Case Study

Knowledge-Based Predictive Tools to Assess Effectiveness of Natural and Nature-Based Solutions for Coastal Restoration and Protection Planning

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Abstract: Predictive tools are widely used to study coastal and deltaic systems in support of basic research, planning efforts, engineering design, and the implementation of restoration or protection strategies. They have been extensively used to evaluate the effectiveness of natural and nature-based solutions (NNBS) to support ecosystem functions and services of coastal ecosystems and human communities experiencing increased risk from sea-level rise and severe storms. The potential benefits of NNBS are being increasingly recognized, particularly in remote areas or areas that are either technically or financially infeasible to be protected with levees or other difficult engineering alternatives. Local communities, however, are often excluded from proposing, screening, or evaluating NNBS as restoration and protection strategies. Communities are also not sufficiently involved in the development or application of the predictive tools. This research effort outlines an approach to developing knowledge-based predictive tools and a community engagement process to evaluate NNBS strategies proposed predominantly by local communities. Incorporating knowledge from local communities benefits and potentially improves the performance of predictive tools and their ability to capture visible trends and observations. To illustrate this concept, the authors present landscape models for coastal Louisiana that successfully reproduced the frequency of flooding of local roads, rate of shoreline erosion, salinity pattern changes, and presence/absence of key species (e.g., brown shrimp, oysters, and so forth). While these qualitative measures are not a substitute for well-established rigorous and quantitative model performance assessment approaches, they offer an effective approach to engage local communities and incorporate their knowledge in the development of the predictive models and the proposed protection and restoration strategies to be examined. **DOI: 10.1061/(ASCE)HY.1943-7900.0001659.**

Introduction

Coastal regions are among the most productive and dynamic eco-geomorphic systems in the world. With a long history of human reliance on their natural resources for food, commerce, recreation, protection, and cultural identity, habitation of coastal areas is still rapidly increasing (Dennison 2008). It has been estimated that 10% of the global population live in coastal areas less than 10 m above sea level (McGranahan et al. 2016) and 25% will live in flood-prone coastal zones by 2050 (Aerts et al. 2014). Immediate threats for deltaic and coastal systems come from the extreme water levels associated with hurricanes and storms, which will be further amplified by sea-level rise (SLR) and subsidence caused by both natural and anthropogenic factors. Because of the complex interaction between the fluvial water and sediment input and near-shore processes, these systems can be significantly reshaped by extreme events yet resilient if given suitable conditions for sedimentation and vegetation growth (Paola et al. 2011; Smith et al. 2015). Therefore, understanding and predicting the long-term impacts on coastal resiliency from acute (hurricanes and storms) and chronic (SLR, subsidence, and waves) environmental drivers is key to a sustainable future for these regions. These natural systems often have significant cultural and substantial economic value. The balance among the health/rigor of the ecosystem, culture, and economy is quite complex. It cannot be addressed purely through technical and scientific solutions while dismissing meaningful involvement of local communities. Natural and nature-based solutions (NNBS) received significant attention in recent years as they have shown to be effective restoration and protection strategies (Reed et al. 2018; Temmerman et al. 2013; Temmerman and Kirwan 2015; Poff et al. 2016; Nesshöver et al. 2017). This study explores the utility of NNBS to accomplish restoration and protection goals for coastal ecosystems.

Predictive models have been widely and successfully applied to coastal and inland watershed landscapes (Baustian et al 2018;

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Fox and Papanicolaou 2008; Abban et al. 2016; Olley 2002). Most biophysical and landscape models do not sufficiently incorporate local knowledge into their design or applications. These predictive tools are mainly developed to answer scientific or management questions from research groups or government entities that likely do not reside in these vulnerable regions and likely do not fully grasp the on-the-ground implications of these coastal hazards. Following examples of participatory modeling and utilization of competency groups (Landström et al. 2011; Halbe et al. 2018; Mendoza and Pabhu 2005), the research effort presented here outlines a process to identify the community's NNBS needs as the foundation for providing effective restoration and protection measures. These measures are aimed at reducing risk and supporting ecosystem functions and services. This paper describes the approach of engaging the community as an integral component of the entire process, the validation and performance assessment of the models, and the development and evaluation of various scenarios and strategies.

Community Engagement Approach

The first step of this research effort was the formation of a competency group (CG), essentially a group of local residents with strong ties (economically, historically, and culturally) to the community. The research team collaboratively with the CG identified the need for two models: one computationally efficient and another to provide more detailed information at high spatial resolutions. The 2017 Louisiana Coastal Master Plan Integrated Compartment Model (ICM) was identified as a computationally efficient option for this study (White et al. 2017, 2018, 2019), while the biophysical Delft3D model (Baustian et al. 2018) was suggested to provide detailed information about flow and salinity patterns, morphology, vegetation spatial distribution, and nutrient dynamics. The CG directly participated in every step of the modeling effort starting with the design of the model domain and model performance assessment, identifying NNBS as restoration and protection strategies, then evaluating and screening these ideas.

Study Site

This study focused on Breton Sound Estuary in southeast Louisiana (Fig. 1). This region is bounded on the west and north by the Mississippi River, Mississippi River levees, and flood walls and gates that comprise portions of the Greater New Orleans Hurricane and Storm Damage Risk Reduction System. The Mississippi River

