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Modelling the Effectiveness of Vegetative Nature-Based Solutions for Coastal Flood Risk Mitigation

Yengi Emmanuel Daro Justine | Avidesh Seenath

Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, UK

Correspondence: Avidesh Seenath (avidesh.seenath@eci.ox.ac.uk)

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ABSTRACT

Traditional grey solutions, such as seawalls, are increasingly recognised as being unsustainable for long-term coastal flood risk management, due to high costs and negative environmental impacts. In response, vegetative nature-based coastal solutions (NBCS), such as saltmarshes, are being increasingly proposed as a more sustainable alternative with wider environmental benefits. However, there is considerable uncertainty on the longevity of such solutions under sea-level rise. We, therefore, examine the effectiveness of vegetative NBCS for mitigating coastal flood risk through scenario modelling using a verified *LISFLOOD-FP* model for Absecon Island in New Jersey, USA. Specifically, we simulate various experimental vegetative NBCS scenarios, each designed to represent a saltmarsh system (young, mid-age, and old), under alternative sea-level conditions. Our results show that these solutions have a marginal influence on flood extent, depth, velocity, and timing under current and future projected sea-level conditions. These findings suggest that reliance on vegetative NBCS *may not* be sustainable for long-term coastal flood risk management, particularly under climate change. We discuss the wider implications of these findings and identify future research pathways towards improving and informing more robust coastal flood risk management decisions.

1 | Introduction

Coastal flooding presents significant risks to millions of coastal residents, particularly those in low-lying coastal zones—zones that are < 10 m above mean sea-level (Fang et al. 2020). Recent estimates suggest that more than two billion people live in coastal regions, of which 898 million live in low-lying coastal zones, with this number expected to exceed one billion by 2050 (Reimann et al. 2023; Justine and Seenath 2025). The increasing concentration of people living (and working) in coastal zones means that the number of individuals and assets exposed to coastal flooding is increasing (Kulp and Strauss 2019; Pörtner et al. 2022; Buzard et al. 2024). This is particularly concerning as coastal flooding (and flooding more broadly) is rapidly becoming one of the most fatal and damaging natural hazards. For example, in the last century, around 7 million deaths and more than USD 700 billion in economic damage and losses globally have been attributed to flooding (Lai et al. 2020; CRED 2022b). More recently, in 2022, flooding has affected more than 40 million people, inflicted more than USD 135 billion in economic damage, and caused more than 5000 fatalities (CRED 2022a, 2022b). These socioeconomic impacts are anticipated to worsen in response to rising sea levels and increasing storm intensity under climate change. The effects of these climate-related hazards are expected to be felt more in low-lying coastal zones in small island states, where economies tend to be socioeconomically dependent on coastal resources (Martyr-Koller et al. 2021). Recent observations indicate that the average global mean sea-level is rising at a rate of 4.3 ± 0.6 mm per year (C3S 2024), with consequences for more intense coastal flood events. Given these rates and the increasing concentration of people residing and working in coastal zones, 1.46% of the world's population is likely to be displaced by coastal flooding by 2200 (Siegel 2020; Desmet et al. 2021).

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Coastal flood risk management, therefore, requires urgent attention globally.

Traditionally, coastal communities have relied on grey (hard engineering) solutions for mitigating and managing flood risks (Edmonds et al. 2020). These conventional solutions, which include seawalls, breakwaters, and groynes, are designed to refract, reflect, and deflect incoming wave energy, thereby protecting shorelines (and coastal environments) from erosion and flooding (Raj et al. 2021; Hosseinzadeh et al. 2022). Until recently, grey solutions have been considered 'robust defences' for flood risk management, due in part to a large evidence pool of their effectiveness in reducing flood damage over the short-term (Justine and Seenath 2025). For instance, seawalls have a demonstrable record of significantly reducing flood damage, with studies indicating potential reductions in expected losses by 70% to 83% (Yoo et al. 2023). However, in the last decade or so, we have seen increasing evidence on: (a) the unsustainability of grey solutions for long-term flood risk management and (b) how grey solutions can compromise long-term coastal environmental sustainability (Justine and Seenath 2025). The least concerning reason for these findings relate to their (grey solutions) implementation requiring substantial financial investment for construction and ongoing maintenance, which is not practical in the long-term (Jonkman et al. 2013; Hinkel et al. 2014; Morris et al. 2018). On the other hand, the more concerning reasons relate to grey solutions disrupting and fragmenting critical natural habitats, leading to ecological degradation and reduced ecological functionality (Airoldi et al. 2005; Dafforn et al. 2015). By reflecting waves, grey solutions simply direct wave energy elsewhere along unprotected segments of the coast, essentially 'shifting the problem' elsewhere (Nunn et al. 2021). Some examples include: (a) coastal groynes in Fortaleza City, Brazil leading to beach erosion up to 25 km downdrift of these structures (Claudino-Sales et al. 2019); (b) coastal breakwaters in Gabicce Marie, Italy altering current circulation patterns and reducing overall water quality (Carugati et al. 2018); (c) the construction of seawalls along the Northern Ireland coastline causing ~2 m decline in beach levels at Portrush and loss of natural beach habitats in Newcastle (Cooper et al. 2020).

Moreover, relating to our previous point on financial practicality, ongoing changes in climatic conditions (e.g., sea-level rise and increasing storm intensity) will require frequent changes to the design of grey solutions, as these solutions are not able to 'adapt' to such changing conditions. This is evidenced by the need to significantly raise existing coastal protection structures in response to projected sea-level rise in various coastal regions globally (Mimura 2013; Arns et al. 2017; Pörtner et al. 2022; Dong et al. 2024). For instance, grey defences in the Bight region of Germany would need to be raised by 48%–56% to account for the additional wave action under rising sea levels (Arns et al. 2017). With considerable uncertainty on the longevity of grey solutions, there is an increasing call for nature-based coastal solutions (NBCS) among the coastal science community, which have the potential to address the limitations of grey solutions with additional benefits for biodiversity, net zero and ecosystem services, among others (Nagelkerken et al. 2008; Serrano et al. 2019; Wahyudi et al. 2020; Van Dam et al. 2021; Zu Ermgassen et al. 2021; Hagger et al. 2022; Xin et al. 2022; Seenath et al. 2025). NBCS is increasingly being advocated as a viable and economically feasible alternative for managing coastal flooding relative to grey solutions (Van Hespen et al. 2023; Seenath et al. 2025). By leveraging coastal vegetation systems, such as saltmarshes, dune grasses and mangrove forests, NBCS can facilitate sediment deposition, increase surface roughness, and dissipate wave energy, reducing storm surge impacts and enhancing coastal resilience (Morris et al. 2018; Gijsman et al. 2021; Van Zelst et al. 2021; Van Hespen et al. 2023). Coastal vegetation helps protect shorelines by dissipating incoming wave energy through increasing surface roughness when their leaves and stems interact with the water column, reducing overall wave heights and the spatial extent of flood propagation (Van Veelen et al. 2021; Rosenberger and Marsooli 2022). Saltmarshes and mangroves have proven to be particularly effective in reducing coastal wave heights (and, in turn, dissipating wave energy), thereby providing a natural defence mechanism against flooding. Empirical studies, for example, have shown that saltmarshes can attenuate wave energy by 72% (Narayan et al. 2016; Garzon et al. 2019; Ma et al. 2023), while mangroves can reduce wave heights by 66% (McIvor et al. 2012; Gijsman et al. 2021; Zhang et al. 2023), underscoring their potential as natural coastal flood defences.

