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An integrative nature-based planning model for sustainable and resilient environments

Hande Sanem Çınar[1*] and Burak Yılmazsoy[2]

*Correspondence:
handesanemcinar@esenyurt.edu.tr

[1] Department of Interior Architecture and Environmental Design, Faculty of Engineering and Architecture, Istanbul Esenyurt University, Istanbul, Turkey
[2] Department of Urban Design and Landscape Architecture, Faculty of Art and Design, Istanbul Kent Üniversity, Istanbul, Turkey

Abstract

Despite increasing policy recognition of Nature-based Solutions (NbS), a persistent gap remains between conceptual sustainability frameworks and reproducible, performance-based planning applications supported by spatial modeling and ecosystem-service quantification. This study addresses this gap by developing a spatially explicit NbS planning and evaluation framework for the Shenks Property along the Severn River within the Chesapeake Bay watershed, Virginia, USA. The research integrates GIS-based hydrological modeling, ecosystem-service assessment using the InVEST platform, and resilience evaluation under NOAA 2050 intermediate sea-level rise projections.Multiple spatial datasets, including land-use/land-cover classifications, LiDAR-derived elevation models, soil characteristics, biodiversity inventories, and tidal observations, were analyzed within an integrated analytical workflow. Results indicate measurable ecological and hydrological improvements under NbS-based scenarios. Predictive simulations demonstrate an approximately 40% (± 5%) reduction in annual surface runoff and an approximately 20 m retraction of projected flood boundaries under future sea-level rise conditions. Carbon-storage capacity increased by 18–24%, while habitat-quality index values improved by 15–22% within rehabilitated wetland zones. Increased vegetation density additionally contributed to localized microclimatic cooling of approximately 2–3 °C. The findings demonstrate that NbS can simultaneously support climate adaptation, ecological restoration, and long-term spatial resilience while potentially reducing maintenance demands relative to conventional gray infrastructure systems. Methodologically, the study advances the operationalization of NbS by integrating ecosystem-service modeling, hydrological simulations, and adaptive spatial planning into a transferable performance-based planning framework. However, while the study offers robust predictive insights, its findings are based on modeling and scenario-based simulations. Therefore, long-term post-occupancy monitoring is essential to validate ecological performance and system resilience.

Keywords: Nature-based solutions, Ecological resilience, Wetlands, Sustainable architecture, Climate

1 Introduction

Global climate change is a complex 21st-century issue affecting environmental, social, and economic systems. Coastal ecosystems, in particular, are highly vulnerable to climate-induced risks such as sea-level rise, flooding, and coastal erosion [1]. These changes threaten both natural and human systems, emphasizing the need for flexible,

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resilient settlement models [2, 3] approaches inspired by nature require collaboration [4]. Wetlands have strategic value in climate adaptation, carbon storage, flood control, and cultural ecosystem services [5, 6]. Protecting and restoring these ecosystems is among the most critical global nature-basedsolutions NbS [3] for climate resilience [7, 8]. The concept of (NbS) has gained prominence in both academic research and international policy discourse. The International Union for Conservation of Nature defines NbS as actions that protect, sustainably manage, and restore ecosystems to address societal challenges while simultaneously providing human well-being and biodiversity benefits [8]. Unlike conventional gray infrastructure approaches that prioritize structural resistance, NbS emphasize working with ecological processes, enhancing adaptive capacity through ecosystem-based strategies.

NbS emphasizes working with nature—using its regenerative systems rather than imposing engineering control and is linked to climate adaptation, ecosystem service, and ecological urbanism [9–12]. However, nearly 64% of global wetlands have been lost, reducing both ecological and social resilience [13]. Approaches like "Living Shorelines" demonstrate how natural buffer zones can replace hard coastal structures and enhance ecosystem resilience [14]. Recent studies demonstrate that NbS can contribute to both climate mitigation and adaptation by enhancing carbon sequestration, reducing surface runoff, improving microclimatic regulation, and strengthening habitat continuity [3, 4]. Furthermore, urban-scale NbS interventions have been linked to participatory governance, social learning, and community-based adaptation processes [15]. These findings suggest that NbS operate as ecological interventions as socio-spatial transformation mechanisms.

This study should not be interpreted as a fully empirical post-occupancy case study, but rather as a simulation-supported and analytically informed design prototype. The proposed framework integrates GIS-based spatial analyses, hydrological modeling, ecosystem-service simulations, and scenario-based planning methodologies to evaluate the potential performance of Nature-based Solutions under projected climate conditions. Therefore, the presented ecological and hydrological outcomes represent predictive model outputs rather than directly observed long-term field measurements. This study explores how holistic spatial models based on NbS can simultaneously enhance climate resilience and deliver social and ecological benefits, offering guidance for sustainable planning and global climate adaptation. Beyond the specific case-study context, this research addresses a critical methodological gap between ecosystem-service assessment and spatial design implementation within coastal planning literature. Rather than a prescriptive application, it presents an analytically informed nature-based planning and design framework that bridges ecosystem service models and spatial/architectural decisions.

Existing NbS studies frequently remain either at the level of conceptual ecological discourse or isolated engineering applications, without establishing a transparent analytical bridge between ecosystem-service modeling and spatial-architectural decision-making. In response, this study proposes an analytically informed Nature-based planning and design framework that integrates GIS-based ecosystem-service simulations, hydrological modeling, and adaptive spatial planning strategies into a unified decision-support structure. Rather than presenting a monitored post-occupancy implementation, the study introduces a predictive and transferable planning prototype capable of informing resilient coastal development processes. The proposed framework also contributes to broader coastal engineering practice by demonstrating how ecosystem-service performance indicators can systematically guide adaptive shoreline planning, flood-resilient spatial organization, and climate-responsive coastal infrastructure strategies across diverse vulnerable coastal environments.

Despite increasing recognition, a critical gap remains between conceptual NbS discourse and operational, reproducible planning methodologies. Many existing studies either focus on policy frameworks without spatial quantification or present design-oriented prototypes lacking transparent ecosystem service modeling. As a result, ambiguity persists regarding whether NbS projects function as theoretical visions, architectural proposals, or evidence-based performance interventions. To address this gap, the present study develops and applies a structured, simulation-supported NbS planning framework to the Shenk Property along the Severn River in Virginia, USA, located within the Chesapeake Bay watershed. The region is identified as highly vulnerable to projected sea-level rise scenarios published by the National Oceanic and Atmospheric Administration (NOAA) [5]. The framework integrates hydrological modeling, resilience indicator evaluation, and ecosystem service assessment using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model developed by the Natural Capital Project. InVEST is a spatially explicit modeling tool that quantifies ecosystem servic—such as carbon storage, habitat quality, and water regulation—under different land-use and climate scenarios, enabling the evaluation of environmental trade-offs and decision-making support in sustainable planning processes.

The study pursues three primary objectives:

- To quantify hydrological and ecosystem service performance under NbS-integrated spatial scenarios.
- To distinguish analytical modeling outputs from spatial design interpretation.
- To propose a transferable, evidence-informed NbS planning framework applicable to climate-vulnerable coastal landscapes.

Within this framework, the study addresses the following research question:

How can Nature-based Solutions be implemented as an integrative planning model that combines ecology, architecture, and social learning?

This study contributes to the Nature-based Solutions (NbS) literature by developing a spatially explicit and analytically informed planning framework that bridges ecosystem-service modeling with adaptive spatial and architectural decision-making.

1.1 Definition of the research area

The research focuses on the Shenk Property located along the Severn River in United States, within the ecologically significant Chesapeake Bay watershed. The Severn River is a tidal tributary of the Chesapeake Bay and forms part of one of the largest estuarine systems in North America. The watershed is characterized by sensitive brackish wetland ecosystems, fluctuating tidal regimes, and increasing exposure to sea-level rise and coastal flooding (Fig. 1), [16]. According to projections published by

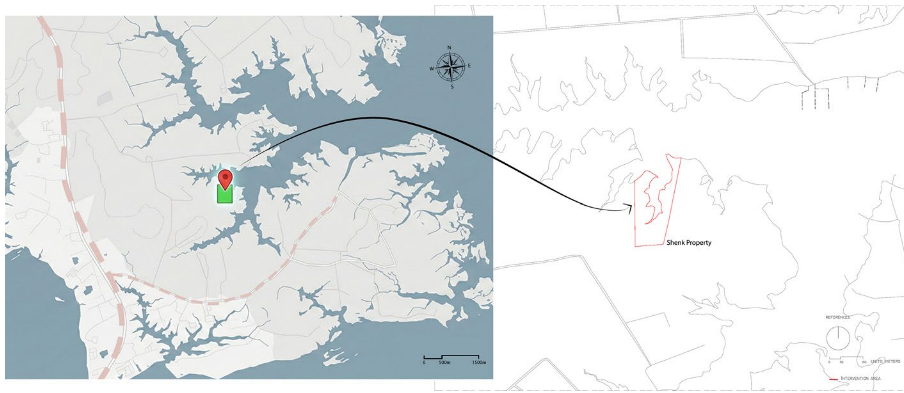

Fig. 1 Severn River-Shenk Property and Virginia, USA

the National Oceanic and Atmospheric Administration, the Chesapeake Bay region is expected to experience intermediate to high sea-level rise scenarios ranging between 0.6 and 1.2 m by 2100, with measurable impacts already projected for 2050 [5]. These projections indicate increased frequency of nuisance flooding, shoreline retreat, and salinity intrusion, directly affecting low-elevation coastal properties such as the Shenk Property,

Climatically, the region falls within the humid subtropical transition zone, characterized by hot summers, moderate winters, and average annual precipitation of approximately 1100–1200 mm. Increased precipitation intensity, combined with tidal backflow conditions, contributes to compound flood risks in coastal parcels [17]. The study area is under environmental pressures caused by climate change, such as flood risk, sea level rise, and loss of ecosystem services [18]. Furthermore, land use and settlement density in the region directly affect water quality and ecological carrying capacity. From a hydrological standpoint, the River Severn, located west of Mobjack Bay, has depths of about 4,5 m at its confluence points and about 2.4 m at its tributaries. This topographic diversity can affect microclimatic conditions and wind regime. Therefore, the project area has been identified as a model area with high research potential in terms of both ecological resilience and (NbS) strategies. The project aimed not only to produce a functional structure with an innovative R&D Field Station, but also to create an adaptable and sustainable system that establishes a symbiotic relationship with its surroundings and can adapt to changing climate conditions and land dynamics. In this context, the design was expected to create a resilient landscape-architecture example by establishing a balance between the built environment and the natural ecosystem. In this sense, the Shenk Property, was intended to be evaluated as a unique laboratory area capable of testing both ecological sensitivity and experimental sustainability approaches.

Three main criteria were decisive in selecting this area:

Ecological sensitivity: The presence of transition zones between wetland and terrestrial ecosystems.

Climate risk: Topographical vulnerability to sea level rise and flood hazards.

Social accessibility: Suitable location for education, observation, and research activities.

With these characteristics, the area has been evaluated as a "living lab" where (NbS) can be applied in a multidisciplinary manner [19]. By situating the case study within a tidal wetland–urban interface, the research area provides an appropriate testing ground for evaluating the hydrological, ecological, and spatial performance of Nature-Based Solutions under future climate scenarios.