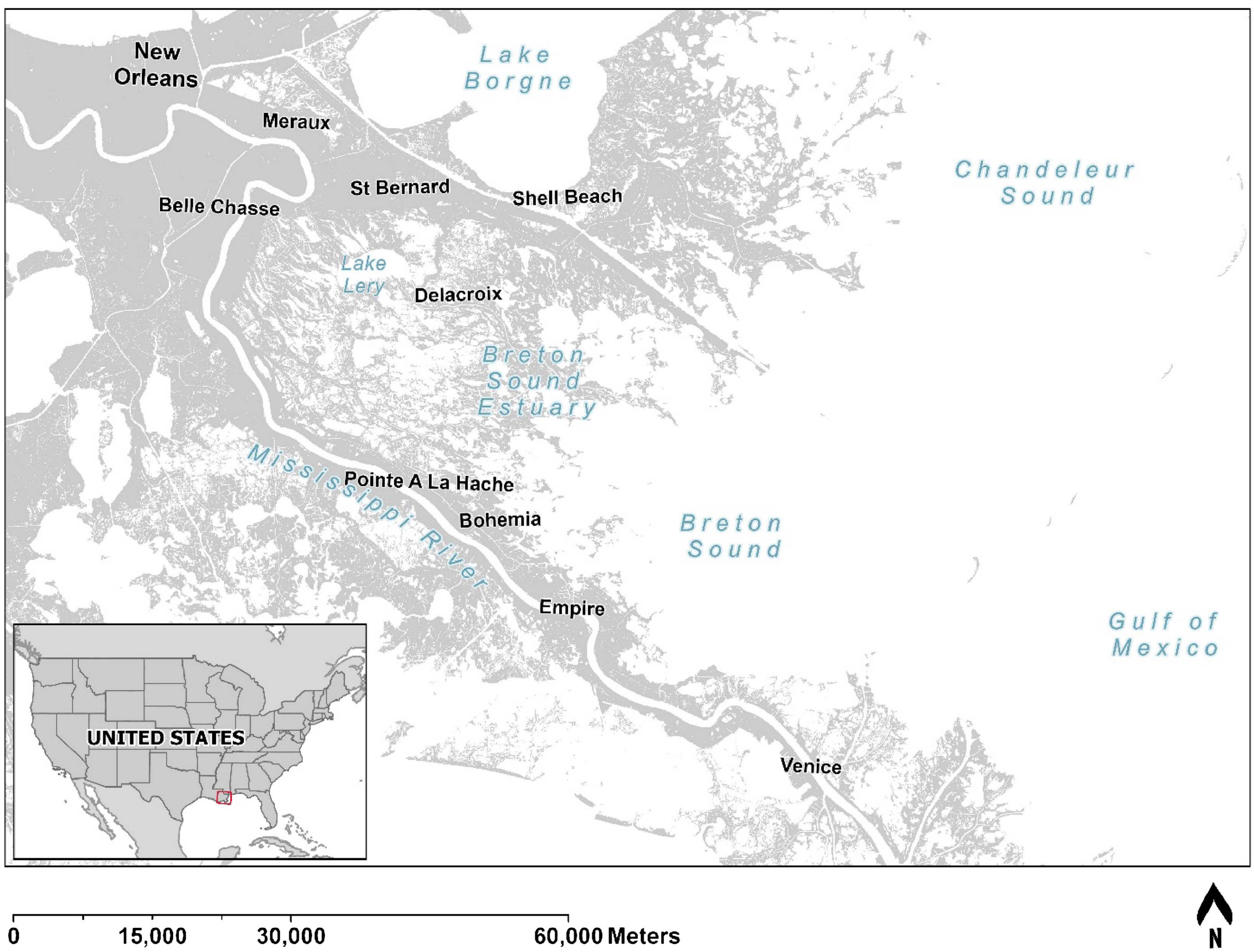

Fig. 1. Location map of Breton Sound Estuary (southeast Louisiana).

Gulf Outlet (an abandoned navigation channel) and its spoil banks separate the Breton Sound Estuary on its eastern/northeastern border from Lake Borgne and the surrounding marsh areas. The southern boundary of the estuary is Breton Sound, which is connected to the Gulf of Mexico. The northern part of the area is mostly fresh and intermediate marsh, gradually transitioning to brackish and saline marsh (Fig. 2). The area is composed of shallow water bodies, broken marsh, and a mixture of natural channels and dredged canals. This region is exposed to tides and waves from the Gulf of Mexico with an annual mean water surface elevation of 0.2 m [based on the North American Vertical Datum of 1988 (NAVD 88)] and an average tidal amplitude of 0.5 m (CPRA 2018). Multiple connection points with the lower Mississippi River provide significant fresh water sources in the upper estuary. The estuary also receives freshwater from a salinity control structure, the Caernarvon Freshwater Diversion.

Predictive Tools

The ICM used in the 2017 Louisiana Coastal Master Plan (CPRA 2017) was utilized in this research to screen and evaluate restoration and protection strategies suggested by the CG. The ICM is a comprehensive landscape tool that captures the interaction and feedback among physical processes (hydrology, sediment transport, and wetland morphology) and ecological processes (vegetation dynamics, water quality/nutrients dynamics). The ICM can be used to perform decadal simulations and examine the impact of environmental drivers—for example, riverine freshwater/sediment/nutrient inflow, tides, waves, wind, evapotranspiration, and major storms (hurricanes) on coastal ecosystems. To increase the computational efficiency of the ICM, simplified assumptions were made to the governing equations; for example, the dynamic terms in the shallow water equations were dropped (Meselhe et al. 2013).

As a complement to the ICM, a biophysical Delft3D model (Baustian et al. 2018) was used to provide information at a higher spatial resolution. The biophysical model (BPM) captures detailed morphodynamics that are beyond the capability of the ICM. The BPM provides predictions of key physical and ecological processes including the impact of drivers such as coastal rivers, Gulf Coast currents, wind, tides, sea-level rise, and marsh vegetation; for example, it predicts the coupled effects of vegetation and morphologic change such as the organic matter contribution to land building. It is, however, more computationally expensive, so it was strategically

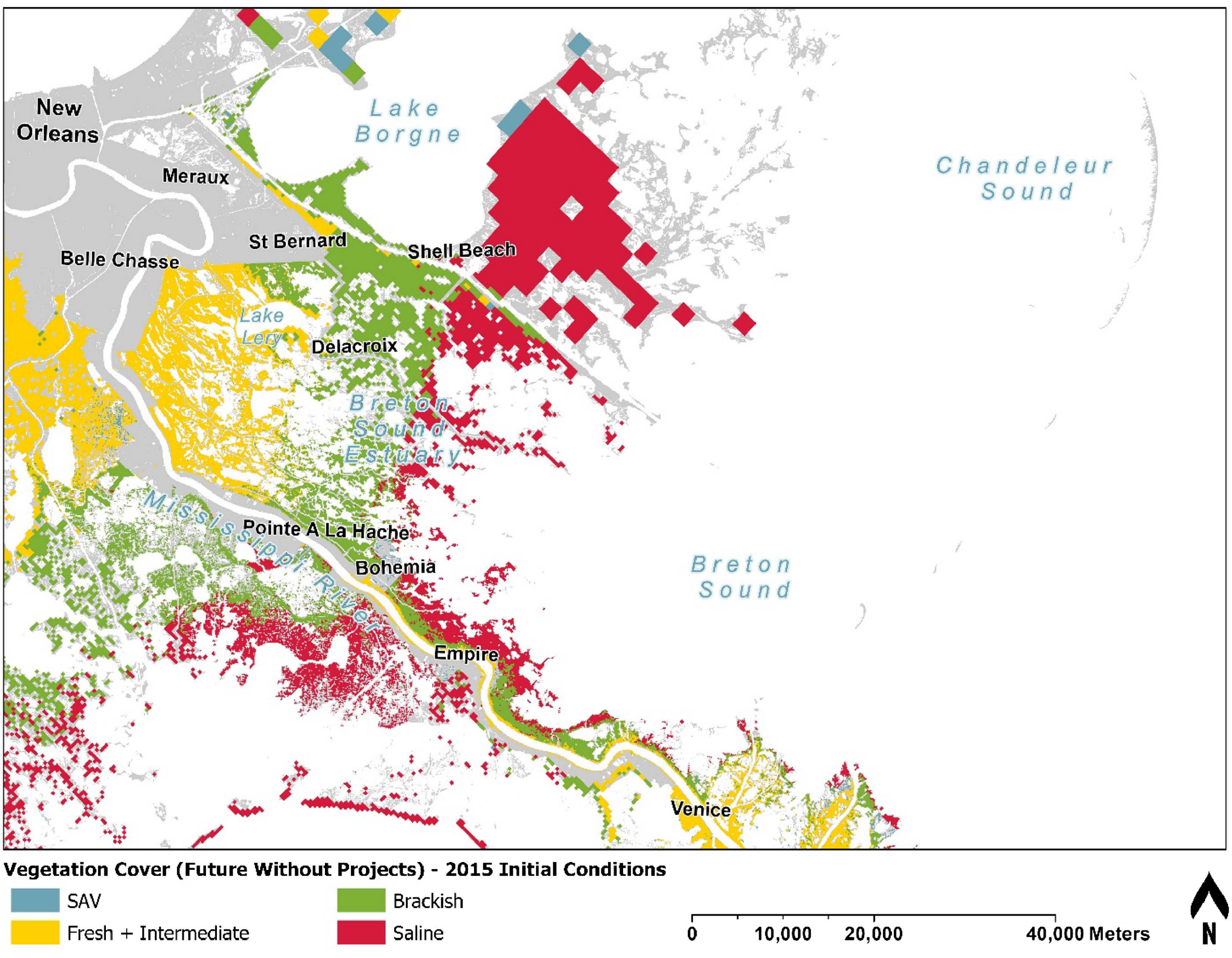

Fig. 2. Spatial distribution of marsh types (representative of 2015) in Breton Sound Estuary.

used in a select number of simulations to illustrate the response of the landscape to the implementation of NNBS under select environmental conditions.