A complex interplay of factors influences the effectiveness of wave attenuation by vegetation (Phan et al. 2019). Vegetation properties such as plant stem height, stiffness, flexibility, and density play an important role in influencing wave characteristics, including wave height and period (Mendez and Losada 2004; Rupprecht et al. 2017). Vegetation-based solutions not only mitigate flooding but also promote diverse ecosystems by providing habitats for various plant and animal species (Nagelkerken et al. 2008). For instance, mangroves create complex root structures that offer shelter and breeding grounds for a wide range of marine and terrestrial species, while saltmarshes support unique plant species adapted to saline environments and serve as nesting sites for birds (Gedan et al. 2009; Whitfield 2017). Additionally, coastal vegetation contributes to climate change mitigation by sequestering carbon dioxide and stabilising shorelines through sediment retention (Mcleod et al. 2011; Duarte et al. 2013). They capture and store significant amounts of carbon dioxide from the atmosphere, which helps to reduce greenhouse gas concentrations (Choudhary et al. 2024). The carbon stored in these ecosystems, referred to as blue carbon, is mainly held in soils for extended periods, making these habitats highly effective and long-term contributors to global carbon sequestration efforts. Despite these benefits and the growing advocacy for NBCS, their long-term sustainability is uncertain due to a lack of evidence-based studies and empirical data to support an understanding of their efficacy and likely scenarios of future sea-level rise (Kumar et al. 2021). Even more so, their long-term sustainability and resilience also remain uncertain due to the dynamic nature of coastal systems and the impact of climate change and human activities such as land use change.

Furthermore, implementing vegetation-based coastal flood risk management solutions faces several environmental and socioeconomic challenges. Ecologically, the effectiveness of coastal vegetation in wave attenuation can vary seasonally, influenced by factors such as plant density, species characteristics, and environmental conditions (Bouma et al. 2014; Sutton-Grier et al. 2015). For example, the protective ability of seagrass along the US Atlantic coast fluctuates with seasonal biomass changes, potentially reducing its effectiveness during periods of decreased abundance (Koch et al. 2009). Additionally, the selection of appropriate species and the need for concrete empirical data on the long-term performance of vegetation in flood protection complicate their use (Feagin et al. 2015). Socioeconomically, the absence of standardised methodologies for evaluating and scaling up NBCS and limited funding and policy support hinder their widespread adoption (Weaver et al. 2013; Kumar et al. 2021). Without consistent evaluation frameworks, it is challenging to measure the effectiveness and benefits of NBCS across different contexts. This inconsistency, coupled with insufficient financial and governmental backing, creates barriers to their adoption on a large scale, preventing these solutions from reaching their full potential in addressing flood challenges. Moreover, differing professional perspectives among ecologists, engineers, and policymakers regarding the uses of vegetation can impede effective collaboration and implementation by creating conflicting priorities and goals, leading to challenges in reaching a consensus on the use of NBCS for flood risk management (Denjean et al. 2017). These challenges highlight the need for further research and empirical evidence on the effectiveness and resilience of vegetation-based solutions for coastal flood risk management.

Given the above context, we, therefore, aim to investigate the effectiveness of vegetative NBCS for coastal flood risk management through a numerical modelling lens. By investigating the effectiveness of vegetative NBCS for coastal flood risk mitigation under varying sea-level conditions through experimental scenario modelling, we seek to offer decision-making support and insights that can inform more robust coastal management initiatives. Our findings will also have theoretical implications for understanding the role of vegetation in flood risk management.

2 | Test Site

We select Absecon Island (Figure 1a), a sandy barrier island in New Jersey, USA, as our test site to investigate the effectiveness of vegetative NBCS in flood risk management for three reasons. *First*, it has plentiful open-access data—tides and Digital Elevation Models (DEMs)—to enable our numerical modelling campaign. *Second*, it has historical flood data against which we can benchmark our flood modelling results. *Third*, the island's geomorphology (Figure 1b)—wide beaches, dune systems and marshes—is representative of the mixed coastal geomorphology that characterises most coastal regions in vulnerable small islands. Therefore, focusing on Absecon Island will enhance the relevancy and transferability of findings to regions where coastal flood risk management requires more urgent attention. We emphasise here that this research is not designed to undertake physically realistic coastal flood risk assessments of Absecon Island. Rather, this study is experimental, designed primarily to gauge the potential of vegetative NBCS for effectively managing coastal flood risk under future sea-level rise conditions, anticipated in response to climate change projections. In other words, our study is designed to offer decision-making support for coastal flood risk management. It, therefore, does not illustrate precise real-world likely conditions. Figure 1c shows the current flood control measures at the test site, which involve groynes and beach nourishment.

3 | Methods and Data

3.1 | Model Selection

We select *LISFLOOD – FP* to investigate the effectiveness of vegetative NBCS for coastal flood risk management, primarily for two key reasons. *First*, *LISFLOOD – FP* is a well-established flood model with a proven record of providing reliable flood predictions across coastal, urban and fluvial environments (Skinner et al. 2015; Seenath et al. 2016; Le Gal et al. 2024). *Second*, *LISFLOOD – FP* is computationally efficient, has limited data requirements—only requiring a DEM and tidal data—and its results are easily integrated within Geographic Information Systems (GIS). This enables us to undertake scenario modelling, thereby facilitating a comprehensive exploratory assessment of the effectiveness of vegetative NBCS for flood risk management at a low computational cost. More importantly, as *LISFLOOD – FP*'s results are easily integrated into GIS, we are able to look at spatial variations in predictions of flood variables in response to vegetation, which is critical for addressing the aim of our study.

Given the focus on Absecon Island and the application of *LISFLOOD – FP*, we extend Seenath (2018) calibrated and validated *LISFLOOD – FP* model for this island to our study. In other words, we continue the existing line of flood modelling work on Absecon Island by building on a verified *LISFLOOD – FP* model for our test site. For further details on this verified *LISFLOOD – FP* model, please see Seenath (2018).

3.2 | Model Description, Parameterisation and Data

LISFLOOD – FP is a simplified raster-based two-dimensional hydrodynamic model based on the principles of flood routing (Bates and De Roo 2000). Using the following equations (Neal et al. 2011), *LISFLOOD – FP* computes water flow (Q^t) between grid cells at a given time (t) based on a cell centred difference scheme decoupled in x and y directions:

$$h_{i,j}^{t+\Delta t} = h_{i,j}^{t} + \Delta t \frac{Q_{xi,j-1}^{t} - Q_{xi,j}^{t} + Q_{xi,j-1}^{t} - Q_{yi,j}^{t}}{\Delta x^{2}} \tag{1}$$

$$Q^{t} = \frac{q^{t} - g h_{flow}^{t} \Delta t \frac{\Delta \left(h^{t} + z\right)}{\Delta x}}{\left(1 + g h_{flow}^{t} \Delta t n^{2} \backslash q^{t-\Delta t} \backslash \left(h_{flow}^{t}\right)^{\frac{10}{3}}\right)} \tag{2}$$

where water depth $h_{i,j}$ is determined at the cell centre, while h_{flow} represents the depth between cells through which water can flow. The cell bed elevation is denoted by z and the Manning roughness coefficient by n. Gravity is represented by g, with q representing the previous time step's flow and Δt representing the time step increment. The cell width is denoted by Δx. For further details on *LISFLOOD – FP*, please see Bates et al. (2005).