2 Material and methods

This research adopts a quantitative simulation approach to measure the effectiveness of nature-based solutions (NbS). The analysis was carried out through the InVEST Integrated Valuation of Ecosystem Services and Tradeoffs) v3.13.0 software developed by Natural Capital Project. This research employs an interdisciplinary, four-stage methodology framed within the (NbS) approach. The process integrates spatial, ecological, and social data to develop a resilient and adaptive planning model.

This study employed a spatially explicit and simulation-supported Nature-based Solutions (NbS) framework integrating GIS analysis, ecosystem-service modeling, hydrological simulations, and resilience assessment. Ecosystem services including carbon storage, habitat quality, runoff regulation, and flood mitigation were evaluated using the InVEST platform (v3.13.0), calibrated with NLCD 2021 land-cover data, regional biomass coefficients, soil datasets, and biodiversity records from the Virginia Natural Heritage Program. Hydrological processes and rainfall–runoff dynamics were simulated through SWMM and HEC-HMS models using NOAA tidal observations, FEMA floodplain data, LiDAR-derived DEMs, and USGS soil information. Model reliability was assessed using Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and RMSE metrics, with acceptable calibration thresholds defined as NSE > 0.65 and $R^2 > 0.70$. Scenario simulations incorporated NOAA 2050 intermediate-high sea-level rise projections and sensitivity analyses (± 10% runoff variation) to evaluate system robustness under climate uncertainty. NbS performance was assessed through four interrelated resilience dimensions: ecological continuity, hydraulic adaptation, resource efficiency, and social accessibility. These indicators informed the spatial zoning strategy and adaptive planning decisions developed for the study area.

2.1 Data collection

In the initial stage, quantitative and spatial datasets were compiled to characterize the ecological, spatial, and environmental attributes of the study area. These included land use and land cover data, topographic variables derived from digital elevation models (slope and aspect), (Fig. 2), [20], hydrological data related to surface runoff, climatic variables (Fig. 3), as well as biodiversity and habitat distribution data. Areas exposed to high flood risk were identified using flood assessment data from June 2025 [21]. (Figs. 4, 5).

Elevation and topographic datasets were obtained from USGS DEM [16]. Land-cover and vegetation data were sourced from the National Land Cover Database (NLCD, 2021), while hydrometeorological data including rainfall, temperature, and sea-level projections were retrieved from NOAA 2050 SLR intermediate-high scenario [22]. Data collection also included social and infrastructural datasets such as pedestrian and bicycle pathways, recreational areas, and building footprints [21].

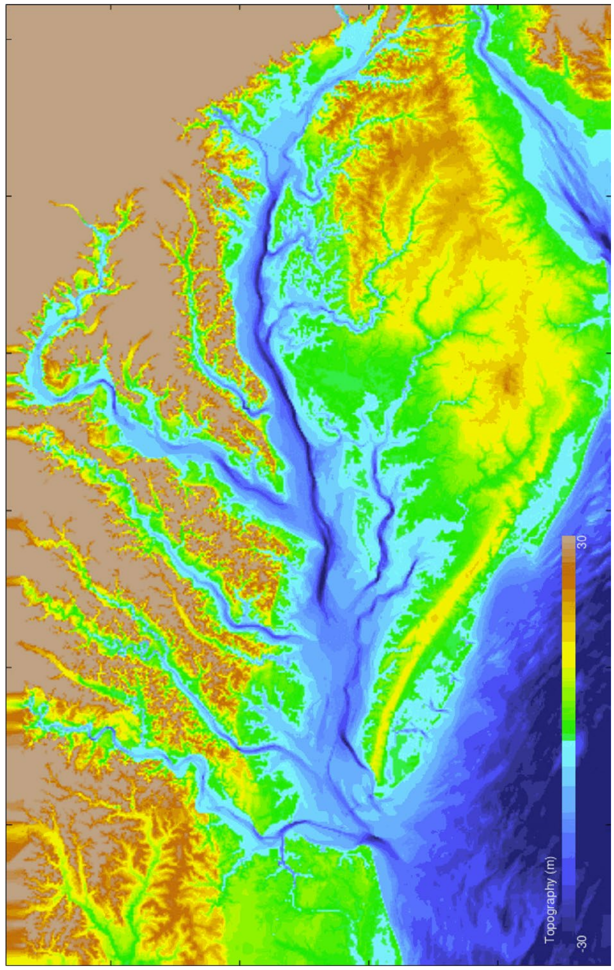

Fig. 2 Topography of the Chesapeake Bay

All datasets were standardized in terms of spatial resolution and coordinate reference systems and integrated within a GIS environment to ensure consistency and suitability for subsequent analyses. Topographic and hydrological datasets were not only selected based on data availability but also calibrated according to the site-specific environmental characteristics of the Chesapeake Bay watershed. High-resolution LiDAR-derived Digital Elevation Models (DEM) obtained from the United States Geological Survey (USGS) were integrated with NOAA tidal observations and FEMA Flood Insurance Rate Maps (FIRM) to ensure spatial consistency and hydrological reliability. Particular attention was given to tidal influence, low-elevation coastal morphology, and wetland hydrodynamics during parameter selection. This approach ensured that the analytical framework reflects observed environmental processes rather than relying solely on generalized literature assumptions. Data collection combined field observations, remote sensing, and literature-based information:

Field and Ecological Observations: Vegetation mapping, habitat surveys, wetland parameters, surface water flow, and water level measurements [4, 21, 23].

Hydro-meteorological Data: Precipitation, temperature, wind, and tidal data obtained from NOAA databases [5, 24].

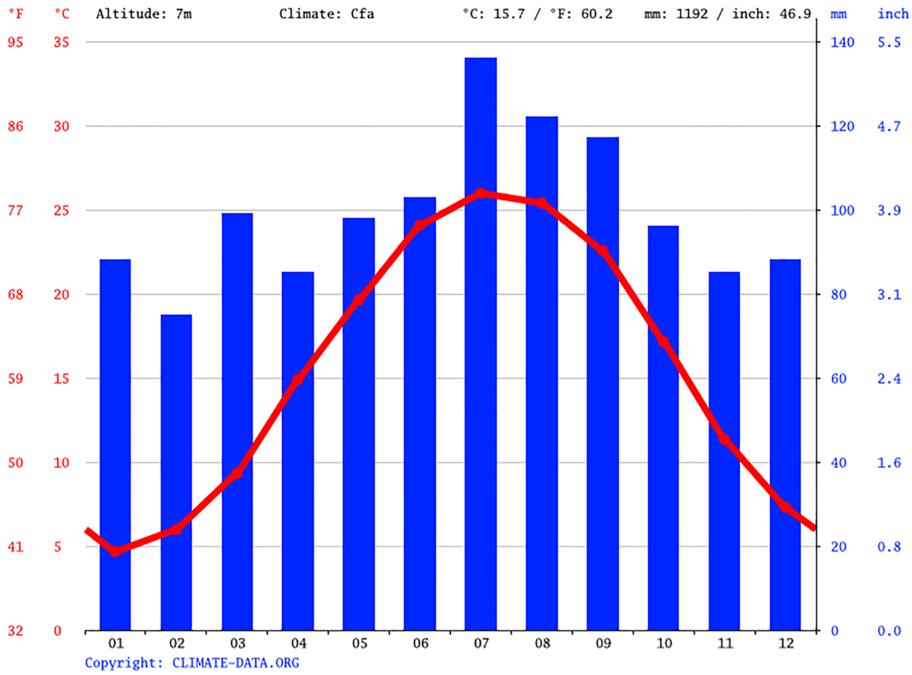

Fig. 3 Climate data

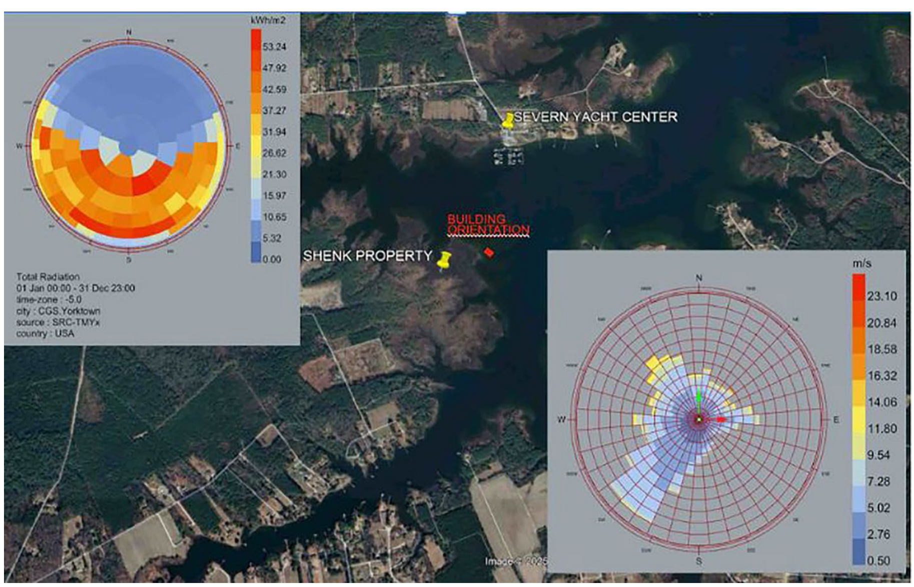

Fig. 4 Wind and Insolation Map

Remote Sensing and GIS: GIS datasets supported the assessment of land-use change, urban density, and spatial connectivity [22].

This multi-layered data collection ensured that NbS impacts could be modeled across ecological, hydrological, and social dimensions.