Development of Community-Based Restoration and Protection Strategies

Traditionally, research groups identify viable restoration and protection strategies based on the best technical judgment and input from concerned agencies. While more effort had recently been placed recently to increase the local community engagement, full participatory modeling approaches remained marginal. The research presented here provides a knowledge-based approach to fully engage local communities in the development and application of predictive tools. The CG fully participated and provided input in the following phases:

1. Selection of the model domain: The CG identified the vulnerable region within the Breton Sound Basin requiring restoration and protection features (Fig. 1). Jointly with the research group, they delineated the model domain. Adjustments (mostly expansion) to the model domain were made by the modeling group to ensure that appropriate boundaries of the domain were incorporated.
2. Selection of the boundary conditions: The research team ensured sediment and nutrients. The research team ensured that all environmental forcings were incorporated: atmospheric (rainfall, wind, evapotranspiration, nutrient loading), open water (tides, waves, salinity), and point sources (connections with the Mississippi River).
3. Model attributes: The research team listed the model output needed to understand the system response to environmental changes and the implementation of NNBS on the landscape. The key outputs identified were spatial distribution of vegetation, spatial and temporal salinity patterns, water elevations, and sediment accretion rates.
4. Restoration and protection strategies: The group focused on restoring ecosystem functions and services. The CG displayed an intimate knowledge of how the system functions and how it evolved over time. They proposed strategies that balance the need for increasing the footprint of marsh areas, while maintaining salinity and water level patterns that accommodate a broad spectrum of fish and shellfish habitats. Specifically, the following two proposed solutions were selected to illustrate

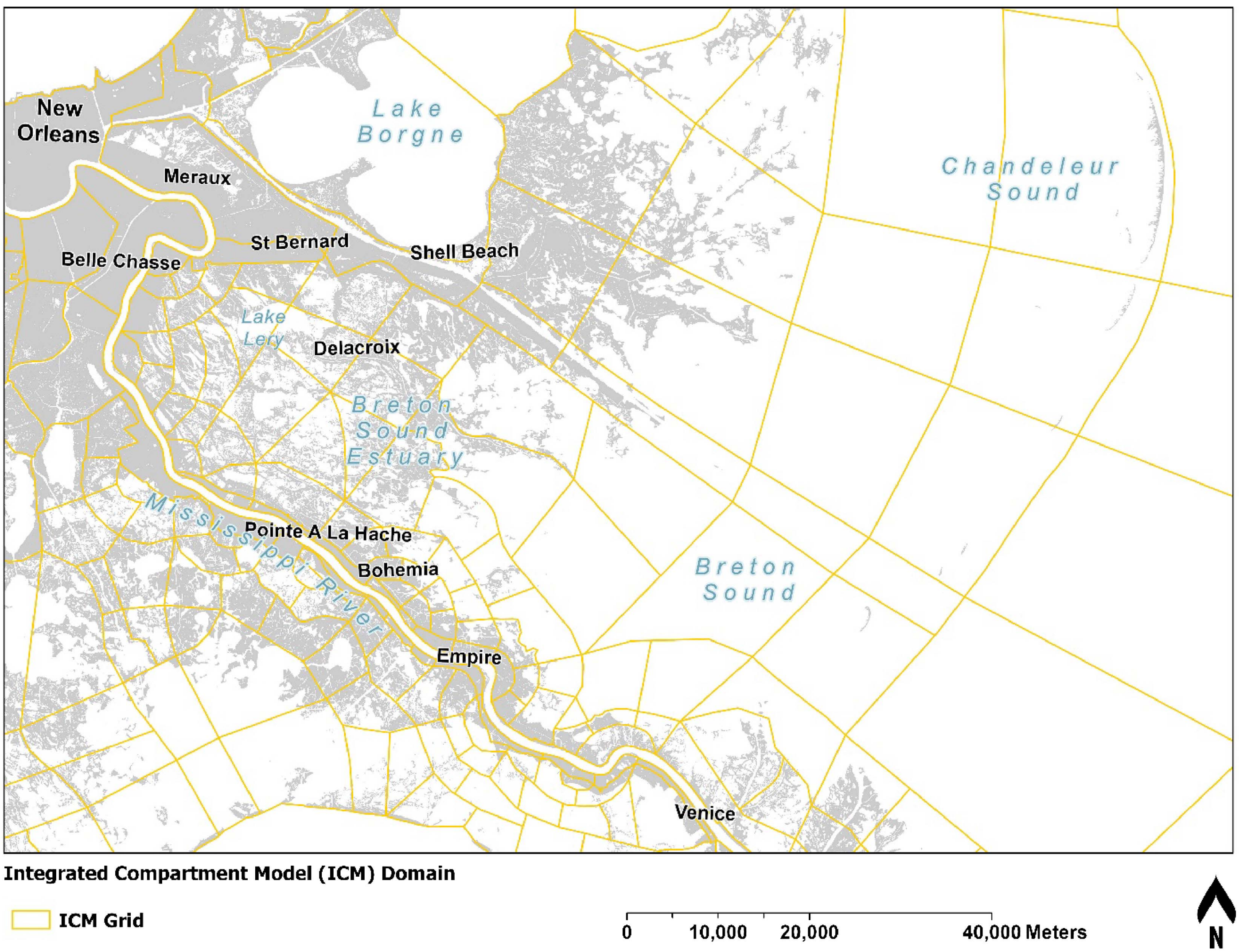

Fig. 3. Model grid/compartment design for the ICM for the Breton Sound region. The compartment size in the area of interest ranged from 1.8 to 218.7 km^2.

the concept of participatory modeling and the value of engaging community members in the various steps of a technical numerical modeling effort:

- Sediment steering and trapping: The CG expressed interest in examining features to retain sediment flowing through the lower Mississippi River and trap it within the coastal zone. As a result, the strategy/project features are geared toward enhancing the retention of suspended sediment to stimulate land creation and maintenance of existing marsh areas.
- Sediment diversion: Given the strong interest from government agencies in sediment diversions (CPRA 2017; Meselhe et al. 2016; Allison and Meselhe 2010), the CG expressed strong interest to examine the efficacy of this approach. This strategy is based on the concept of reconnecting the lower Mississippi River to the adjacent basins to emulate the natural process of crevasses. The intent of this strategy is to create a new prograding delta to compensate for the land loss due to sea-level rise and subsidence.