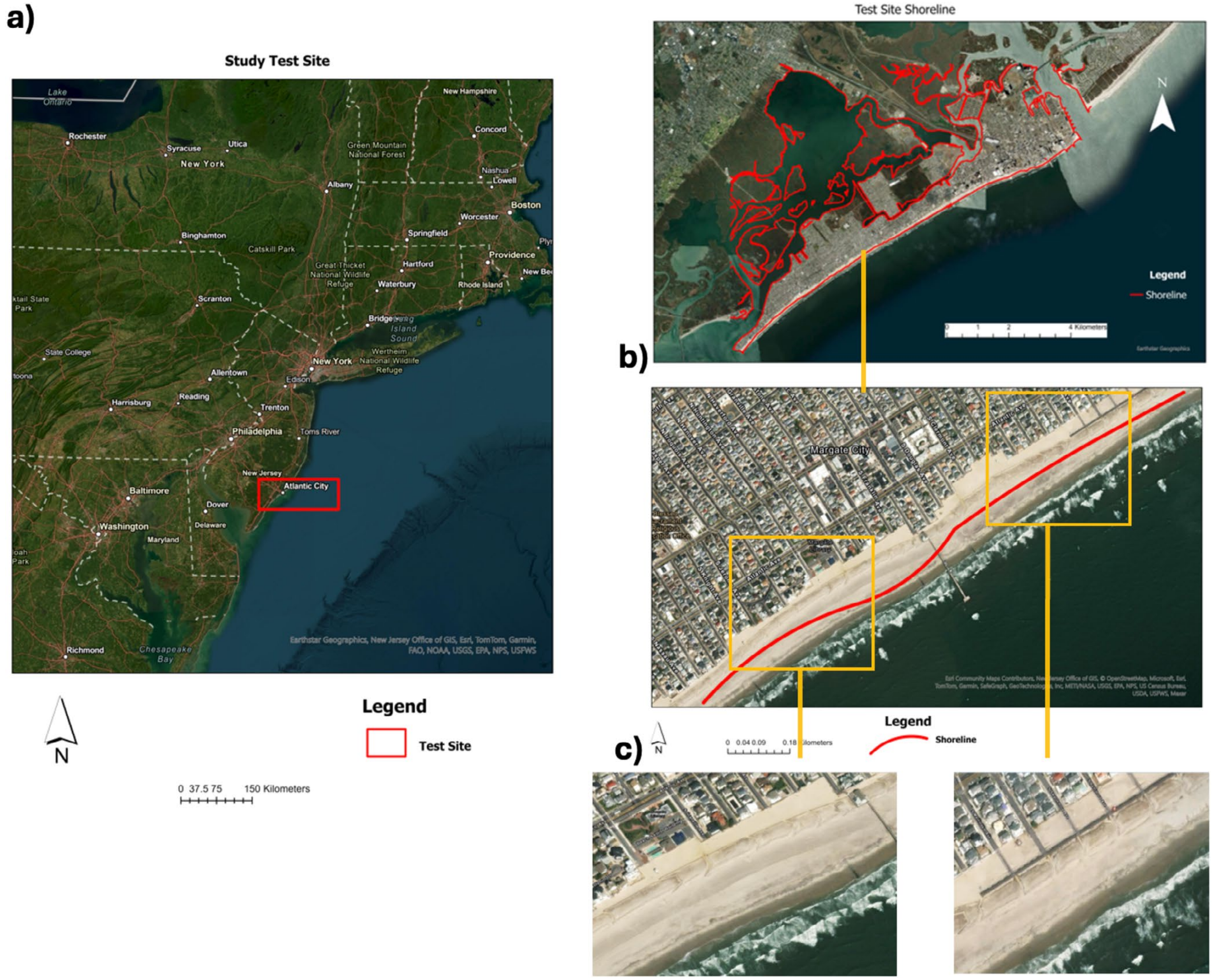

FIGURE 1 | Test site overview. (a) Shows the geographic location of our test site. (b) Indicates the shoreline position. Herein, the shoreline position is considered to be the North American Vertical Datum of 1988 (NAVD 88) line. (c) Shows the current infrastructure and grey defenses at the site.

3.3 | Model Parameterisation and Calibration

As previously mentioned, we extend Seenath (2018) calibrated and validated *LISFLOOD – FP* model for Absecon Island to this study. This model is based on a 10 m resolution post-Hurricane Sandy coastal DEM of Absecon Island (Figure 2), developed by the National Centres for Environmental Information (NCEI) (Eakins et al. 2015). The DEM is vertically referenced to the North American Vertical Datum of 1988 (NAVD 88) and horizontally referenced to the World Geodetic System (WGS) 84 datum in metres.

To drive flow in the model, we obtain a 24-h spring tide dataset, observed on 03 January 2014, from the National Oceanic and Atmospheric Administration's (NOAA) Atlantic City tide gauge station (Station ID: 8534720) and force this dataset on the offshore boundary of the DEM (NOAA 2018). The tidal levels are also vertically referenced to the NAVD 88 and are in 6-min intervals (Figure 3). We select this spring tide event because it represents the highest verified spring tides recorded at NOAA's Atlantic City tide gauge station, which records tidal levels for the area around Absecon Island. Therefore, using this spring tide event will allow us to examine flood risk under current site characteristics and in response to our vegetative NBCS scenarios (Section 3.4).

Other model inputs include: (a) 0.02 bed friction based on Manning's *n* coefficient, characteristic of the sandy coastal environment at Absecon (Seenath 2018) and (b) a simulation period of 86,040 s (representative of the 24 h duration of the observed spring tide event). We also set up *LISFLOOD – FP* to run in acceleration mode and produce outputs every 1000 s of the simulation on flood depth, timings, and velocities, following the guidelines in Bates et al. (2013). The acceleration mode, as detailed in Bates et al. (2013), represents the most accurate flow solver in *LISFLOOD – FP* for 2D flood extent simulation (Neal et al. 2012; Le Gal et al. 2023).

3.4 | Incorporating Vegetative NBCS

To investigate the effectiveness of vegetative NBCS for coastal flood risk management, we create vegetation hotspots within the computational DEM (domain) using ArcGIS Pro,