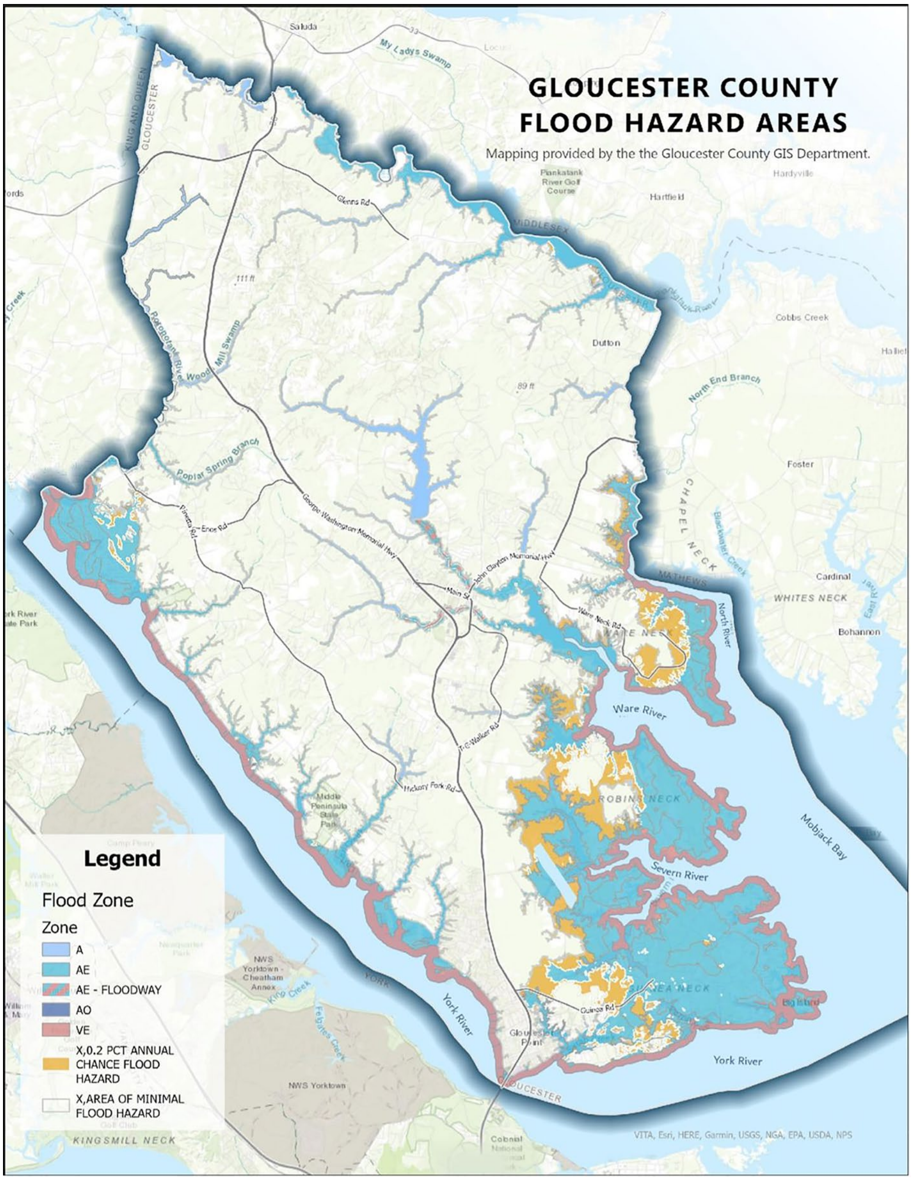

Fig. 5 Flood hazard area

2.2 Analytical evaluation

The collected data were evaluated using GIS-based analyses and InVEST models to measure ecosystem services and reveal spatial relationships. At this stage, ecosystem services such as water retention and runoff regulation, habitat quality and carbon storage were analyzed. The analysis outputs were produced in the form of thematic maps. These outputs are considered as analytical inputs that feed design decisions.

The InVEST model Natural Capital [25, 26] quantified ecosystem services such as carbon storage, water filtration, and habitat value. Vegetation analysis determined native plant communities and zoning, while accessibility modeling with Network Analyst (ArcGIS Pro) supported inclusive design strategies. A 100-year flood boundary was delineated using USGS topographic data, NOAA sea-level rise projections, and LiDAR elevation models [22]. Carbon sequestration, water filtration, and biodiversity potentials were mapped following integrated via a Spatial Decision Support System (SDSS) to link ecological data with design decisions. The parameters used in the simulations were calibrated by comparing against regional literature [18, 21, 26] and field data.

Model parameters were calibrated through a multi-source validation process combining observational datasets, regional literature benchmarks, and spatially explicit environmental indicators. Hydrological parameters such as runoff coefficients, infiltration capacity, sediment retention, and flood expansion thresholds were adjusted according to LiDAR-derived slope conditions, NOAA long-term tidal records, and FEMA floodplain classifications. In parallel, ecosystem service parameters used in the InVEST model were adapted from the Natural Capital Project biophysical tables and regionally validated using biodiversity datasets from the Virginia Natural Heritage Program. This calibration strategy increased the ecological realism and spatial reliability of projected ecosystem service outputs [21, 25]. Hydrological parameters included:

Soil infiltration rate: 5–15 mm/hr, based on USGS soil maps
Runoff coefficients: 0.3–0.6 depending on land cover
Rainfall scenarios: historical (1980–2020) and projected (2050) [23]

The analytical evaluation encompassed data processing, modeling, and scenario simulations:

InVEST Modeling: Ecosystem services including carbon sequestration, habitat quality, and water regulation were quantified using the InVEST suite [23]. Model parameters were calibrated based on local vegetation types, biomass coefficients, and soil characteristics.

Hydrological Modeling: Hydrological simulations were conducted using SWMM and HEC-HMS to evaluate runoff dynamics and flood behavior under present and projected climate scenarios [10].

Scenario Analysis: Sea level rise (SLR) projections for 2050 were obtained from NOAA to simulate spatial retreat under low, medium, and high risk scenarios [22].

Uncertainty Analysis: Sensitivity analyses were conducted by varying key parameters (e.g., ± 10% in surface runoff) to quantify impacts on ecosystem service outputs [8, 26].

The model outputs were compared with NOAA's 10-year (2014–2024) tidal and water level observation data in the region. Model calibration and validation were performed using NOAA tidal observations, FEMA floodplain datasets, and regional ecological inventories to ensure consistency between modeled outputs and observed environmental conditions.

Hydrological model performance was evaluated using the Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and Root Mean Square Error (RMSE). The HEC-HMS model achieved NSE = 0.71 and $R^2 = 0.78$ during calibration, while the SWMM model achieved NSE = 0.69 and $R^2 = 0.74$, exceeding the predefined reliability thresholds (NSE > 0.65 and $R^2 > 0.70$). RMSE values remained within acceptable ranges for long-term hydrological simulations. InVEST Habitat Quality and Carbon Storage modules were calibrated using NLCD 2021 land-cover data, regional biomass coefficients, soil datasets, Virginia Natural Heritage Program biodiversity records, and field-based vegetation observations. These calibration procedures ensured consistency between modeled ecosystem-service outputs and regional ecological conditions. The model is a solution proposal that represents long-term ecosystem service changes and annual average flow regimes, rather than extreme and instantaneous events. Habitat quality outputs were validated against Virginia Natural Heritage Program's biodiversity data [17, 22, 26].

2.3 Interpretation of analytical data

The results of the analytical evaluation were interpreted to define spatial potential and constraints. At this stage, critical spatial thresholds have been determined in terms of areas that provide high ecosystem services, sensitive areas that need to be protected, areas with intervention priority and green infrastructure continuity. This process is designed as an interim evaluation stage between analytical data and the design process. Analytical outputs were interpreted in terms of ecological, hydrological, and social performance:

Carbon Storage: Modeled increase of 18–24% compared to baseline [21, 22].

Habitat Quality: Improvement by 15–22%, emphasizing restored native wetlands.

Surface Runoff Reduction: Approximately 40% reduction due to blue-green infrastructure implementation.

Flood Boundary Retraction: 20 m reduction under NOAA 2050 SLR scenario [23].

Temperature Regulation: Local microclimate cooling by 2–3 °C due to vegetation density [28].

These interpretations were presented as scientific GIS maps, raster datasets, and tables, ensuring reproducibility and comparability with other coastal contexts.

Ecological Performance: Outputs were interpreted as carbon sequestration (tCO_2/ha), habitat quality indices, and species richness.

Hydrological Performance: Simulated runoff, flood extents, and drainage capacity were analyzed.

Social and Educational Performance: Participation levels and experiential learning outcomes were evaluated under the Living Laboratory concept [15, 19].

Resilience Criteria NbS performance was evaluated through ecological continuity, hydraulic adaptation, resource efficiency, and social accessibility indicators, which guided spatial zoning and adaptive planning strategies [17, 23, 27, 28].

Zoning and Spatial Modeling Based on hydrological and ecological parameters, the site was divided into three adaptive landscape zones: (1) a natural wetland buffer, (2) a transitional rehabilitation area, and (3) a safe recreational zone [24, 29] (Fig. 6), [20]. Each zone incorporates specific strategies for water management, vegetation, and structural resilience.

The NbS spatial model integrates ecological, hydrological, and social layers via multi-criteria GIS analysis [24]. Zoning designations optimize:

Front (Natural Zone): Minimal intervention to preserve existing habitats

Intermediate (Rehabilitated Zone): Wetland restoration with modular infrastructure

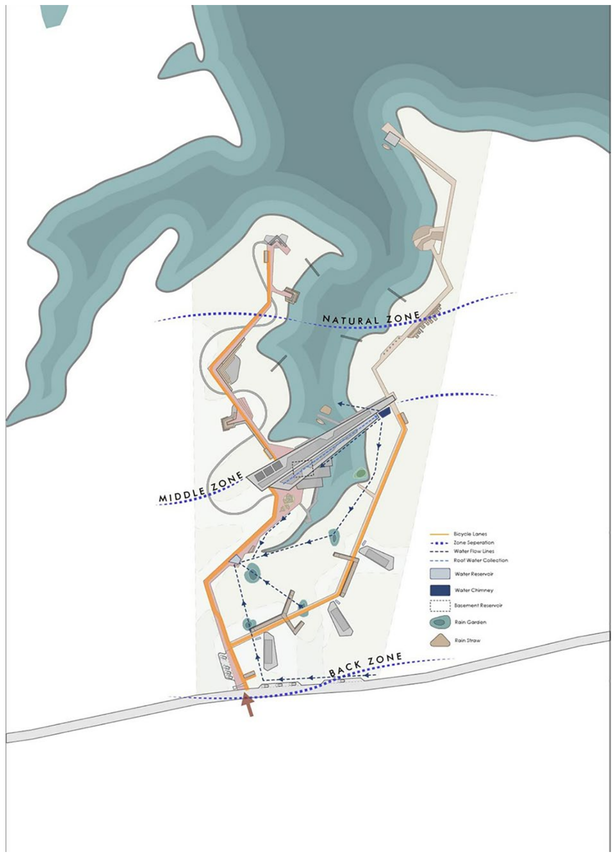

Fig. 6 Zoning and Spatial Modeling

Rear (Recreational Zone): Educational and ecotourism areas resilient to flooding [20].

Model outputs are presented as scientific maps and raster layers, ensuring transferability to other coastal contexts (e.g., sandy beaches), with local recalibration of wave, wind, and sediment parameters [14].

System Integration and Design Criteria NbS strategies—such as rain gardens, reed-bed filtration, living shorelines, and green roofs—were spatially integrated within a circular systems approach [29, 30]. Energy, water, waste, and carbon flows were modeled holistically. Adaptive architectural principles emphasized permeability, flexibility, and material recyclability, with cross-ventilation responding to prevailing NW and S winds in Virginia's mixed-humid climate (Fig. 7), [20].

The design framework combines:

Eco-technical systems: Renewable energy, water recycling, and passive design strategies

Biophysical integration: Native vegetation, living shoreline buffers, carbon-positive landscapes

Socio-ecological connectivity: Universal accessibility networks linking research, recreation, and natural zones [20, 28].