Details of how these strategies were modeled along with assessments and discussions of the output are presented in the next section.

Model Setup and Validation

To examine the solutions proposed by the CG, the ICM and BPM were set up to perform the analysis. The model grids for the region of interest are shown in Figs. 3 and 4. However, one of the challenges in participatory modeling effort is the ability of the CG to trust and believe in the viability of numerical modeling tools. The default perception is skepticism. Hence, there was a need to utilize model validation tools that would establish confidence and facilitate acceptance of numerical models by the CG. Knowledge-based model performance assessment might require capturing trends and patterns that are observed by local community members during their interaction with the ecosystem—for example, overtopping frequency of roads, ridges, or other features; formation of splays due to sediment deposition; disappearance of specific species of interest; or emergence of specific vegetation type.

If numerical models even qualitatively display similar behavior to that observed by the CG, community members are likely to develop confidence in the viability of these predictive tools. Fig. 5 shows a comparison between the frequency of a local road overtopping by high tide and cold fronts (winter storms) based on field observations and as predicted by the BPM. The comparison in

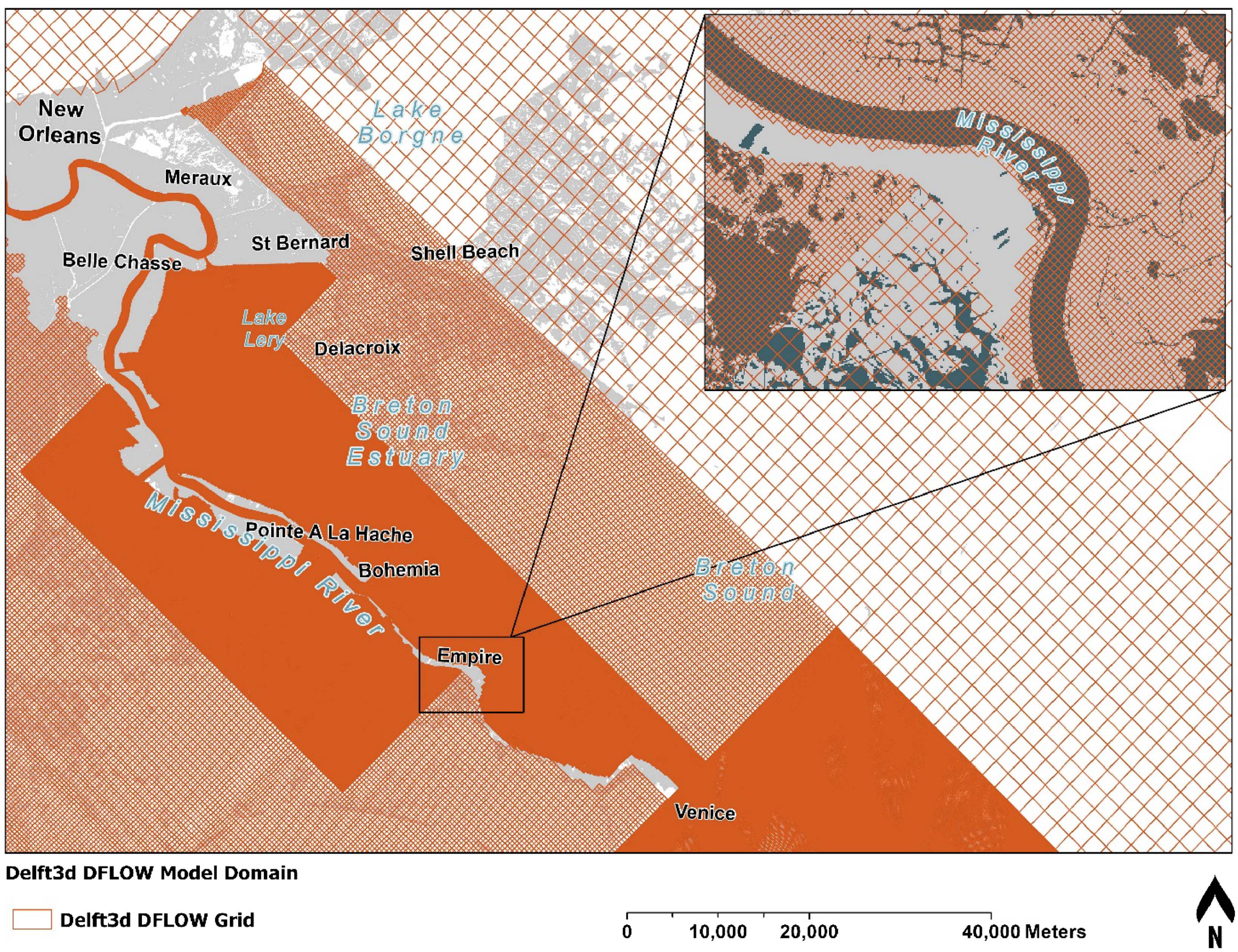

Fig. 4. Model grid design for the BPM for the Breton Sound region. The grid size ranged from 0.0126 (near the connection of the River with the basin) to 16 km^2 (offshore cells).

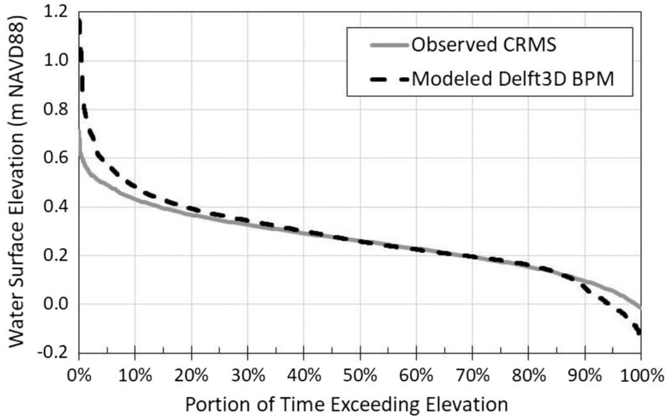

Fig. 5. Comparison of model output to field observations near local roads and ridges.

Fig. 5 illustrates reasonable agreement between the frequency of flooding of features and roads at various elevations. These comparisons resonated well with the CG. Fig. 6 shows how the model predicted the evolution of a splay in the outfall area of a salinity control diversion (Caernarvon Freshwater Diversion), which was clearly observed in the field. Finally, Fig. 7 shows a habitat suitability index (HSI) for brown shrimp (*Farfantepenaeus aztecus*). As seen in Fig. 7, the Breton Sound Estuary exhibits low HSI for brown shrimp in the majority of the area as a result of low salinities, an observation confirmed by local fishermen.

These knowledge-based validation outputs, while may seem trivial from a pure science point of view, actually have tangible benefits of increasing the confidence of the CG in the viability of the predictive tools being used. It should be emphasized, however, that the knowledge-based validation approaches are not meant to be a substitute for the more scientifically rigorous statistical and visual performance assessment of models. Actually, both the ICM and BPM had been thoroughly calibrated and validated using both statistical measures and visual comparisons (Baustian et al. 2018; Brown et al. 2017).

Implementation of the NNBS

The following two NNBS examples were solutions identified by the CG and examined using the modeling tools described earlier, namely, the ICM and BPM.