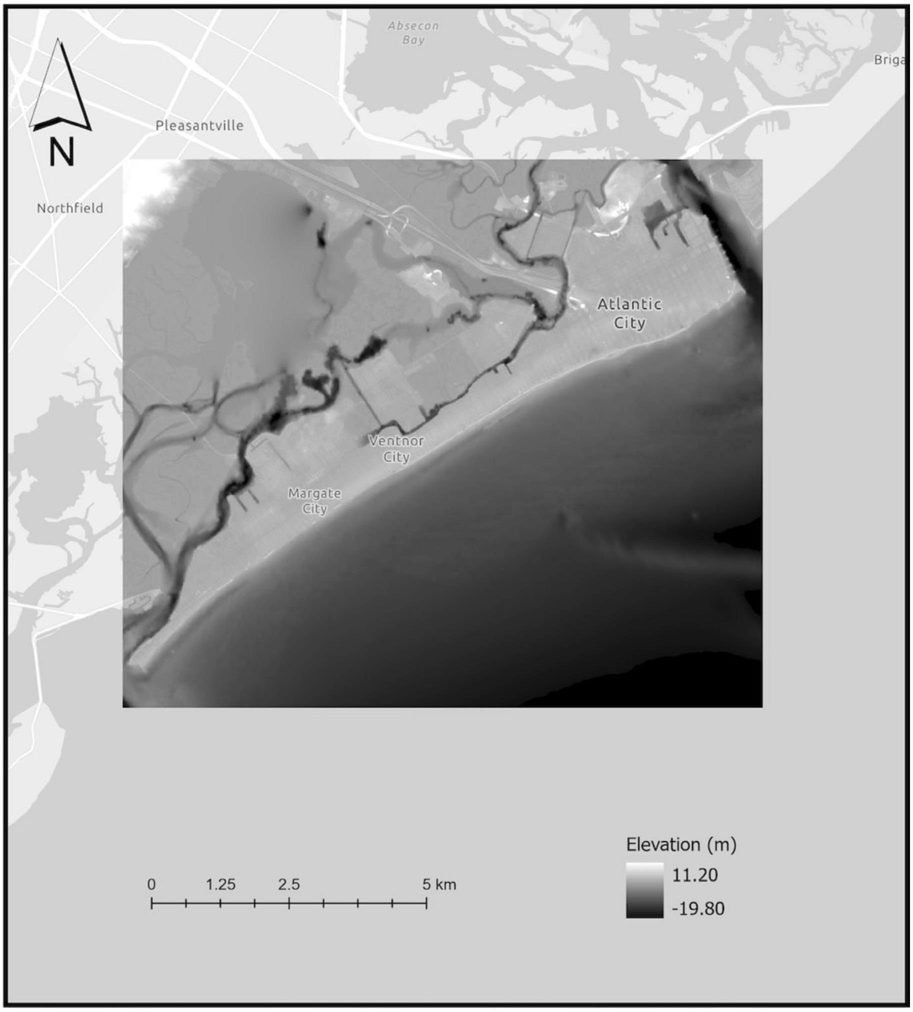

FIGURE 2 | Absecon Island DEM and *LISFLOOD – FP* computational domain applied in this study. Credits: ESRI basemap.

following established characteristics for young, mid-age (medium), and old saltmarshes. To do this, we create polygons in strategic areas for defining new vegetation zones based on considerations of areas classified to be at risk of flooding in the publicly available flood risk map for Absecon Island (Street 2024). We then convert these polygons to raster outputs with a spatial resolution of 0.1 m. Following this, we convert the rasterised polygon vegetation hotspots to points in order to generate a point dataset within each hotspot at 0.1 m spacing (Figure 4)—indicative of a high-density vegetation (saltmarsh) system.

To create a young vegetation scenario, we randomly allocate elevation values ranging from 0.1 to 0.99 m to the points dataset created above. We then convert this points dataset with the young vegetation elevations to a raster output and superimpose it onto the computational DEM (Figure 4) for Absecon Island—in turn, creating a young vegetative NBCS DEM for scenario modelling. We repeat these processes to create: (a) a mid-age (medium) vegetative NBCS DEM using elevation values ranging from 1 to 2 m and (b) an old vegetative NBCS DEM using elevation values ranging from 2 to 2.7 m. The elevation values used herein are derived from previous studies on saltmarsh vegetation age, heights, and densities (Ysebaert et al. 2011; Yang et al. 2012; Vuik et al. 2016).

3.5 | Sea-Level Scenarios

To investigate the effectiveness of vegetative NBCS, mirrored through saltmarsh hotspots, we generate five sea-level rise (SLR) scenarios (Figure 5), as outlined below:

1. *Scenario 1* is our baseline scenario, based on the observed 03 January 2014 spring tide dataset obtained.
2. *Scenario 2* is the same 03 January 2014 spring tide event under the minimum 2050 projected SLR value (105.3 mm) for New Jersey (NOAA 2024). To generate this scenario, we superimpose a 105.3 mm SLR onto the 03 January 2014 spring tide dataset obtained.
3. *Scenario 3* is the same 03 January 2014 spring tide event under the maximum 2050 projected SLR (113.1 mm) for New Jersey (NOAA 2024). To generate this scenario, we superimpose a 113.1 mm SLR onto the 03 January 2014 spring tide dataset obtained.
4. *Scenario 4* is the same 03 January 2014 spring tide event under the minimum 2100 projected SLR (307.8 mm) for New Jersey (NOAA 2024). To generate this scenario, we superimpose a 307.8 mm SLR onto the 03 January 2014 spring tide dataset obtained.

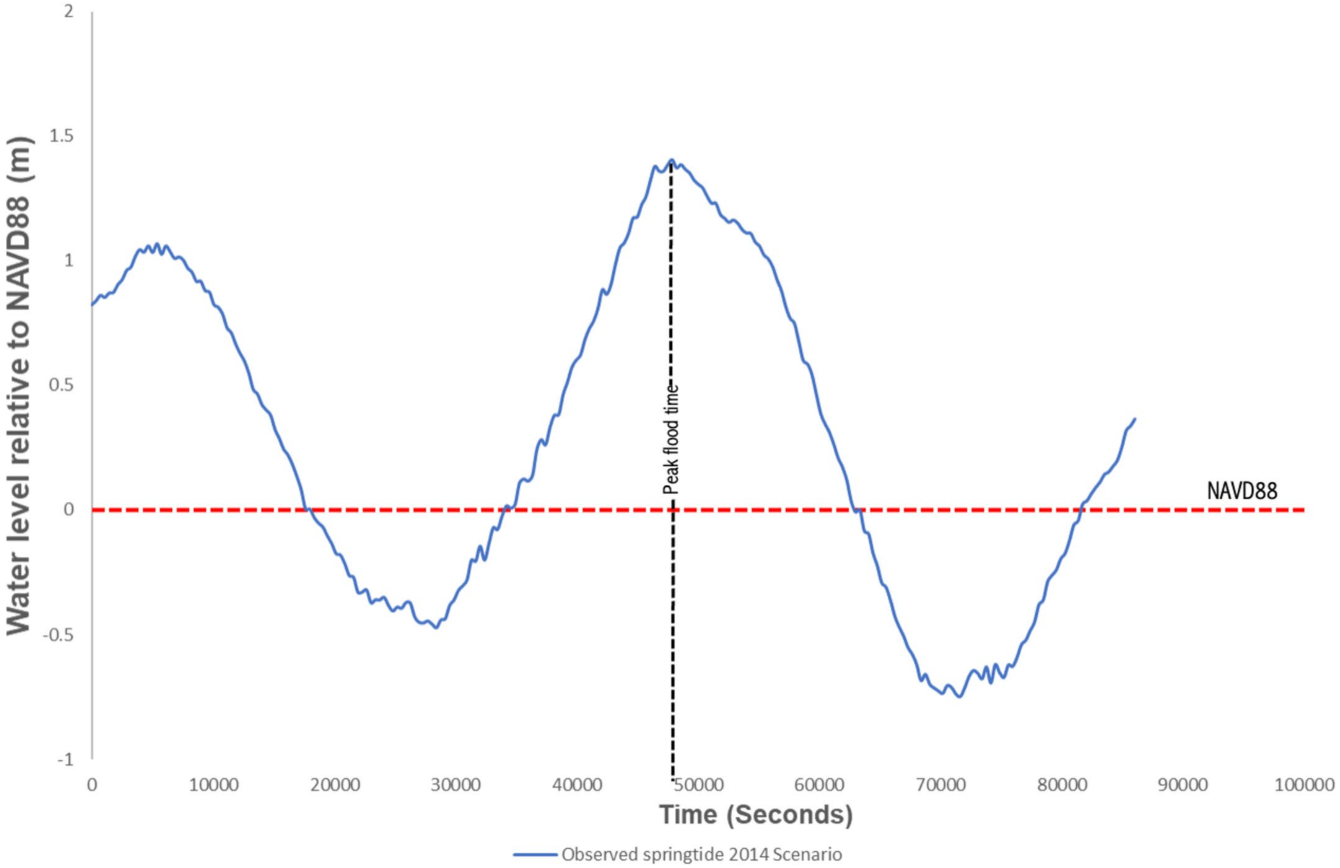

FIGURE 3 | Time series plot of the observed 03 January 2014 spring tide event. NAVD88 = North American Vertical Datum of 1988 (NOAA 2024).