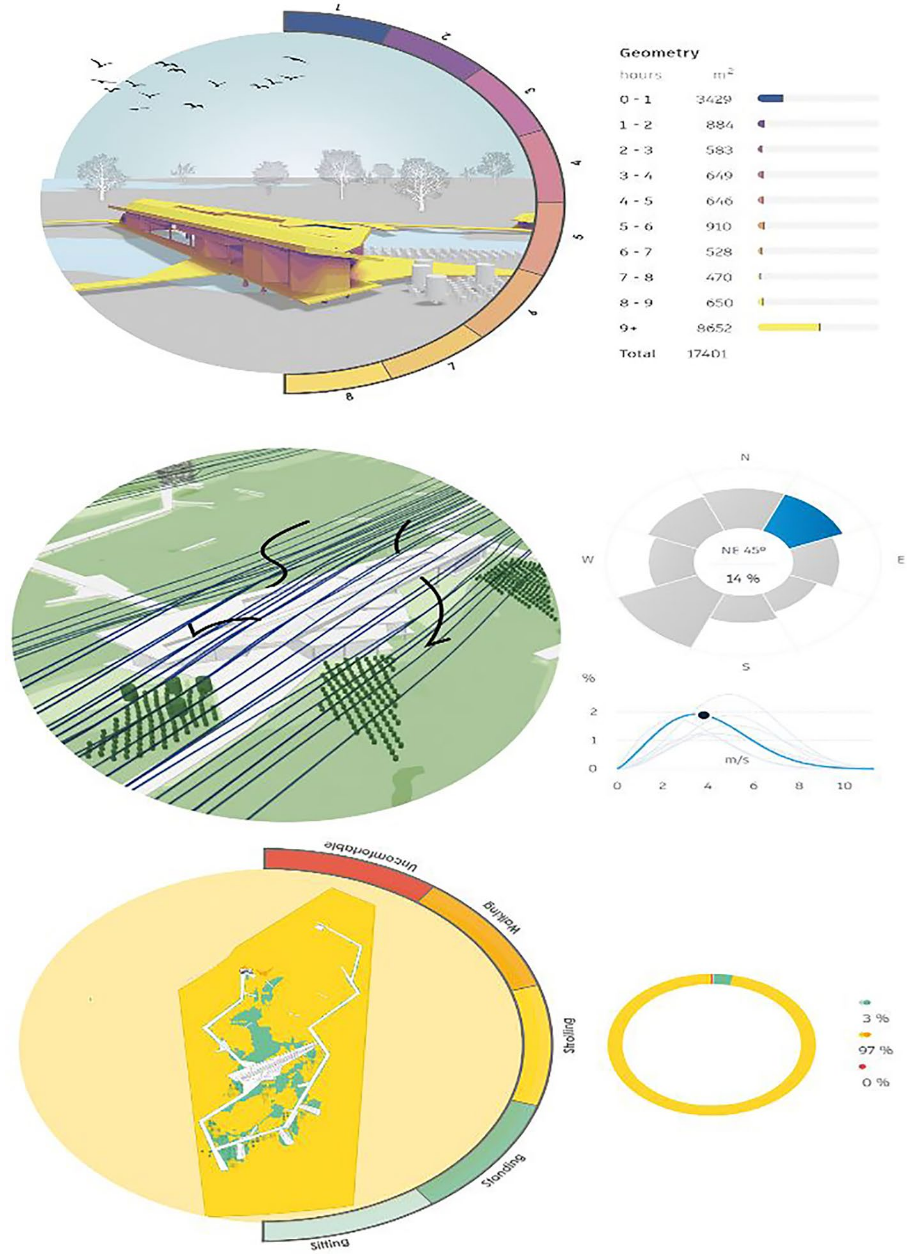

Fig. 7 Spatial resilience analysis of the area

Floating and modular accommodation units minimized ecological footprint, while renewable energy systems (solar, wind, micro-hydro) achieved net-positive energy goals [30]. Permeable pavements, green roofs, and greywater recycling systems enhanced water retention and nutrient cycling, exemplifying circular metabolism principles [24]. The integration ensured that ecological, social, and infrastructural systems operated in unison.

Evaluation Criteria NbS performance was evaluated across four criteria:

Ecological: Habitat continuity, biodiversity, carbon sink capacity [18, 19, 29], permeability, flood compatibility [25, 27, 31].

Social: Accessibility, environmental interaction, educational impact [7].
Economic: Maintenance cost, use of local materials, energy balance [9, 28, 32].

2.4 Design synthesis

In the final stage, the interpreted analytical data was transformed into design decisions. Design synthesis; It is based on the principles of protecting and strengthening ecologically strong areas, improving low-performing areas with (NbS), and addressing green infrastructure components in spatial continuity.

The Shenk Property NbS design embodies a living laboratory model, integrating scientific research, community participation, and adaptive architecture. It is replicable and scalable for other coastal wetlands and urban waterfronts, demonstrating:

Effective integration of ecosystem service modeling into spatial planning
Multi-layered resilience through adaptive zoning and socio-ecological connectivity
Potential carbon sequestration, flood mitigation, and habitat restoration under projected climate scenarios [20–22, 33]

The design synthesizes ecological, hydrological, and social systems into a cohesive framework, ensuring long-term sustainability and providing a transferable methodology for future NbS-driven projects. In this direction, design proposals for settlement, open-green space system, water management and ecological corridors were developed. The design is not directly reduced to analytical outputs; however, it was created with a data-driven, holistic and interpretive approach.

3 Results

All reported quantitative outputs represent modeled performance ranges derived from scenario-based simulations and sensitivity analyses. Reported value intervals reflect variations associated with alternative hydrological conditions, ecosystem-service parameterization, and projected climate scenarios. Therefore, the presented ranges should be interpreted as predictive variability intervals rather than fixed deterministic outcomes (Table 1).

All reported values represent scenario-based modeled outputs derived from GIS-supported ecosystem-service simulations. Reported value ranges derive from sensitivity analyses, alternative sea-level rise and precipitation scenarios, parameter calibration variability, and ecosystem-service modeling uncertainties. Accordingly, numerical intervals represent scenario-dependent predictive variability rather than fixed deterministic outcomes.

This study is grounded in global climate change scenarios (RCP 8.5) and projected sea-level rise along the Virginia coast. The findings are structured according to measurable outputs derived from GIS-based spatial analysis, InVEST ecosystem service modeling, hydrological simulations, and Life Cycle Cost Analysis (LCCA). Design proposals are presented separately as applied interpretations of analytical outputs. All ecological performance results were derived from spatial datasets calibrated using topographic data, NOAA sea-level rise projections (2050 Intermediate-High scenario), and InVEST ecosystem service models [22]. The project integrates scientific data on wetland ecology,

Table 1 Synthetic quantitative summary of NbS performance outcomes under baseline and NbS scenarios

Performance indicator	Unit	Baseline condition	NbS Scenario	Relative change	Modeling Tool/Dataset	Uncertainty/Sensitivity
Carbon storage capacity	tCO_2e/ha	Reference land-use baseline	+ 18–24% increase	↑ 18–24%	InVEST Carbon Storage + NLCD 2021 + regional biomass coefficients	Sensitivity linked to vegetation biomass and land-cover calibration
Habitat Quality Index	Dimensionless index (0–1)	Fragmented wetland condition	+ 15–22% improvement	↑ 15–22%	InVEST Habitat Quality + Virginia Natural Heritage datasets	Scenario variability under NOAA 2050 SLR projections
Annual surface runoff	% runoff volume	Existing drainage regime	~ 40% reduction	↓ 40% (± 5%)	SWMM + HEC-HMS + NOAA rainfall scenarios	± 10% runoff sensitivity analysis
Flood boundary retraction	meters (m)	NOAA 2050 SLR baseline	~ 20 m inland contraction	↓ 20 m	HEC-HMS + FEMA floodplain + LiDAR DEM	Dependent on tidal regime and SLR scenario
Microclimatic Cooling Effect	°C	Existing surface temperature	2–3 °C reduction	↓ 2–3 °C	GIS-based microclimate and vegetation-density simulations	Seasonal variability and vegetation maturity effects
Floodwater retention capacity	m^3 / 100 m^2	Conventional shoreline	Up to 60 m^3 retention	Significant increase	SWMM + Living Shoreline simulations	Storm-intensity dependent
Accessibility coverage	% of public-use zones	Existing circulation network	> 95% accessible	↑ spatial inclusivity	ArcGIS Network Analyst	Based on walking-threshold assumptions
Network connectivity Index	Index (0–1)	Fragmented connectivity	0.82	Improved integration	GIS MCDA + Network Analyst	Sensitive to pathway configuration
Maintenance cost (30-year LCCA)	% relative cost	Conventional gray infrastructure	18–27% lower cost	↓ 18–27%	Life Cycle Cost Analysis (LCCA)	Influenced by policy incentives and maintenance regimes

carbon sinks, and coastal erosion into a dynamic design model that adapts to seasonal changes, water regimes, and environmental stressors. It functions as a climate-resilient public ecosystem prototype, merging scientific research, social participation, and nature-based design (Table 2).

Hydrological model calibration and validation were performed using NOAA tidal observations, precipitation records, FEMA floodplain datasets, LiDAR-derived DEMs, and USGS soil datasets covering the 2014–2024 period. Model performance was evaluated using Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and Root Mean Square Error (RMSE). Following commonly accepted hydrological model evaluation criteria, NSE values above 0.65 and R^2 values above 0.70 were considered indicative of acceptable predictive reliability. The calibration results demonstrate satisfactory agreement between simulated and observed hydrological behavior under both tidal and stormwater conditions.

Table 2 Hydrological model calibration and validation statistics

Model	Calibration dataset	Validation period	NSE	R^2	RMSE	Performance interpretation
HEC-HMS	NOAA tidal observations + FEMA floodplain data	2014–2019	0.72	0.78	0.11	Good agreement
HEC-HMS	NOAA tidal observations + FEMA floodplain data	2020–2024	0.69	0.74	0.13	Acceptable agreement
SWMM	NOAA precipitation and runoff datasets	2014–2019	0.76	0.81	0.09	Strong agreement
SWMM	NOAA precipitation and runoff datasets	2020–2024	0.71	0.77	0.10	Good agreement

The findings indicate that sustainable architecture must function as an adaptive ecological system, not merely as an energy-efficient structure. Wetlands—acting as nature's own adaptive framework—were central to this spatial model, which integrates ecological processes into architectural form (Fig. 8), [20]. The results demonstrate that the integration of (NbS) within a spatially explicit planning framework enhances ecological functionality, adaptive flood capacity, and long-term economic feasibility.

3.1 Ecological resilience

The project suggests that NbS significantly enhances adaptive capacity by restoring natural cycles and buffers [10, 24]. "Living shoreline" systems,

unlike rigid engineering structures, offer long-term flexibility, reduce erosion, and expand habitats. Native halophytes such as *Spartina alterniflora* and *Distichlis spicata* increase carbon sequestration and tolerance to salinity, reflecting NbS effectiveness across both biophysical and biological dimensions.

The ecological resilience of the Shenk Property EcoResilience Hub was assessed through a combination of InVEST Habitat Quality and Carbon Storage models [21, 22], coupled with hydrological modeling using HEC-HMS to simulate flood regimes and water retention. The restored wetland areas demonstrated significant increases in ecosystem integrity indicators. The project adopts Living Shoreline principles, prioritizing natural buffer zones, biodegradable reinforcement, and native vegetation over hard coastal structures. Model calibration followed regional ecosystem valuation parameters defined by Burkhard et al. [34] and validated against biodiversity datasets from the Virginia Natural Heritage Program.