Sediment Steering and Trapping

Figs. 8 and 9 show how the ICM and BPM captured and evaluated this solution of a rock jetty to influence the flow of the water. While the ICM results may seem crude due to the large compartment sizes,

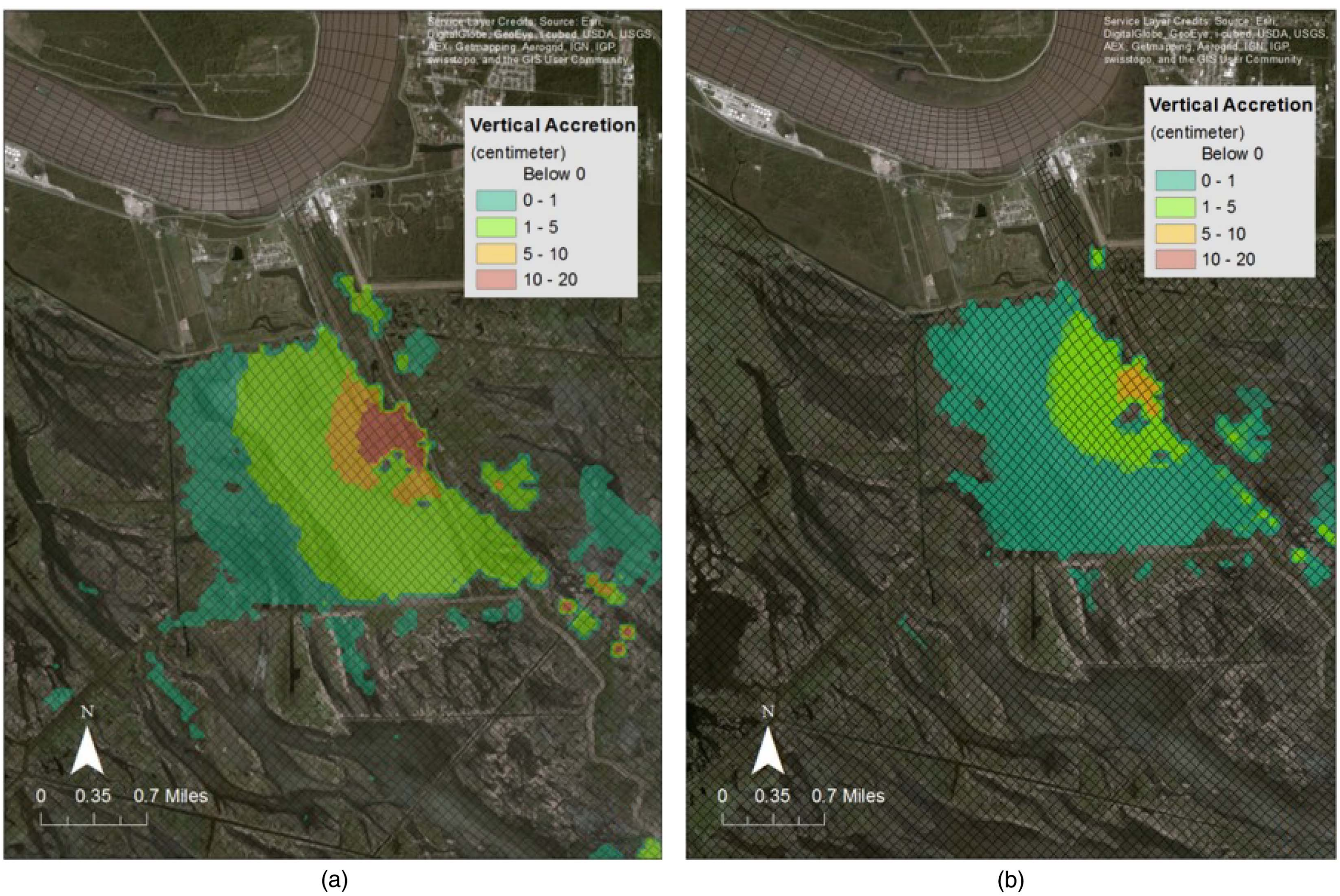

Fig. 6. Splay evolution—Breton Sound: (a) 2011; and (b) 2014, with deposition rates of 1.71/0.85 cm/year. Field observations measured deposition rates in the range of 0.75–1.57 cm/year. (Data from Day et al. 2009; map courtesy of United States Geological Survey.)

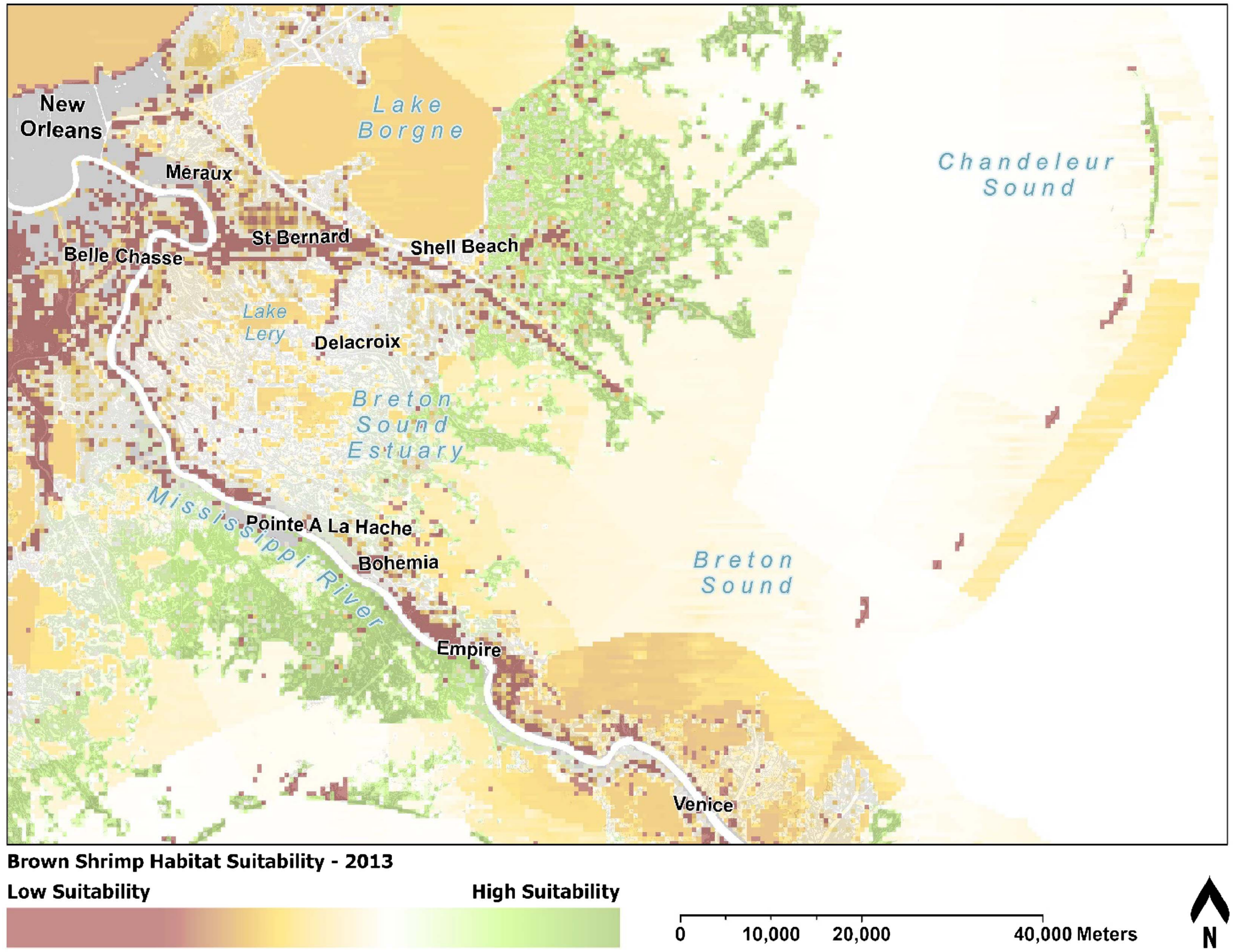

Fig. 7. HSI map for brown shrimp in 2013.