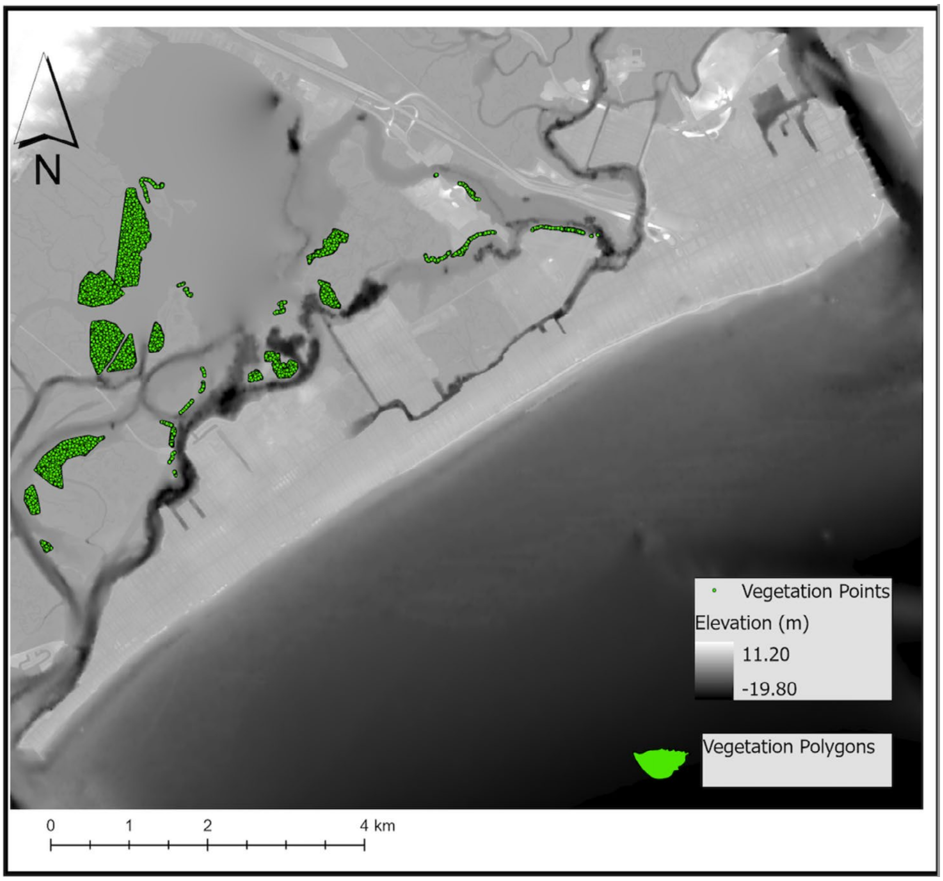

FIGURE 4 | Vegetation hotspots created for our scenario modelling.

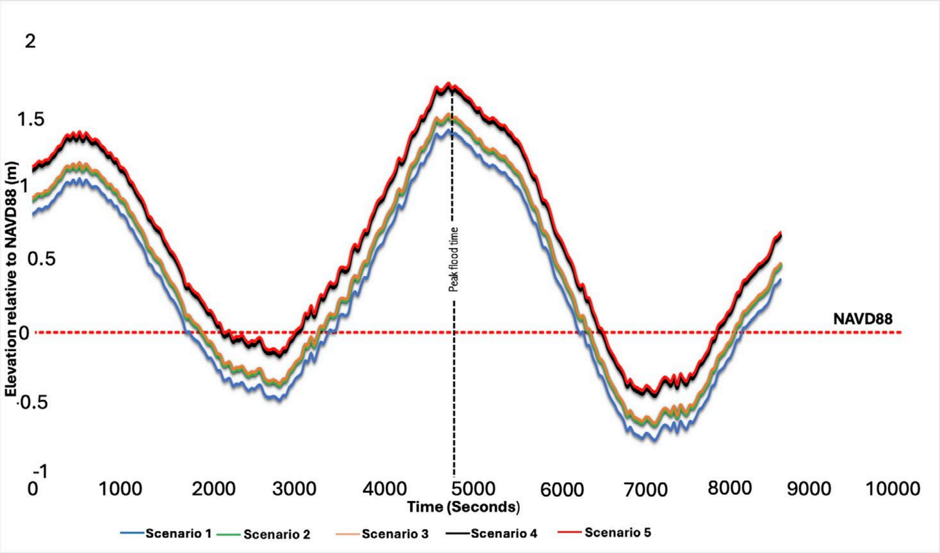

FIGURE 5 | Time series plot for 24-h tidal cycle for the projected sea-level rise scenarios. NAVD88 = North American Vertical Datum of 1988.

5. *Scenario 5* is the same 03 January 2014 spring tide event under the maximum 2100 projected SLR (0.3306 mm) for New Jersey (NOAA 2024). To generate this scenario, we superimpose a 0.3306 mm SLR onto the 03 January 2014 spring tide dataset obtained.

3.6 | Flood Simulations

Following the creation of our vegetative NBCS and SLR scenarios, we run 20 flood simulations in *LISFLOOD – FP* for Absecon Island, as summarised in Table 1. These include scenarios with and without vegetative NBCS, so that we can gauge how effective vegetative NBCS can potentially be for mitigating coastal flood risk under fluctuating sea-level conditions. As previously mentioned, our study is experimental, not designed to illustrate precise real-world likely conditions. Rather, our study is designed to offer decision-making support for coastal flood risk management.

3.7 | Geospatial Analysis

We quantify the predicted flood extent from each simulation and compare flood extent predictions between non-vegetation and vegetation scenarios to examine whether vegetative NBCS can reduce flood risk in our test site under alternative SLR conditions. To do this, we use the maximum flood depth output from each simulation and apply a depth threshold of >0.1 m. In other words, we consider any grid cell in the DEM that has a predicted flood depth of >0.1 m to be flooded. Flood depths below this level usually have little consequence and, therefore, provide an extreme indication of flood extent (Aronica et al. 2002). For each flood scenario, we quantify the total land area predicted to flood in percentages in ArcGIS Pro and then compare predicted flooded areas between non-vegetation and vegetation scenarios to examine the effectiveness of vegetative NBCS for flood risk mitigation. Additionally, following Seenath (2015), we apply a DEMs of Difference approach in ArcGIS Pro to examine spatial differences in flood timing (initial time of flooding, hrs), maximum flood velocity (m/s), and maximum flood depth (m) between non-vegetation and vegetation scenarios, again to evaluate the impact of vegetative NBCS in flood risk mitigation.