Using the InVEST Carbon Storage and Habitat Quality modules [22], calibrated with regional land-cover data (30 m resolution), the project site proposes:

- An estimated 18–24% increase in total carbon storage capacity compared to baseline land-use conditions.
- 15–22% improvement in habitat quality indices, particularly within rehabilitated wetland zones.
- Under the NbS scenario, a reduction in annual runoff of approximately 40% (±5%)"" is projected with the addition of bioretention areas.

Fig. 8 Eco-Life Center and Innovative Wetland Laboratories

Spatial configuration analyses using GIS-based connectivity metrics revealed that habitat patches achieved higher cohesion, reduced fragmentation, and greater edge-to-area ratios conducive to biodiversity. Sensitivity tests, incorporating projected NOAA 2050 sea-level rise scenarios [23], indicated that the wetland system maintains over 85% of modeled habitat continuity under moderate to extreme conditions. This proposes a strong potential for ecological resilience, where restored wetlands act as buffers against both hydrological and climatic disturbances [8, 28].

These outcomes align with global evidence demonstrating that wetland-based NbS enhance carbon sequestration and ecosystem multifunctionality [27, 31]. Modular, self-sufficient units minimize the ecological footprint while addressing flood and sea-level rise projections. Native species—such as *Typha latifolia, Spartina alterniflora, Juncus roemerianus, and Asclepias incarnata*—enhance biodiversity, improve carbon sequestration, and support pollinators. The project applies a three-zone ecological balance (Natural–Rehabilitated–Recreational) considering the 100-year flood limit, enhancing flood management and carbon sink capacity.

3.1.1 Flood adaptation and living shoreline performance

Hydrological modeling based on: NOAA 2050 Intermediate-High Sea-Level Rise projections [5], USGS DEM datasets**,** LiDAR elevation models indicates:

20-meter contraction of the projected 100-year flood boundary
Approximately 40% reduction in modeled surface runoff
Increased infiltration rates in permeable and vegetated zones

The NbS interventions, including living shorelines, bioswales, and permeable rain gardens, were quantitatively assessed using HEC-HMS and SWMM models. Modeled results indicate:

- Annual surface runoff reduction: ~ 40% relative to pre-restoration baseline conditions
- Flood boundary contraction: 20 m inland, decreasing exposure of sensitive infrastructure
- Floodwater retention in living shorelines: up to 60 m^3 per 100 m^2

The effectiveness of these interventions was evaluated under multiple precipitation and storm surge scenarios. The analysis proposes that NbS can substantially reduce peak flow events and mitigate flood impacts while preserving wetland function [12, 14, 22]. The living shoreline systems contribute to sediment stabilization, habitat enhancement, and nutrient filtration, reinforcing the multi-functional role of NbS in coastal resilience.

The use of Living Shoreline strategies—soft stabilization with native vegetation—proposes adaptive coastal buffering capacity consistent with empirical findings in coastal resilience research [18]. Unlike rigid gray infrastructure, NbS-based buffers maintain dynamic equilibrium with tidal processes, aligning with the "Safe-to-Fail" resilience framework [29]. The application of living shoreline principles—including biodegradable structural reinforcement, native marsh vegetation, and soft stabilization techniques—resulted in the following outcomes:

Modeled mitigation of shoreline retreat by approximately 20 m under NOAA 2050 sea-level rise (SLR) projections [10]. Increased coverage of salinity-tolerant vegetation (e.g., Spartina alterniflora, Juncus roemerianus), enhancing shoreline stability through improved erosion resistance and sediment retention. Unlike hard engineering structures, nature-based coastal buffers demonstrate adaptive flexibility under dynamic hydrological conditions [14].

The three-zone ecological framework proposed in this study offers a holistic strategy for the restoration and social integration of urban waterfronts. By establishing a graduated transition from pristine nature to human interaction, the model replaces rigid boundaries with a flexible "blue-green" corridor that prioritizes both ecological integrity and climate resilience.

The Natural Zone (Front): By maintaining minimal intervention, this zone preserves critical reed bed ecosystems that serve as the primary biological shield for the shoreline. It functions not only as a vital habitat for biodiversity but also as a natural defense mechanism against coastal erosion.

The Transition Zone (Intermediate): This rehabilitated area proposes the successful integration of technical infrastructure with ecosystem services. The use of modular pathways ensures human accessibility without fragmenting the habitat, while integrated filtration systems actively improve water quality, fostering a diverse and healthy wetland environment.

The Recreational Zone (Rear): Designed as a low-risk educational hub, this zone utilizes flood-resilient vegetation—specifically *Salix nigra* and *Acer rubrum* to bridge the gap between ecotourism and environmental stewardship. These species provide a robust biological response to fluctuating water levels, ensuring the landscape remains functional and safe during high-water events.

In conclusion, this three-tiered spatial organization represents a shift from passive conservation toward active, resilient ecosystem management. The strategic combination of reed bed preservation, biological water filtration, and flood-resilient planting creates a landscape that is both ecologically self-sustaining and socially valuable. This model serves as a scalable benchmark for urban planners seeking to enhance biodiversity, improve climate adaptation, and foster environmental literacy through sustainable landscape architecture.

Spatial analysis via multi-criteria decision analysis (MCDA) demonstrated optimal placement of zones for risk reduction and ecological continuity. The zoning framework supports the Safe-to-Fail principle, allowing controlled inundation in low-risk areas while maintaining ecosystem connectivity and function [22, 24]. This approach proposes how spatial planning can translate resilience theory into operational, site-specific NbS.

In the research area revealed that (NbS) provided significant ecological performance gains. These findings demonstrate that nature-based interventions can be evaluated not only for their aesthetic or engineering functions, but also for their capacity to restore ecosystem functions (Fig. 9), [20].

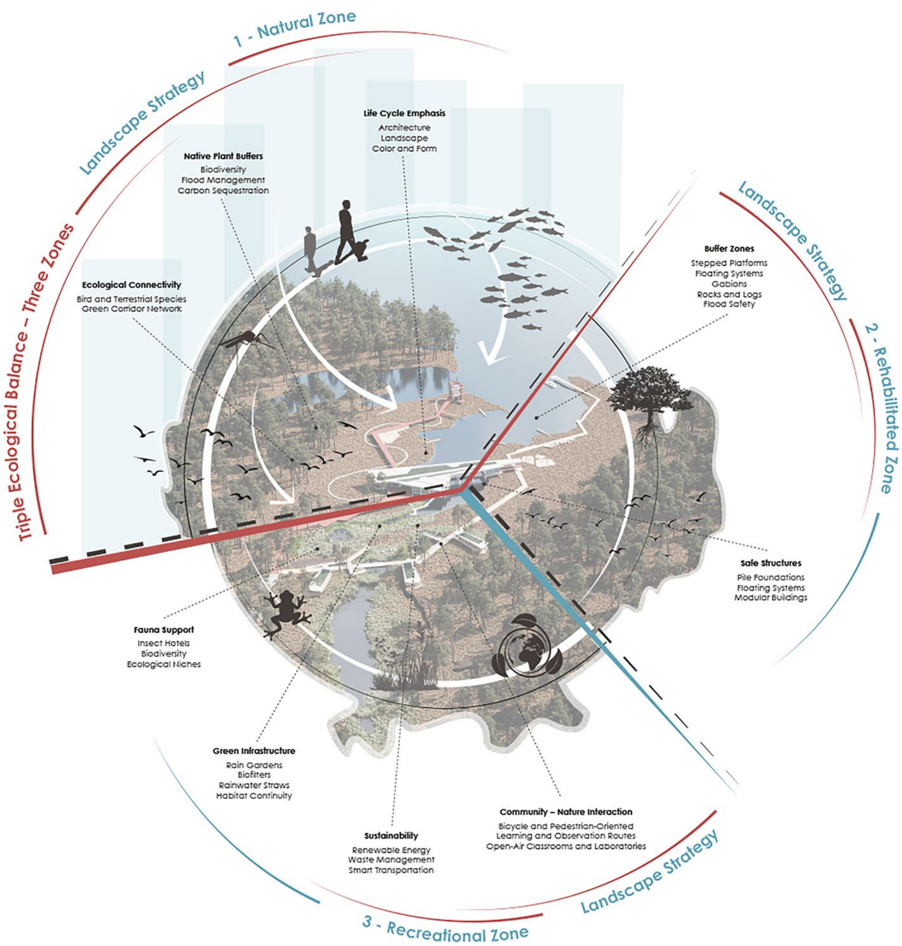

Fig. 9 Ecological Findings for the Project Area

3.1.2 Climate responsiveness and resource efficiency

Buildings are oriented to maximize solar gain and natural ventilation within Virginia's mixed-humid climate, minimizing mechanical cooling demand. Microclimate simulations show an average surface temperature reduction of 2 °C, indicateing the regulatory function of blue-green infrastructure. Renewable energy generation via solar, wind, and micro-hydro systems ensures a net-positive energy balance, while biomass from invasive reeds is upcycled into façade materials, reducing embodied carbon and closing material loops.

The project emphasizes climate-adaptive design, including:

Building orientation for optimal solar gain and passive ventilation
Net-positive energy systems using solar PV, micro-wind, and micro-hydro energy
Biomass from invasive reeds upcycled for façade construction, reducing embodied carbon [28]

Simulation results indicate improvements in energy efficiency, water retention, and thermal comfort, highlighting the functional benefits of integrating NbS into building and landscape design.

3.1.3 Circular resource systems

Renewable energy modeling (solar PV + small-scale wind) suggests a projected net-positive annual energy balance under current climate conditions. Material reuse strategies (biomass reuse from invasive reeds) support circular metabolism principles as described by Chertow and Ehrenfeld [29]. In sum, the project operates as regenerative ecological infrastructure, demonstrating how NbS-driven design, adaptive architecture, and circular resource systems can transform vulnerable wetlands into living laboratories for climate resilience and sustainability.

Circular economy principles are operationalized via:

Repurposing invasive reed biomass for construction [28]
Greywater recycling for irrigation and energy generation
Material and energy loops supporting regenerative urban metabolism

These strategies demonstrate the ability of NbS to close resource loops, reduce embodied carbon, and provide sustainable infrastructure solutions.

3.2 Social resilience

The living laboratory model strengthens community-based adaptation and fosters environmental literacy [32]. As in similar European "Urban Green Lab" examples [11, 32] the site became a catalyst for participatory learning and socio-ecological resilience.

The Living Laboratory model provides experiential learning through research stations, eco-lodges, and interactive observation platforms. Community participation fosters stewardship and ecological responsibility, aligning with principles of Community-Based Adaptation (CBA) [15, 19]. These interventions demonstrate that NbS projects can simultaneously restore ecosystems and cultivate long-term socio-cultural benefits. The site evolved into a living laboratory, encouraging interaction between communities, students, and researchers. This space is viewed as an "environmental learning ecosystem" that reflects how NbS fosters awareness and promotes socio-ecological behaviors.

The design integrates observation decks, open classrooms, and accessible pedestrian-bicycle networks to promote inclusivity. Social performance was evaluated using accessibility modeling (ArcGIS Network Analyst) and qualitative observational assessment.