its computational efficiency allowed the CG to visualize the outcome of their ideas in a timely manner. It provided general insights about the potential performance of this proposed concept. As a planning tool, the insight was sufficient to merit further analysis by the BPM. The higher resolution model provided more details about the likely deposition and erosion zones and more quantitative estimates of how much sediment could potentially be retained to nourish existing marsh and build new land areas.

Sediment Diversion

The models were also used to evaluate reconnecting the Mississippi River to the Breton Sound Estuary through a controlled (gated structure) sediment diversion at the Caernarvon Freshwater Diversion. The models showed land building and nourishment of existing marsh area due to the sediment delivered from the river to the basin side. However, because of the large volume of freshwater, change in the marsh type (from saline/brackish toward fresh/intermediate marsh) was predicted. Additionally, the increased volume of freshwater could have implications on various marsh vegetation species, affecting the community economically and culturally. Further, the model showed implications on water level and potential overtopping of existing levees and roads, also affecting local communities. Fig. 10 shows an example of the land gain/sustained resulting from the sediment diversion as predicted by the ICM.

Evaluating the Effectiveness of the Competency Group Method of Participatory Modeling

A total of 10 CG members participated in a survey of the effectiveness of the competency group methodology. The survey contained a series of short, opened-ended questions and 12 questions with a Likert-type scale (from poor to excellent) to assess aspects of the CG process and logistics (Table 1). Of the 10 members who filled out the survey, one provided the same answer (excellent or extremely) for each of the multiple-choice questions regardless of the directionality of the question. These results were not included in the analysis results, leaving a total of nine members assessed through the multiple-choice portion of the survey.

The questions about meeting logistics had mean values ranging from 3.2 to 4.2, suggesting that the quality and organization of the meeting, clarity of the goals, and opinions considered resulted in

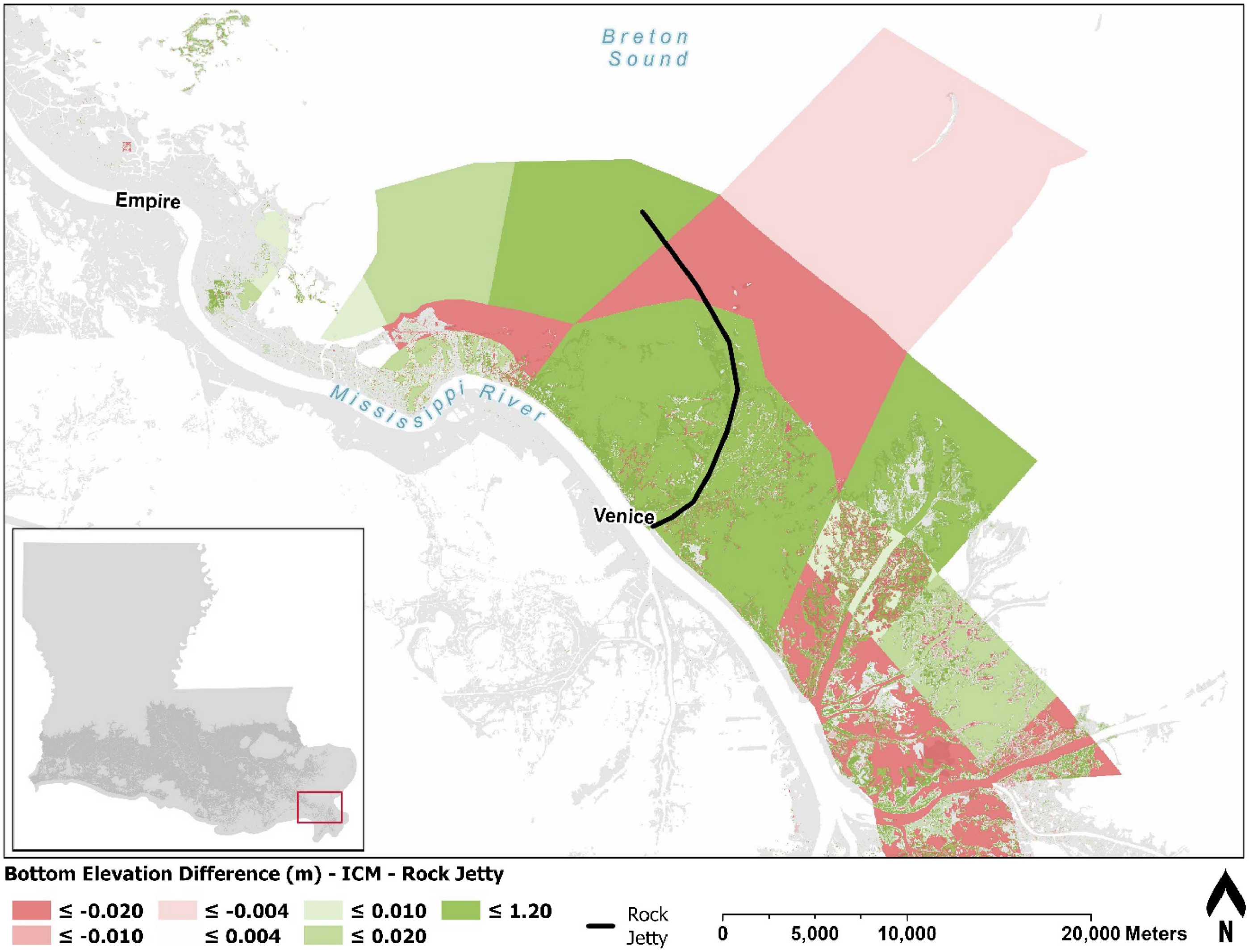

Fig. 8. Predicted bottom elevation difference with the sediment steering and trapping feature (solid black line) from the ICM at year 20.

the good to very good range [Fig. 11(a)]. The responses about meeting outcomes had a mean value range between 1.9 and 4.3 [Fig. 11(b)]. The highest mean response was from Q6 about meeting outcome, which asked, "Do you feel like you learned something from your collaborators?" The response to this question was in the range of very good to excellent. The lowest mean response (1.9) was from Q5 about whether certain members had too much of an influence on the selected projects and models, which suggested that the members felt that other members didn't have too much or only a slight amount of influence over selected projects. This is consistent with the mean response (4.2 or between considerably and extremely) to meeting outcome Q1 about whether the members felt their voice was heard during the CG meeting.