4 | Results

We find marginal to negligible differences in flood area (average: $<5\%$), maximum flood depth (average: 0 m), and maximum flood velocity ($\sim 0 - <0.35$ m/s) predictions in response to our vegetative NBCS hotspots relative to our non-vegetation (current site conditions) scenario under each sea-level scenario simulated (Figures 6–8; Supporting Information S1–S3). Given the marginal differences in flood variables under each scenario, we only present a subset of the results here, primarily corresponding to our more extreme sea-level scenarios for 2050 and 2100, with the remaining results as Supporting Information. An interesting observation here is that there is a miniscule increase in total flooded area in response to our medium and old vegetation scenarios under four sea-level scenarios. Furthermore, although our results show a difference of up to ~10 h in initial time of flooding in response to our vegetative NBCS hotspots, a closer inspection of the spatial variations in initial flood timing differences reveals an average difference of ~0 h in response to all our vegetation scenarios under each sea-level scenario simulated (Figures 6–8; Supporting Information S1–S3). Collectively, these findings indicate that vegetative NBCS are not effective for sustainable coastal flood risk management (i.e., long-term management under SLR), contrary to their purported effectiveness in related literature. These findings, however, may be attributed to: (a) the location of our vegetation hotspots or (b) the inability of vegetation to counteract the effects of rising sea-levels—previous studies show that rising sea-levels and associated wave action can overcome the frictional effects of vegetation (see Seenath 2015).

TABLE 1 | Summary of our simulations.

Model	DEM	Sea-level scenario	Sim. time	Friction	Outputs
Model 1	Absecon Island DEM	Scenario 1 (obs. spring tide)	86,040 s	0.02	Flood extent Flood depth Flood velocity Flood timing
Model 2		Scenario 2 (obs. spring tide under min 2050 SLR)			
Model 3		Scenario 3 (obs. spring tide under max 2050 SLR)			
Model 4		Scenario 4 (obs. spring tide under min 2100 SLR)			
Model 5		Scenario 5 (obs. spring tide under max 2100 SLR)			
Model 6	Absecon Island DEM superimposed with young vegetative NBCS raster (Section 3.4)	Scenario 1 (obs. spring tide)			
Model 7		Scenario 2 (obs. spring tide under min 2050 SLR)			
Model 8		Scenario 3 (obs. spring tide under max 2050 SLR)			
Model 9		Scenario 4 (obs. spring tide under min 2100 SLR)			
Model 10		Scenario 5 (obs. spring tide under max 2100 SLR)			
Model 11	Absecon Island DEM superimposed with mid-age (medium) vegetative NBCS raster (Section 3.4)	Scenario 1 (obs. spring tide)			
Model 12		Scenario 2 (obs. spring tide under min 2050 SLR)			
Model 13		Scenario 3 (obs. spring tide under max 2050 SLR)			
Model 14		Scenario 4 (obs. spring tide under min 2100 SLR)			
Model 15		Scenario 5 (obs. spring tide under max 2100 SLR)			
Model 16	Absecon Island DEM superimposed with old vegetative NBCS raster (Section 3.4)	Scenario 1 (obs. spring tide)			
Model 17		Scenario 2 (obs. spring tide under min 2050 SLR)			
Model 18		Scenario 3 (obs. spring tide under max 2050 SLR)			
Model 19		Scenario 4 (obs. spring tide under min 2100 SLR)			
Model 20		Scenario 5 (obs. spring tide under max 2100 SLR)			

Abbreviations: obs. = observed; max = maximum; min = minimum; SLR = sea-level rise.

5 | Discussion

Our findings indicate that while vegetative NBCS can contribute to a slight reduction in flood extent, their long-term effectiveness is limited, especially under rising sea levels. The minimal effects of vegetative NBCS on flood extent predicted across all our vegetation and SLR scenarios indicate that over-reliance on vegetative NBCS *may not* be a sustainable solution for coastal flood risk mitigation under climate change, aligning with the findings of McIvor et al. (2012), Seddon et al. (2020), and Fagherazzi et al. (2020). In the context of saltmarshes, for example, rising sea levels will result in part or most of these vegetation systems becoming submerged, reducing their overall ability to diffuse incoming wave energy and/or flood propagation waves (Best et al. 2018; Pannozzo et al. 2021). The end result will inevitably be flooding of inland areas. This reinforces the notion that while vegetative NBCS have broader environmental benefits, they may not be sufficient as a standalone approach for long-term coastal flood risk protection.

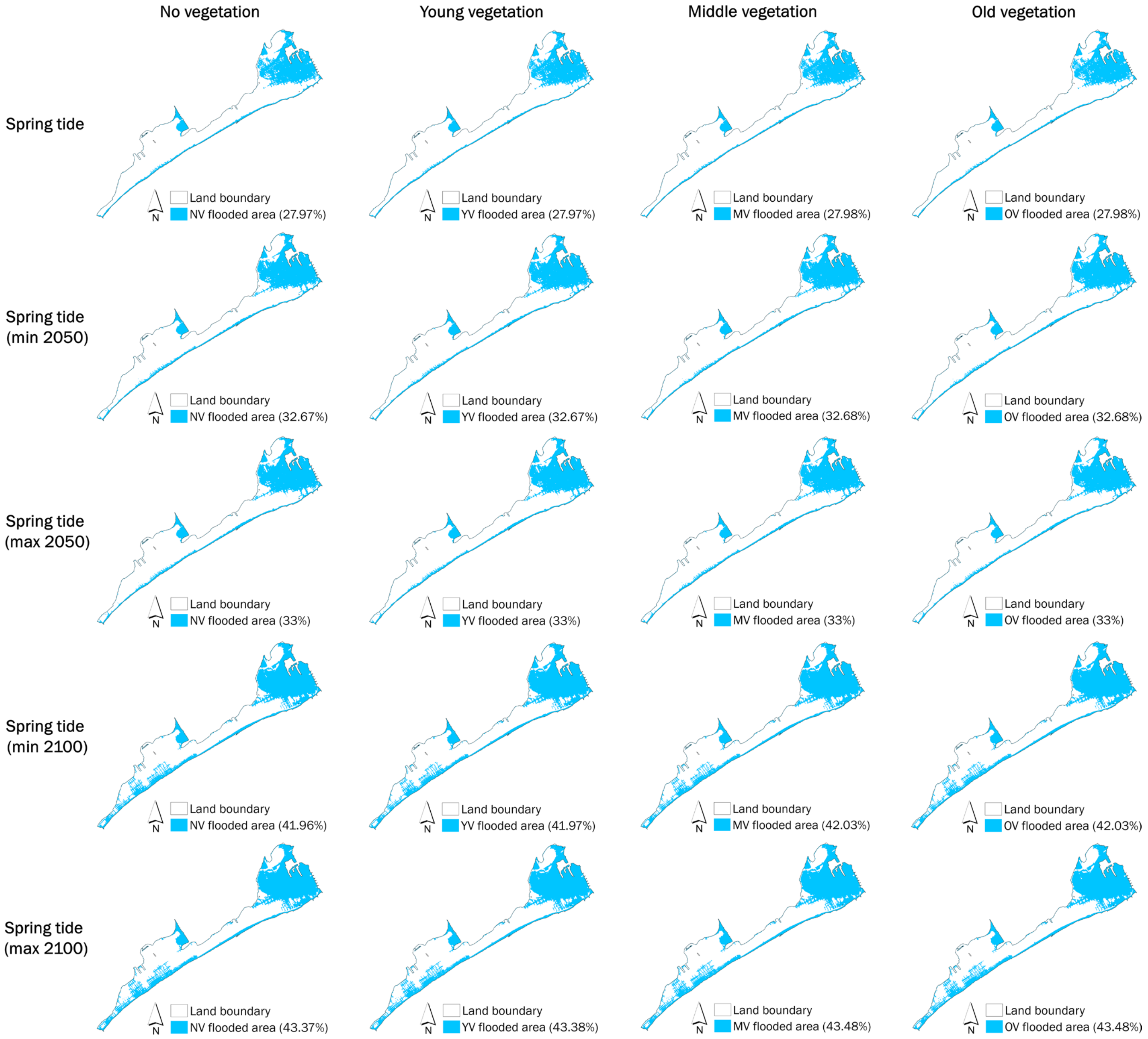

FIGURE 6 | Flood extent predictions with and without vegetative NBCS under alternative sea-level conditions.