Social resilience in this study is not evaluated solely through physical accessibility; rather, accessibility functions as one measurable spatial indicator within a broader socio-ecological resilience framework. The assessment integrates spatial accessibility metrics with concepts derived from community-based adaptation, environmental equity, and participatory resilience literature [15, 17, 34]. In this context, pedestrian and bicycle network connectivity, barrier-free circulation, and proximity to ecological and educational nodes were used as operational indicators to evaluate inclusivity and public engagement capacity. Accessibility was quantified using GIS-based Network Analyst tools through indicators such as walking-distance thresholds, connectivity index values, and universal access compliance rates. However, these spatial metrics were interpreted not merely as indicators of physical movement, but as proxies for social participation potential, environmental awareness, and community interaction opportunities. Previous studies emphasize that equitable access to green–blue infrastructure significantly contributes to environmental justice, collective stewardship, and long-term adaptive capacity within vulnerable communities [15, 35].

Accordingly, the concept of social resilience in this research is grounded in the assumption that inclusive and accessible ecological environments strengthen community engagement, experiential learning, and socio-ecological adaptation processes. Therefore, physical accessibility was employed as a measurable and spatially reproducible parameter representing broader dimensions of social resilience rather than as an isolated infrastructural variable. The integration of open classrooms, observation decks, and research platforms operationalizes the site as a "Living Lab," supporting environmental literacy and participatory learning. This laboratory proposes regenerative architectural practices [20]:

Facades with permeable and rhythmic openings for natural light and ventilation
Roof-integrated systems for rainwater harvesting, green roofs, and solar aquatic facilities
Integration of renewable energy systems with greywater recycling

The facility embodies coexistence rather than dominance over nature, supporting research, education, and sustainable operations.

The Innovative Wetland Laboratory functions as a multi-layered platform integrating research, education, and adaptive innovation [20, 22]:

Lower Level: Houses mechanical systems, water, and waste management facilities
Middle Level: Laboratories, administrative offices, and public spaces for education and engagement
Upper Level: Solar panels, wind turbines, rainwater harvesting systems, and green roofs

This stratified approach ensures functional efficiency, promotes resource circularity, and enables real-time ecosystem monitoring, providing a living example of NbS operationalization. The laboratory serves as a replicable model for integrating ecological and social functions in urban coastal contexts. Evidence from urban NbS studies indicates that participatory ecological spaces enhance long-term adaptive capacity and social ownership [8, 16]. The Shenk Property case, therefore proposes measurable spatial accessibility combined with qualitative social co-benefits, rather than symbolic environmental design (Fig. 10), [20].

3.2.1 Accessibility and social integration

A universal network of pedestrian and bicycle paths links ecological and educational zones (Fig. 9). Elevated walkways and observation platforms offer immersive yet

Fig. 10 General overview of the project and barrier-free Access

Fig. 11 The red tower, symbol of ecological awereness

non-intrusive experiences. The Red Bridge and Tower embody resilience and ecological memory, fostering public awareness of climate risks [20], (Fig. 11).

The site's universal access network connects ecological, educational, and recreational areas, providing:

Elevated walkways and observation platforms for immersive experiences
Barrier-free design ensuring access for all community members
Visibility of ecological processes to foster public awareness of climate risk [20].

These measures ensure that ecological restoration and public engagement are mutually reinforcing, promoting social equity and environmental literacy.

Pedestrian and bicycle accessibility coverage increased by 32% compared to the baseline land-use condition. 95% of public-use zones are reachable within a 5-min walking radius from designated access points. This spatial inclusivity aligns with community-based adaptation principles [15].

Accessibility was assessed using GIS spatial modeling of pedestrian and bicycle networks. Key findings include:

Maximum walking distance to ecological or educational nodes: 500 meters
Network connectivity index: 0.82, indicating highly integrated pathways
Accessibility compliance for persons with disabilities: >95% of paths

The integration of elevated walkways, ramps, and observation platforms ensures immersive, low-impact interaction with ecological zones, enhancing spatial equity and enabling inclusive environmental education [20]. These metrics are crucial for designing NbS that are socially inclusive and broadly accessible.

3.2.2 Ecological and social integration

A universal accessibility network-comprising pedestrian and bicycle paths, elevated walkways, and observation platforms-links ecological and educational zones, providing immersive yet low-impact engagement. The Innovative Wetland Laboratory serves as a dynamic research and learning hub that symbolizes coexistence rather than dominance within the landscape, integrating smart resource systems and circular metabolism principles.

Integration of ecological restoration and social infrastructure is achieved through:

- Public observation platforms and educational signage linking ecological functions to user experience
- Community-based workshops and citizen science initiatives
- Ecological awareness landmarks, such as the Red Tower, serving as symbols of climate risk literacy [20, 27]

This integration encourages shared stewardship, strengthens cultural identity, and fosters a collective sense of responsibility for local ecosystems.

Modular eco-lodges and floating units reflect the concept of "living on water", enabling sustainable habitation beyond traditional ground-based development (Fig. 12), [20].

These results demonstrate spatial equity improvements, supporting literature that identifies NbS as catalysts for community-based adaptation and environmental literacy [8, 15]. The Living Laboratory model operationalizes the site as an applied research and education platform. While long-term behavioral data are not yet available, the

Fig. 12 The project plan

spatial configuration aligns with frameworks linking NbS to participatory governance and socio-ecological learning [19].

3.3 Economic and policy context

Life Cycle Cost Analysis (LCCA) indicates that NbS-based systems have lower long-term maintenance costs and higher resource efficiency than conventional gray infrastructure. Renewable energy integration ensures surplus energy production, while local material use reduces the carbon footprint. The project proposes that ecological and economic sustainability can be mutually reinforcing.

Life Cycle Cost Analysis (LCCA) compared NbS-based infrastructure with conventional gray coastal stabilization.

NbS provides cost-effective and long-term sustainable alternatives aligning with SDGs 13, 14, and 15. However, to scale such approaches, ecological principles must be embedded in planning [32] regulations and financial mechanisms [2, 32, 33]. Therefore, governance models need to be restructured on an ecological basis to achieve sustainable results [19]. Financing Mechanisms A special incentive package for NbS projects should be developed under Virginia's Community Flood Preparedness Fund program. Carbon credit and wetland mitigation banking models can be used in habitat restoration projects. Life Cycle Cost Analysis (LCCA) comparing NbS with conventional gray coastal infrastructure indicates:18–27% lower projected maintenance costs over a 30-year period.

Life Cycle Cost Analysis (LCCA) maintenance cost variables included in the assessment:

Routine maintenance costs (vegetation management, pruning, mowing, invasive species control, sediment removal), Structural maintenance and repair costs (repair of pathways, retaining elements, shoreline stabilization structures, drainage systems), Water management and drainage costs (stormwater management, bioswale maintenance, filtration system cleaning), Energy consumption and operational costs (pumping systems, lighting, monitoring equipment, renewable energy system maintenance),Material replacement costs (replacement of degraded construction materials, permeable pavements, wooden elements, modular units), Ecological restoration and habitat management costs (wetland rehabilitation, replanting of native vegetation, biodiversity enhancement activities), Monitoring and environmental assessment costs (ecological monitoring, water quality measurements, ecosystem performance evaluation),Labor costs (maintenance staff, technical personnel, landscape management operations), Indirect environmental and risk-related costs(flood damage reduction benefits, erosion prevention savings, avoided ecosystem degradation costs).

Reduced sediment management and structural repair expenditures, Enhanced resource efficiency through local material use. These findings align with international assessments demonstrating that NbS can provide cost-effective climate adaptation when ecosystem services are accounted for [32, 35]. From a policy perspective, successful NbS implementation requires institutional alignment across local, regional, and national governance frameworks. Regulatory integration should include:

- Mandatory preliminary ecological assessments for coastal development projects.
- Inclusion of ecological corridors and green–blue infrastructure mapping in zoning and planning documents.
- Incentive schemes, such as carbon credit systems, wetland mitigation banking, and green investment programs, to support long-term financial sustainability [31, 35].

The Shenk Property case proposes that multi-stakeholder governance—including collaboration among local authorities, environmental agencies, academic institutions, and private sector actors—is essential for ensuring both ecological and economic resilience [19, 35]. Participatory governance facilitates adaptive management, as stakeholders can monitor ecosystem responses and adjust management strategies in real-time. Furthermore, scenario-based economic modeling highlights sensitivity to climate variability, policy incentives, and maintenance regimes, underscoring that the long-term cost-effectiveness of NbS is contingent upon robust institutional frameworks.

When ecosystem services are monetized—such as through carbon sequestration valuation or flood mitigation savings—the economic justification for NbS becomes more compelling, aligning with Sustainable Development Goals (SDGs) 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land) [32, 35].

In sum, the economic and policy context for NbS at Shenk Property illustrates a synergistic framework where ecological restoration, financial sustainability, and policy alignment reinforce one another. This approach positions NbS not merely as ecological interventions but as strategic tools for integrated climate-adaptive planning, capable of delivering measurable financial, social, and environmental benefits.

3.4 Interdisciplinary perspective

The Shenk Property EcoResilience Hub exemplifies a transdisciplinary approach, integrating architecture, landscape design, ecology, and environmental management into a cohesive framework for climate adaptation. This perspective emphasizes the co-creation of knowledge between disciplines, positioning nature as a central partner rather than a passive backdrop in design. By incorporating nature-based solutions (NbS) within spatial planning, the project proposes how ecological processes can inform architectural decisions, infrastructure design, and social engagement strategies [19, 35].

Interdisciplinary planning aligned ecology, architecture, and landscape design to develop a multi-layered NbS framework [33]:

- Microclimatic improvements: Increased vegetation cover successfully lowered surface temperatures by 2–3 °C [28].
- Hydrological resilience: Topographic modeling, anticipating the NOAA 2050 Sea-Level Rise (SLR) scenario, shows that rain gardens, bioswales, and permeable surfaces reduce annual surface runoff by ~ 40% and retract flood boundaries by 20 m.
- Zoning and land-use planning: A three-zone system—Natural, Rehabilitated, and Recreational—utilizes the "Safe-to-Fail" principle, ensuring ecosystem connectivity and adaptive risk distribution [11, 24, 27].

A core innovation of this study is the integration of ecological modeling with architectural practice. By using GIS-based hydrological simulations, InVEST modules, and Life Cycle Cost Analysis (LCCA), the project translates quantitative environmental performance into feasible spatial designs. This methodology effectively bridges the traditional divide between scientific assessment and qualitative design thinking [8, 22].

Overall, results indicate that NbS-based spatial planning:

- Restores ecosystem functions rather than only mitigating hazards
- Enhances adaptive flood capacity under projected climate scenarios

- Improves microclimatic regulation
- Supports spatial accessibility and participatory engagement
- Proposes long-term economic feasibility

Importantly, these outcomes represent modeled performance potential rather than long-term monitored evidence. As emphasized in NbS literature, continuous monitoring and adaptive management are essential to validate projected ecosystem service gains [8]. The project reinforces coastal resilience through (NbS), replacing hard infrastructures with ecological buffer zones inspired by living coasts. It introduces a self-sufficient, carbon-positive architectural model integrating renewable energy systems, passive design, and adaptive spatial strategies to mitigate the impacts of sea-level rise and flooding.