Overall, the survey results indicated that a CG approach to fostering collaborations between local residents and scientists can be an effective way to update ecosystem models and test ideas about potential NNBS to coastal hazards. The CG gave highly ranked responses to learning something from this collaboration, their voices were heard, and certain members did not have too much of an influence on the discussion and decision to include NNBS or adjustments to the models. By coordinating five competency group meetings, the team was able to bridge the knowledge gap among groups on how ecosystem models can be adjusted and used to test ideas on coastal restoration projects. Also, the CG methodology fostered trust among the group members because of the frequent meetings that delivered and shared modeling information and traditional ecological knowledge.

Discussions

The approach of using two predictive models (ICM and BPM) was beneficial to the CG for illustrating the utility of various tools with a range of computational efficiency and level of detail. Engaging the CG in all phases of the modeling effort was essential to communicate the limitations and capabilities of the various predictive tools that are often used at the state and federal level to make decisions. The CG approach, as reflected in the survey results, is an effective approach to incorporate local knowledge and engage the community in the process of developing, validating, and applying predictive tools to examine protection and restoration strategies to natural systems. Engaging the CG in the workshops/meetings allowed them to develop an understanding and recognize that the predictive tools exhibit some uncertainties and errors but remain valuable and informative. The models reproduced critical field observations such as frequency of flooding of local features and roads, low suitability

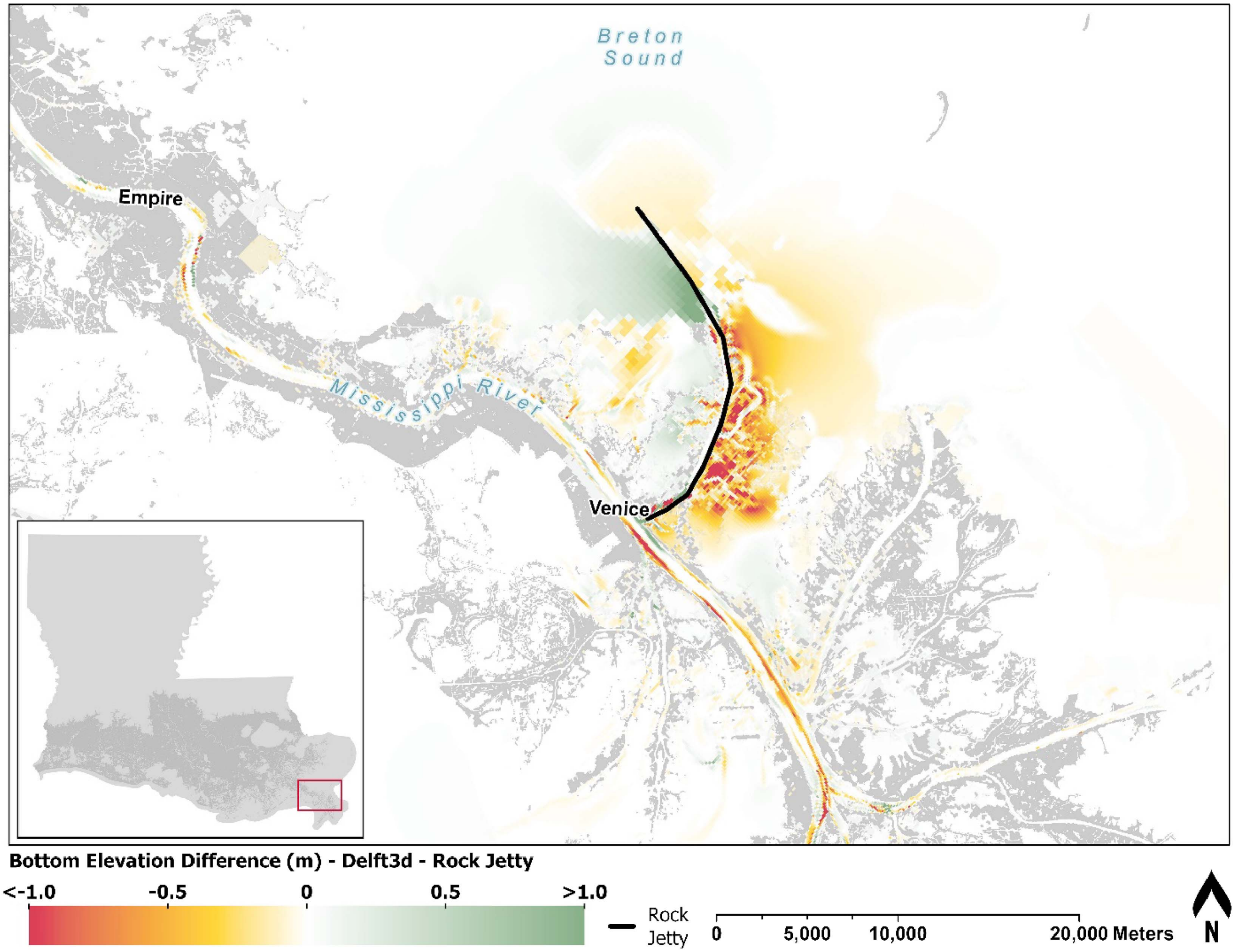

Fig. 9. Predicted bottom elevation difference with the sediment steering and trapping feature (solid black line) from the integrated BPM at year 20.

of key species (in this case, brown shrimp), shifts in the marsh vegetation composition, and the formation of a splay in the outfall area of a diversion structure.

The models provided valuable insights regarding the two sample NNBS described previously. The sediment steering and capturing strategy was shown to be somewhat effective in retaining sediment and nourishing existing marsh areas. However, these features might get ultimately inundated by the rise in sea levels. If these features are made with heavy materials (e.g., rocks), they might sink under their own weight because of the weak soil property of the area.

The sediment diversion concept proved to be effective in creating new land areas at 20-year and nourishing existing marsh through the supply of fine materials (silt and clay). Sediment diversion could influence the inundation and salinity pattern (by increasing the freshwater supply) and, in turn, the marsh type by converting brackish/saline marsh toward fresh/intermediate. It could also impact the composition of the various species living in the estuary (e.g., fish, shellfish, and marine mammals). These insights were valuable for the CG because they developed a deeper understanding of the outcome of their own ideas. The visuals produced by the predictive models were key to help communicate the science to the local community. These visuals also helped the CG understand the trade-offs from implementing the various NNBS.

Conclusions and Closing Remarks

This research effort focused on developing a community engagement approach to develop and apply predictive tools for coastal and deltaic systems to evaluate various NNBS. While extensive research has been done on using numerical models to study natural systems (Paola et al. 2011; Reed et al. 2018; Temmerman and Kirwan 2015; Fox and Papanicolaou 2008; Abban et al. 2016; Olley 2002), local communities have not been sufficiently involved in the development of these concepts, despite being impacted the most by such implementations. This paper provided an example of engaging a CG in the development and application of two predictive tools to examine NNBS for an estuary in coastal Louisiana. Two NNBS were selected to demonstrate how the CG participated in the model setup and implementation NNBS.