Furthermore, while vegetative NBCS have the potential to dissipate wave energy and reduce storm surges, their long-term effectiveness depends on various ecological and environmental factors (Justine and Seenath 2025). These factors include seasonal fluctuations in biomass, vegetation species-specific traits, and external stressors, such as climate change and anthropogenic activities such as deforestation (Justine and Seenath 2025). For instance, seagrass meadows are most effective at wave attenuation during the summer, when biomass is at its peak. However, their protective capabilities diminish in the autumn and winter, often coinciding with increased storm activity. Additionally, existing flood management policies and regulations frequently do not explicitly incorporate vegetative NBCS for coastal flood risk reduction, adding complexity to the reliability and adoption of NBCS over the medium term (Kumar et al. 2021). Another key challenge to the adoption of NBCS is the lack of established and standardised methodologies for their performance evaluation and scaling up implementation (Kumar et al. 2021; Justine and Seenath 2025). This unpredictability means that we should be cautious of relying solely on and advocating for the use of NBCS for coastal flood risk mitigation.

Given the results from our model scenarios, we see merit in the need to explore hybrid interventions for coastal flood risk management, combining conventional grey infrastructure with nature-based solutions. This combined approach integrates established grey infrastructure—such as seawalls and levees—which provide immediate flood protection, especially during extreme events, with vegetative systems contributing to wave attenuation, sediment stabilisation, and ecosystem services, such as carbon sequestration and biodiversity enhancement (Mcleod et al. 2011; Serrano et al. 2019). For example, using mangroves alongside offshore breakwaters can significantly reduce wave heights, minimising the risk of overtopping and structural damage (Risheharan et al. 2025). Furthermore, hybrid solutions may extend the lifespan of grey infrastructure by decreasing maintenance needs and alleviating physical stress through natural wave energy dissipation (Anfuso et al. 2011; Semeoshenkova

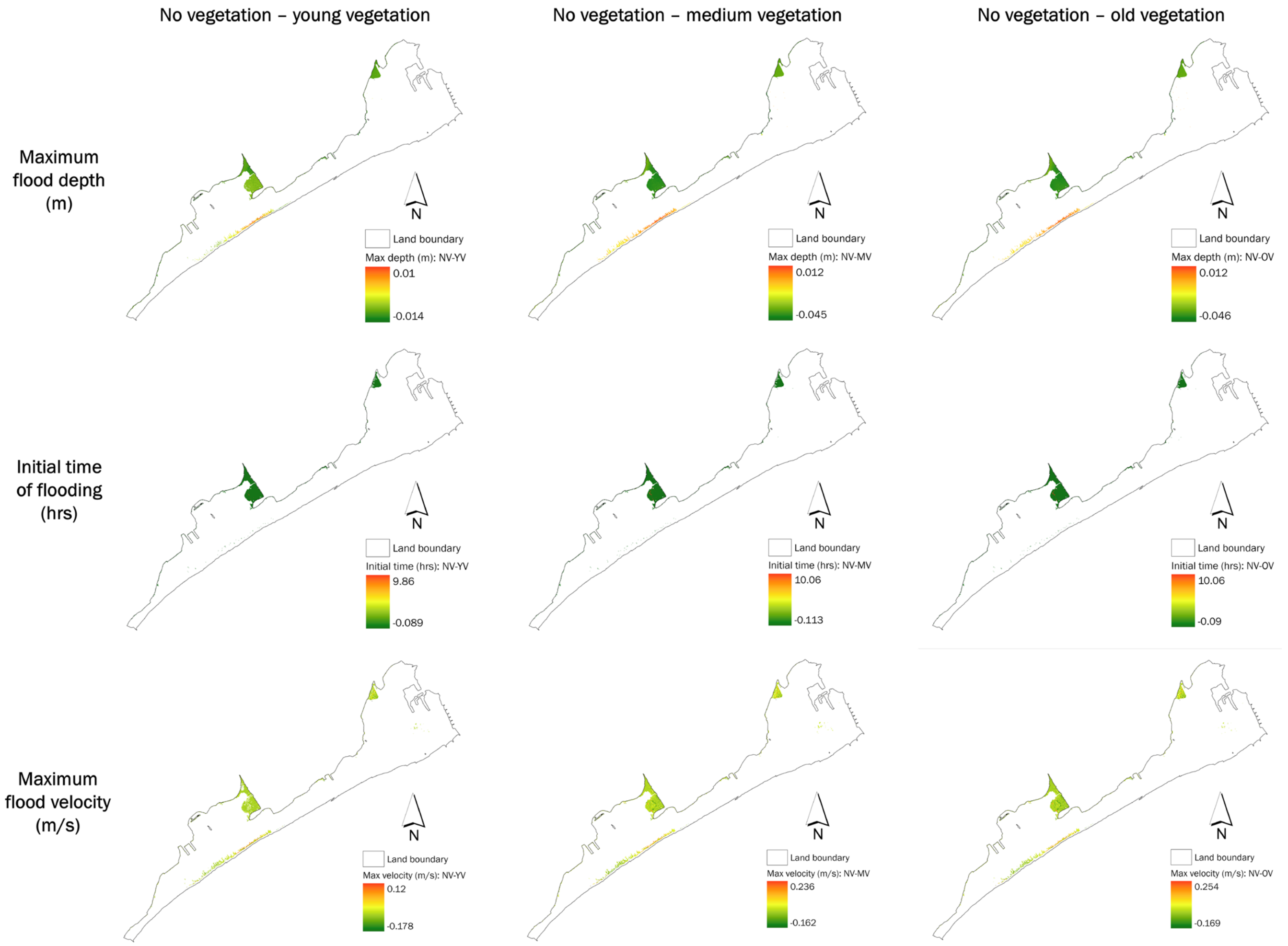

FIGURE 7 | Spatial differences in maximum flood depth (m), initial time of flooding (hours), and maximum flood velocity (m/s) between our non-vegetation and each vegetative NBCS scenario under our third sea-level scenario—max 2050 SLR superimposed onto the observed 03 January 2014 spring tide.

and Newton 2015; Rangel-Buitrago et al. 2018; Lepesant 2024). While grey solutions have limited adaptability to rapid sea-level rise and more intense storm patterns, the inherent adaptability of vegetation complements static infrastructure, potentially adding a dynamic layer of coastal flood defence (Justine and Seenath 2025). By leveraging the strengths of both approaches, hybrid solutions *may in theory* provide a more resilient and sustainable strategy for long-term coastal flood risk management, addressing the limitations of each method individually. However, the implementation of hybrid solutions relies on having ample space for nature-based systems, such as saltmarshes or mangroves (Sutton-Grier et al. 2015; Almarshed et al. 2019; Sowińska-Świerkosz and García 2022). Yet, finding such space is often scarce in densely populated or developed coastal areas that are prone to floods. In addition, hybrid solutions may require significant initial investment and their effectiveness is also uncertain under climate change (Du et al. 2020). Therefore, we recommend that future research should systematically evaluate the integrated performance of hybrid solutions under various environmental and climate change scenarios to provide empirical evidence for sustainable coastal flood risk management decisions.