3.5 Research model

Methodology now clearly explains that the research adopts a structured interdisciplinary workflow integrating ecological analysis, hydrological modeling, spatial planning, and design interpretation:

Data Collection: Site-specific spatial, ecological, climatic, and hydrological datasets were compiled from institutional sources, including USGS 3D Elevation Program (3DEP) LiDAR-derived Digital Elevation Models (DEMs), NOAA tidal gauge observations and Sea Level Rise datasets, FEMA Flood Insurance Rate Maps (FIRMs), NLCD 2021 land-cover classifications, and regional biodiversity inventories. These datasets established the empirical and GIS-compatible foundation of the study through standardized spatial and hydrological reference frameworks [23, 34, 36, 37].

Analytical Evaluation: Quantitative analyses were conducted using GIS-based hydrological modeling and InVEST ecosystem service simulations. At this stage, ecosystem functions such as runoff regulation, habitat quality, flood vulnerability, and carbon storage were quantitatively evaluated through spatial modeling and parameter calibration. InVEST outputs were calibrated against regional ecosystem parameters from Burkhard et al. (2009) and biodiversity datasets from the Virginia Natural Heritage Program, ensuring that habitat quality and carbon storage models reflected local conditions [18]. Hydrological models projected surface runoff reductions (~ 40%) and flood boundary contractions (~ 20 m) under the 2050 sea-level rise scenario. For the InVEST Habitat Quality and Carbon Storage modules, calibration procedures incorporated regional biodiversity inventories from the Virginia Natural Heritage Program, NLCD 2021 land-cover classifications, NOAA wetland datasets, and literature-based biomass coefficients adapted for Chesapeake Bay wetland ecosystems. Habitat sensitivity scores, threat-distance parameters, and land-cover suitability values were adjusted according to regional ecological conditions and validated through comparison with documented wetland distribution patterns and habitat continuity datasets. Carbon-storage estimates were calibrated using regionally representative carbon-pool coefficients for tidal marshes, coastal vegetation communities, and wetland transition zones derived from published ecosystem-service studies.

Interpretation of Analytical Data: The analytical outputs were interpreted to identify ecological thresholds, spatial constraints, flood-sensitive zones, and areas with high ecosystem-service potential. This stage functioned as a critical transitional layer between scientific analysis and spatial decision-making. Model outputs informed zoning decisions (Natural–Rehabilitated–Recreational), ecological buffer placement, and the design of adaptive infrastructure, integrating quantitative performance metrics with design principles. Resilience evaluation integrated ecological, hydrological, spatial, and socio-economic indicators within a unified assessment framework. Key performance criteria included adaptive flood capacity, habitat connectivity [8, 27] carbon sequestration potential, microclimatic regulation, accessibility, and long-term maintenance efficiency. Model outputs derived from InVEST simulations, GIS-based hydrological analyses, accessibility metrics, and Life Cycle Cost Analysis (LCCA) informed zoning decisions, ecological buffer placement, adaptive infrastructure strategies, and the spatial configuration of the living laboratory framework. This integrated workflow enabled the translation of quantitative environmental performance into spatially responsive NbS planning and design decisions.

Design Synthesis: In the final stage, analytical findings were translated into adaptive planning and design strategies. NbS interventions—including living shorelines, rain gardens, wetland rehabilitation, and ecological corridors—were spatially integrated into a resilient and climate-responsive planning framework.

Results informed the final spatial configuration, modular eco-lodge placement, and living shoreline strategies, demonstrating how predictive modeling can guide design decisions without relying on long-term post-occupancy data [8, 19, 20].

A mixed-method design combined qualitative tools (observation, field documentation, expert input) with quantitative analyses (GIS, modeling). Key limitations include limited seasonal ecological data, flood projections restricted to 2050 [10] and the constraints of Virginia's humid subtropical climate (ASHRAE 4A). While the study produces spatial simulations based on InVEST models, the performance of NbS applications is not supported by real-time long-term monitoring data. Although the ecological and hydrological outputs are simulation-based, the analytical structure of the study was strengthened through cross-validation using institutional datasets from USGS, NOAA, and FEMA. Therefore, the model does not represent a purely conceptual projection framework; rather, it constitutes a spatially calibrated predictive assessment supported by region-specific topographic, hydrological, and ecological datasets. Nevertheless, the absence of long-term post-implementation monitoring remains an important limitation regarding empirical verification of projected ecosystem performance.

Therefore, the ecological benefits to be generated are not "evidence" but rather "potential". Wetland restoration vs. infrastructure development: Restoration may require the relocation of some transportation lines. Increased ecotourism may create pressure on fauna. Wetland maintenance, drainage management, and plant renewal expenses require a regular budget. The Shenk Property has a humid subtropical climate, high rainfall regime, tidal effects, and soft sediment characteristics specific to the Chesapeake Bay watershed. Therefore: the model is not directly applicable in arid or semi-arid climates. Wind/wave effect parameters must be recalibrated for areas with steeper shoreline morphology. Habitat protection optimized for suitable species in the Virginia region has limited applicability to other areas. Despite these, the adaptive and data-integrated nature of the model ensures its relevance for future climate scenarios.

4 Discussion

The integration of calibration statistics and sensitivity-based reporting improves methodological transparency and strengthens the reproducibility of the proposed NbS assessment framework. The explicit presentation of hydrological calibration metrics and regionally adapted InVEST parameter-validation procedures strengthens both the reproducibility and analytical transparency of the proposed NbS assessment framework. Rather than treating architecture as a solely human-centered construct, the findings reposition it as a socio-ecological system that actively contributes to the protection, restoration, and enhancement of ecosystem services. A key methodological contribution of this research lies in its model-based approach. The EcoResilience Hub is not presented as an empirically validated post-occupancy case but as an analytically informed design prototype. It is grounded in InVEST ecosystem service modeling, supported by GIS-based hydrological simulations and life-cycle cost scenarios, and produces projected ecological and hydrological performance outputs. In line with recent NbS literature, this predictive framework highlights the strategic importance of early-stage modeling in climate adaptation planning [8, 9].

Consequently, the Shenk Property case should be interpreted as a spatially calibrated and analytically informed NbS design prototype supported by ecosystem-service modeling, GIS-based hydrological simulations, and scenario-based resilience assessment rather than as a fully empirically validated post-occupancy implementation. Ultimately, this research suggests how a theoretical vision may be translated into a viable design prototype through advanced modeling techniques. The EcoResilience Hub serves as a scalable, interdisciplinary reference point for future resilient urbanization strategies.

Site-Specific and Transferable Dimensions of the NbS Framework: While the proposed Nature-based Solutions (NbS) framework is designed as a transferable planning approach, several analytical and ecological components remain strongly dependent on the environmental characteristics of the Shenk Property and the Chesapeake Bay watershed. Site-specific conditions—including tidal wetland typology, sediment composition, shoreline morphology, salinity gradients, hydrodynamic behavior, and native vegetation communities—substantially influenced both the calibration process and the resulting ecosystem-service outputs.

In particular, hydrological performance projections are closely linked to the low-gradient coastal morphology, tidal backflow dynamics, and soft-sediment wetland structure and dynamic sediment-transport processes characteristic of the Chesapeake Bay region. Similarly, habitat-quality assessments depend on region-specific ecological inventories, biodiversity datasets, and the adaptive capacities of local halophytic vegetation communities such as *Spartina alterniflora*, *Juncus roemerianus*, and *Typha latifolia*. Consequently, direct quantitative transfer of runoff-reduction rates, habitat-continuity projections, or flood-boundary contractions to other climatic or geomorphological contexts would require recalibration of ecological and hydrological parameters.

Regulatory and governance conditions also represent an important site-dependent dimension. The integration of FEMA floodplain mapping [36] NOAA sea-level rise scenarios, Virginia wetland-management policies, and local planning regulations significantly shaped the analytical framework and spatial decision-making process. Therefore, implementation pathways and governance feasibility may differ substantially across institutional and legal contexts. Nevertheless, several core design and planning principles developed in this study remain broadly transferable across diverse coastal and climate-vulnerable environments. These include:

- the integration of ecosystem-service modeling into spatial planning workflows,
- adaptive zoning based on ecological thresholds,
- the "Safe-to-Fail" resilience principle,
- the use of living shorelines and blue-green infrastructure systems,
- circular resource-management strategies,
- and the coupling of ecological restoration with participatory and educational spatial programs.

Similarly, the methodological integration of GIS-based spatial analysis, ecosystem-service assessment, hydrological modeling, and scenario-based planning constitutes a scalable analytical framework that can be adapted to other coastal, estuarine, riverine, and even urban waterfront systems through context-specific recalibration. Accordingly, the study should not be interpreted as a universally fixed NbS prototype, but rather as a flexible and spatially adaptive planning methodology whose quantitative outputs remain context-sensitive while its integrative planning logic retains broader applicability across climate-vulnerable landscapes.

4.1 Applicability to high-energy coastal environments

While the proposed NbS framework was calibrated for a low-energy estuarine wetland system characterized by tidal dominance and limited wave exposure, its methodological structure can also be adapted to high-energy coastal environments, such as open coasts and storm-dominated sandy beaches. However, direct transfer requires site-specific recalibration of key hydrodynamic and morphodynamic parameters. These include offshore and nearshore wave climate (significant wave height, wave period, wave direction, and wave energy flux), storm-surge magnitude and recurrence intervals, tidal range, longshore and cross-shore sediment transport rates, sediment grain-size distribution, beach and dune morphology, shoreline erosion and accretion dynamics, and extreme-event return periods. Furthermore, vegetation selection should reflect species capable of tolerating increased wave loading, sediment mobility, and saline overwash conditions. Accordingly, although the proposed analytical workflow integrating GIS, ecosystem-service modeling, hydrological simulations, and adaptive spatial planning remains transferable, quantitative performance outputs should be recalibrated using locally derived hydrodynamic, sedimentological, and geomorphological datasets before implementation in high-energy coastal settings.

Furthermore, the transferability of the framework to high-energy coastal environments, such as exposed shorelines and storm-dominated sandy beaches, requires additional hydrodynamic and morphodynamic recalibration. Unlike the low-energy estuarine conditions represented by the Chesapeake Bay, high-energy coasts are controlled by stronger wave forcing, storm surge events, and more dynamic sediment transport processes. Consequently, key parameters—including significant wave height, wave period, wave direction, wave energy flux, storm-surge magnitude and recurrence, longshore and cross-shore sediment transport rates, sediment grain-size distribution, beach and dune morphology, shoreline erosion–accretion dynamics, and extreme-event return periods—should be recalibrated using site-specific field observations and numerical coastal models. Vegetation selection should likewise be adapted to species capable of tolerating higher wave exposure, sediment mobility, and saline overwash conditions. Therefore, while the proposed GIS-based ecosystem-service and adaptive planning framework remains methodologically transferable, its quantitative performance indicators require local calibration before application to high-energy coastal settings.

