategies, such as restoring dunes in combination with raising beach elevations and widening the beach, should be considered for more extreme SLR scenarios.

The final leadership meeting also focused on how to plan funding routes for each of the strategies considered. Within three years of this project's conclusion, the Town of Dauphin Island has implemented or sought to implement the three adaptation strategies evaluated at the borrow pits site. At the aquifer site, a beach nourishment design similar to the AQWR strategy considered in this project was initiated before this project concluded. Beach nourishment was implemented along the East End shoreline to protect habitats, historic Fort Gaines, and the freshwater lakes included in the aquifer site model domain. As of November 13, 2024, approximately 856,000 m^3 (1,120,000 cy) of sand had been placed to restore dunes, raise beach elevations, and widen the beach.

Many of this study's limitations are areas of ongoing work, such as the long-term estimation of barrier island evolution to SLR and incorporating the effects of nonlinear SLR effects in coastal management and planning. Due to the highly dynamic and complex nature of barrier islands, future barrier island responses are difficult to predict, and the response is further complicated when the island is developed due to the interactions between natural responses and civil infrastructure. Quantifiable metrics relating physical characteristics and resilience are areas of ongoing research and will likely inform the storm protection capacity and long-term impacts of adaptation strategies. As such, pre-, during-, and post- event data are required for the development, calibration, and validation of any model, and its collection should remain a priority. Future work may consider a broader definition of damage beyond only a physical response and include the impacts of adaptation strategies on biodiversity and people as identified by (Seddon et al., 2021). Other processes affecting an aquifer's water quality and mechanisms for saltwater contamination, such as leaching, were outside of the scope of this project and beyond the capabilities of XBeach. However, it is acknowledged that the continued viability of the aquifer as a freshwater supply for Dauphin Island is dependent on many processes and mechanisms and should be considered. Also, when engaging with communities, future studies should minimize stakeholder selection bias and, to the extent possible, represent economically vulnerable populations while reducing overrepresentation of entrenched interests.

6 Conclusions

This project revealed adaptation pathway dependency on site selection and definitions of tipping points. As such, adaptation planning should consider a holistic, systems-level approach from multiple perspectives to determine critically vulnerable locations and possible solutions. The integrated coastal engineering and science extension methodologies employed highlight the importance of community engagement early in project planning and development to promote buy-in and incorporate local knowledge that may improve the quality of the work. In this study, three adaptation pathways using three different definitions of damage were generated for two focus locations on Dauphin Island, AL. Involving the community from the onset of the project allowed their feedback to guide the project, including the locations selected for pathway development, adaptation strategies considered for evaluation, and SLR scenarios most appropriate for planning. Stakeholder feedback was essential for identifying an aquifer vulnerable to storms and SLR, a site not realized during the project planning phase and optimizing project resources by limiting the number of adaptation strategies evaluated to those of greatest interest. The effectiveness of adaptation strategies, all of which were comprised of NNBF, were evaluated individually but reveal the potential for trade-offs such that a strategy may have both positive and negative consequences. In this study, a trade-off was observed such that raising driveways to create a continuous dune feature effectively mitigated overtopping during a hurricane, but it also starved the barrier island's interior of sediment. These results highlight the importance of considering the barrier island's resilience from multiple perspectives. By using a calibrated process-based numerical model, this study produced a tool that may be used for seemingly unlimited what-if scenarios and analyses. As community opinions change, barrier islands evolve, and new data become available, adaptation pathways should be revisited and updated accordingly. This approach may provide maximum flexibility for future planning, optimize the use of resources for SLR adaptation, and improve developed barrier island community resilience.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

SP: Funding acquisition, Methodology, Conceptualization, Writing – original draft, Supervision, Data curation, Formal Analysis, Visualization, Project administration, Validation. RC: Writing – review & editing, Conceptualization, Funding acquisition, Project administration, Visualization, Methodology, Supervision. BD: Software, Investigation, Writing – review & editing. KB: Writing – review & editing, Investigation, Software. MH: Resources, Writing – review & editing. PC: Writing – review & editing, Investigation, Software.

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Conflict of interest

Author PC was employed by company Moffatt & Nichol. Author BD was employed by company Great Lakes Dredge & Dock Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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