Although our results show that vegetative NBCS are ineffective for coastal flood risk management, we are mindful that there are potentially two limitations of our study. In the *first* instance, our scenario modelling and use of *LISFLOOD – FP* mean that we simplified the representation of complex coastal systems by primarily focusing on hydrodynamic response to vegetation structures. As a result, our study overlooks critical feedback mechanisms and interdependencies, limiting our ability to fully reflect the intricate dynamics of coastal systems. The *second* limitation relates to the location of our vegetation hotspots and the setup of vegetation structures. We considered existing flood risk maps for Absecon Island to identify areas where flood risk mitigation is needed, in order to inform the location of our vegetative NBCS hotspots. The vegetation structures, primarily in terms of elevation, and density, were designed based on a careful consideration of established saltmarsh characteristics. However, despite the careful thought process in the design and location of our vegetative NBCS hotspots, further work is needed to ascertain our findings, particularly considering that our modelled results are only as good as our data and the credibility of the model used. We, therefore, recommend a coupled morphology and flood modelling approach to determine whether vegetative NBCS can keep up with rising sea levels and provide a natural and sustainable flood risk defence mechanism, as often purported in wider (but related) literature. A coupled morphology and flood modelling approach may provide a better understanding of the

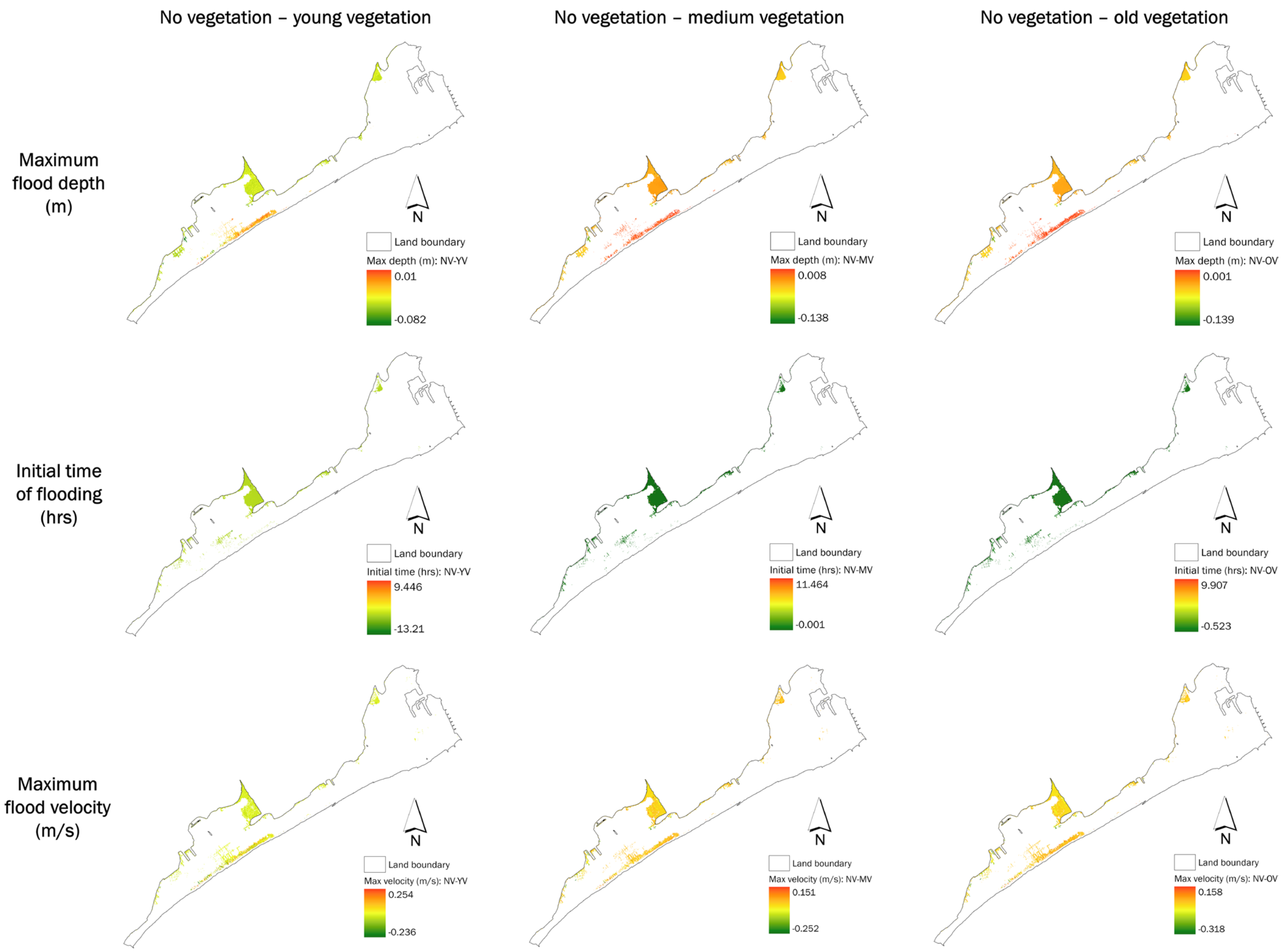

FIGURE 8 | Spatial differences in maximum flood depth (m), initial time of flooding (hours), and maximum flood velocity (m/s) between our non-vegetation and each vegetative NBCS scenario under our fifth sea-level scenario—max 2100 SLR superimposed onto the observed 03 January 2014 spring tide.

interplay between vegetation-based coastal solutions (NBCS), hydrodynamic processes, and geomorphological changes. This is useful in evaluating the dynamic interactions between vegetation, sediment, and water flow under various sea-level rise scenarios.

6 | Conclusions

We investigate the effectiveness of vegetative NBCS on coastal flood risk mitigation by applying a verified *LISFLOOD*-FP model of Absecon Island to simulate the effects of three vegetative NBCS hotspot scenarios (young, mid-age, and old saltmarsh structures) on coastal flood risk under alternative sea-level rise conditions. We find that vegetative NBCS have marginal to negligible effects on flood extent, maximum flood depth, initial time of (inland) flooding and maximum flood velocity relative to scenarios with no vegetative NBCS. These findings indicate that, contrary to the growing advocacy for NBCS, primary reliance on vegetative NBCS for coastal flood risk mitigation is not sustainable under rising sea levels. However, we are mindful that this finding may be attributed to the location and design of our vegetative hotspots and our modelling approach, despite these being guided by existing flood risk maps for the test site, theoretically realistic elevation ranges for saltmarsh vegetation of varying ages, and established flood modelling practices. We, therefore, recommend further research on investigating whether vegetative NBCS can keep up with rising sea levels and provide a natural and sustainable flood risk defence mechanism, as often purported in wider literature, potentially through a coupled morphology and flood modelling approach.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data available on request from the authors.

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Supporting Information

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