A knowledge-based validation approach was devised as an approach to capture local knowledge and engage the local community in the development and application of predictive tools to natural systems. The two models, ICM and BPM, were used to reproduce

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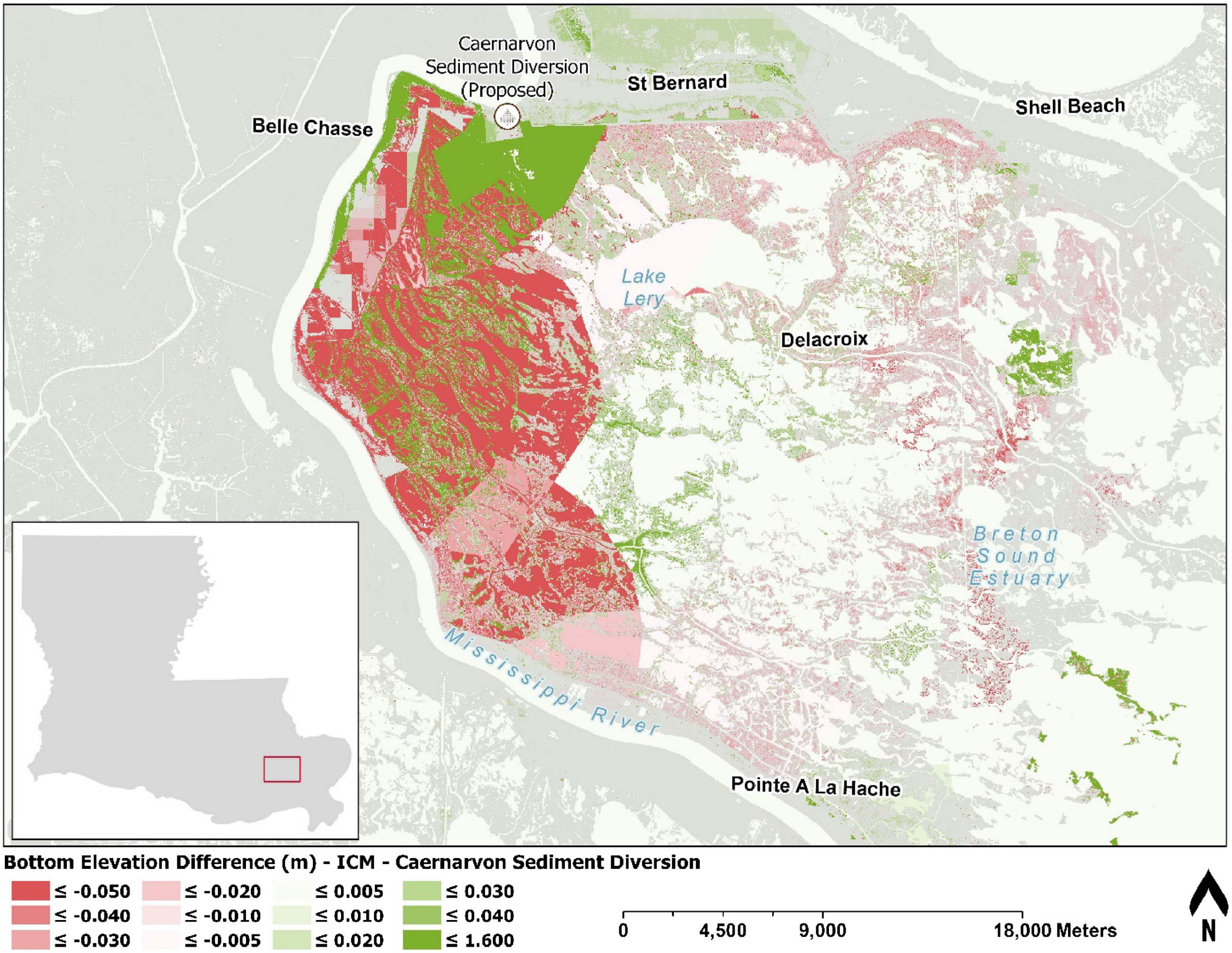

Fig. 10. Bottom elevation difference resulting from the sediment diversion at year 20 that replaced the Caernarvon Freshwater Diversion as predicted by ICM in the Breton Sound Estuary.

Table 1. Survey questions used to assess the effectiveness of competency group process and logistics

Question number	Question
Meeting logistics	
1	Quality of the meeting preparation and communication
2	Clarity of project goals
3	Meeting organization and conduct
4	All opinions were considered during the group meetings.
Meeting outcomes	
1	Do you feel like your voice was heard during our group meetings?
2	Do you feel that your perspective was represented in the restoration projects?
3	Did your opinions and understanding of restoration projects change over the course of our meetings?
4	Did your understanding of the modeling process change over the course of the group meetings?
5	Do you feel certain members of the group had too much of an influence over selected projects and models?
6	Do you feel like you learned something from your collaborators?
7	Do you feel that the groups' models and projects were distinct from state projects and processes [i.e., Coastal Protection and Restoration Authority (CPRA)/Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA)]?
8	Overall, do you feel that the project outcomes reflected the project goals?

key field observations, namely, overtopping of local features (roads, ridges, etc.), shifts in vegetation and marsh type composition, and low suitability of brown shrimp habitat. While these qualitative outcomes do not substitute for the more scientifically rigorous approach of fully assessing the performance of numerical models, they were critical for fully engaging the local community in the entire process of developing and applying numerical models to investigate and evaluate restoration and protection strategies of natural systems.

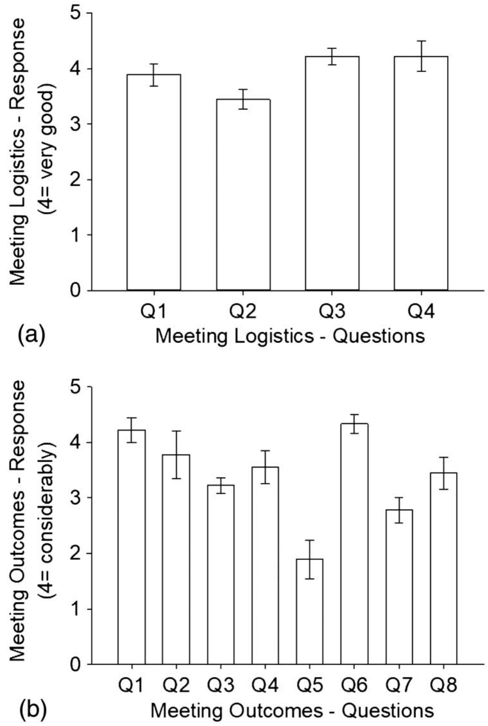

Fig. 11. Responses (mean ± standard error) from competency group members ($n = 9$) about (a) meeting logistics; and (b) meeting outcomes of the five meetings.

Predictive numerical models can provide visuals that substantially facilitate the communication of the science to the local community, and the full engagement of the CG offers the opportunity to develop a sense of ownership and involvement in the process of evaluating restoration and protection strategies.

Data Availability Statement

Some or all data, models, or code used during the study were provided by a third party, the Integrated Compartment Model (ICM). The ICM sinformation can be found at this URL: http://coastal.la.gov/our-plan/2017-coastal-master-plan/.

Acknowledgments

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