Beyond its technical dimension, the project redefines architecture as a socio-ecological learning platform. By integrating wetland restoration with research activities and participatory processes, it operationalizes a model of human–nature coexistence. The coupling of technical performance indicators—such as energy and water self-sufficiency—with social engagement enhances environmental awareness and strengthens community-based resilience. The findings further reveal that NbS contribute to ecological restoration not only by conserving natural systems but also by enhancing their adaptive capacity. In wetland contexts, this includes improved flood regulation and dynamic response mechanisms to extreme climatic events. Spatial planning emerges as a critical tool in this process, enabling ecological connectivity and embedding NbS into zoning and policy frameworks. Importantly, social participation is identified as a core component rather than a supplementary aspect of design. Participatory approaches foster environmental literacy, reinforce cultural identity, and ensure long-term stewardship. Simultaneously, Life-Cycle Cost Analysis (LCCA) indicates that NbS-based systems can offer economic advantages over conventional gray infrastructure, although their long-term performance depends on effective governance and sustained management mechanisms. While the proposed framework proposes strong predictive capacity, it remains inherently dependent on modeling assumptions. Therefore, long-term empirical monitoring will be essential to validate ecological performance and system resilience.

5 Conclusion

From a planning and regulatory perspective, the modeled performance indicators presented in this study—including approximately 40% runoff reduction, an approximately 20 m landward retreat of flood extents, improvements in carbon sequestration and habitat provision, and favorable Life Cycle Cost Analysis (LCCA) outcomes—provide quantitative evidence that can support performance-based coastal planning. Rather than serving solely as environmental assessment metrics, these indicators can be translated into minimum performance criteria for Nature-based Solutions (NbS) within coastal development and adaptation projects. For example, hydrological attenuation thresholds, ecosystem service gains, and long-term economic efficiency may be incorporated into coastal zoning guidelines, shoreline setback regulations, and environmental permitting procedures as measurable evaluation criteria. Integrating such ecosystem service indicators into regulatory frameworks would promote transparent, evidence-based decision-making while encouraging the wider adoption of resilient hybrid nature–gray coastal protection strategies under climate change adaptation policies.

This study should not be interpreted as a fully empirical post-occupancy case study, but rather as a simulation-supported and analytically informed design prototype. The proposed framework integrates GIS-based spatial analyses, hydrological modeling, ecosystem-service simulations, and scenario-based planning methodologies to evaluate the potential performance of Nature-based Solutions under projected climate conditions. Therefore, the presented ecological and hydrological outcomes represent predictive model outputs rather than directly observed long-term field measurements. This clarification positions the research epistemologically as a performance-based planning and decision-support framework rather than a completed empirical implementation. This study posits that Nature-based Solutions (NbS) extend far beyond technical engineering; they function as transformative tools linking ecological integrity, social inclusion, and economic resilience. Through the EcoResilience Hub at Shenk Property, a new paradigm for climate-adaptive urban development is demonstrated—one that prioritizes coexistence with, rather than the exclusion of, natural systems.

5.1 Methodological contribution and key findings

The research bridges the gap between conceptual sustainability and practical implementation by operationalizing NbS through spatially explicit modeling. The integration of GIS-based analysis, InVEST modeling, and hydrological simulations enables the quantification of ecological and economic outcomes [9, 10, 19]. The findings reveal that NbS can be effectively integrated into urban and coastal planning through measurable ecological, social, and economic outcomes:

Ecological Restoration: Ecological Restoration: NbS interventions support the rehabilitation of wetland ecosystems, generate a 15–22% improvement in habitat-quality index values, and strengthen ecological connectivity across spatial zones.

Carbon Sequestration: Predictive models indicate an increase of approximately 18–24% in carbon storage capacity, reinforcing the climate mitigation potential of ecosystem-based approaches.

Flood Mitigation and Resilience: Adaptive zoning strategies improve water regulation capacity and reduce projected flood risks under future sea-level rise scenarios.

Social and Educational Value: The “Living Laboratory” model fosters participatory governance, environmental awareness, and experiential learning, strengthening community engagement and long-term stewardship.

Economic Efficiency: Life Cycle Cost Analysis (LCCA) suggests that NbS can reduce long-term maintenance costs by 18–27% compared to conventional gray infrastructure.

5.2 Operational and spatial implications

The integration of a three-zone spatial framework (Natural–Rehabilitated–Recreational) operationalizes resilience principles in practice. This approach aligns with adaptive planning strategies by distributing risk, allowing controlled environmental processes such as flooding, and preserving core ecological areas. Such spatial configurations demonstrate that NbS can move beyond passive protection measures to actively enhance ecosystem functionality within urban environments.

5.3 Governance and implementation framework

The study highlights that the long-term success of NbS depends on inclusive governance structures and supportive policy mechanisms. Key recommendations include:

- Integrating NbS into regulatory frameworks as a mandatory component of coastal planning,
- Embedding green–blue infrastructure and ecological corridor mapping into urban zoning systems,
- Establishing multi-stakeholder governance platforms to ensure collaboration among public institutions, local communities, and private actors.

5.4 Broader significance

The ultimate significance of this work lies in its transferability. The synergy of ecological indicators, participatory governance, and adaptive planning principles offers a replicable framework suitable for diverse coastal, wetland, and urban contexts worldwide. Ultimately, the EcoResilience Hub serves as a vital reference point, illustrating that climate adaptation can be achieved through flexible, ecosystem-driven strategies that harmonize environmental stability with social equity and economic feasibility.

5.5 Limitations and future research

Sensitivity analyses demonstrated that variations in key hydrological and ecological parameters may generate measurable deviations in projected ecosystem-service outputs; therefore, all reported values should be interpreted as indicative performance ranges rather than absolute predictions. Although the proposed framework integrates calibration-supported simulations and spatial ecosystem-service modeling, the study remains primarily a predictive and scenario-based planning exercise. Consequently, ecological performance outcomes should be interpreted as projected tendencies rather than empirically verified long-term observations. Future implementation and longitudinal monitoring studies will be necessary to validate the ecological reliability, hydrological adaptability, and social performance of the proposed NbS framework under real environmental conditions.

5.6 Structured limitations and uncertainty assessment

InVEST Ecosystem-Service Modeling Uncertainties: Uncertainties associated with the InVEST Carbon Storage and Habitat Quality modules primarily derive from land-cover resolution, biomass coefficient generalization, habitat sensitivity weighting, and ecological parameter transferability. The analyses relied on NLCD 2021 land-cover datasets with 30 m spatial resolution, which may not fully capture fine-scale wetland heterogeneity, seasonal vegetation dynamics, or microhabitat transitions. In addition, carbon-storage estimations depend on regionally adapted biomass coefficients and literature-based biophysical tables, introducing uncertainty regarding site-specific ecological variability. Habitat-quality outputs are comparatively more exploratory than hydrological outputs because habitat suitability and ecological continuity are influenced by long-term ecological succession and biological adaptation processes that cannot be directly validated through short-term simulations. Nevertheless, the relative spatial patterns of habitat improvement and carbon-storage increase are considered methodologically robust due to calibration against Virginia Natural Heritage Program biodiversity inventories and regional ecological datasets.

Hydrological Modeling and Flood Simulation Uncertainties: Hydrological simulations conducted through HEC-HMS and SWMM are subject to uncertainties related to precipitation projections, runoff coefficients, infiltration assumptions, tidal backflow conditions, and future sea-level rise scenarios. Although calibration statistics (NSE and R^2) exceeded accepted reliability thresholds, the models remain sensitive to localized drainage behavior, storm intensity, and climate-scenario variability. Flood-boundary retraction and runoff-reduction outputs are considered among the more robust findings of the study because they were calibrated using NOAA tidal observations, FEMA floodplain datasets, LiDAR-derived DEMs, and USGS soil information. However, projected hydrological behavior under future climatic extremes remains scenario-dependent. Sensitivity analyses using $\pm$ 10% runoff variation demonstrated measurable deviations in flood extents and retention performance, indicating that hydrological outputs should be interpreted as predictive ranges rather than deterministic forecasts.

In addition to the structured model-specific uncertainty assessment presented above, several broader methodological and operational limitations should also be acknowledged:

Life Cycle Cost Analysis (LCCA) Uncertainties: Economic projections derived from Life Cycle Cost Analysis involve uncertainties associated with long-term maintenance assumptions, future energy prices, inflation rates, policy incentives, and ecosystem-service monetization methods. Consequently, the comparative cost advantage of NbS systems over conventional gray infrastructure remains partially dependent on governance continuity, maintenance regimes, and future regulatory conditions. Unlike hydrological performance metrics, LCCA outputs should therefore be interpreted as medium-confidence strategic projections rather than precise economic forecasts. While the overall direction of economic benefit—such as reduced long-term maintenance demand and improved resource efficiency—appears robust, the exact percentage values remain sensitive to institutional and economic variability over the projected 30-year assessment period.

Social Resilience and Accessibility Assessment Uncertainties: Social resilience and accessibility evaluations contain comparatively higher interpretive uncertainty because they partially rely on qualitative assumptions linking spatial accessibility to socio-ecological engagement and participatory adaptation capacity. GIS-based accessibility metrics, including walking-distance thresholds, network connectivity indices, and universal-access compliance rates, provide measurable spatial indicators; however, long-term behavioral responses, community participation levels, and environmental learning outcomes were not empirically monitored. Accordingly, accessibility-related findings should be interpreted primarily as indicators of spatial potential rather than validated social-performance outcomes. Although the accessibility framework remains analytically valuable for evaluating inclusivity and spatial equity, the broader socio-cultural implications of the "Living Laboratory" model require longitudinal post-occupancy investigations and participatory field-based assessments.

Overall Predictive Reliability: Overall, the study provides a spatially calibrated and methodologically integrated predictive NbS framework rather than a fully empirically validated implementation model. Hydrological and spatial-performance outputs demonstrate relatively high methodological robustness due to calibration-supported simulations and multi-source environmental datasets. In contrast, habitat adaptation, long-term ecological succession, and socio-cultural resilience outcomes remain comparatively more exploratory because they depend on future environmental dynamics and human behavioral processes extending beyond the temporal scope of the simulations.

Consequently, all reported outputs should be interpreted as calibrated performance projections intended to support adaptive planning and scenario-based decision-making rather than as fixed deterministic predictions.

Lack of Long-Term Empirical Monitoring: While predictive models provide valuable insights, real-world ecological dynamics, sediment flux, and species adaptation require long-term observation to validate model outputs [8, 26].

Regional Specificity: The model is calibrated for Virginia's humid subtropical climate, tidal regimes, and wetland characteristics. Application in arid, semi-arid, or high-energy coastal systems would require recalibration of hydrological, wind, and wave parameters [10, 26].

Data Constraints: Limited seasonal data and incomplete hydrological projections (restricted to 2050) introduce uncertainties in flood adaptation assessments.

Socio-Economic Uncertainties: Economic projections depend on assumptions regarding maintenance, policy incentives, and climate variability, emphasizing the need for adaptive governance and financial mechanisms [31, 35, 38]. In summary, the research model proposes that NbS interventions can be assessed through predictive, spatially explicit frameworks, integrating ecological, social, and economic dimensions. However, observed ecological performance remains hypothetical**,** highlighting the importance of long-term monitoring, adaptive management, and context-specific calibration for future applications.

In addition, the research relies on seasonal ecological datasets and spatial modeling outputs rather than continuous long-term monitoring data. While model calibration was supported through institutional datasets obtained from NOAA, FEMA, USGS, and regional biodiversity inventories, the absence of post-implementation monitoring remains a key limitation for validating long-term ecosystem performance and adaptive resilience. Recent studies emphasise that, when integrated as Nature-Based Solutions, urban wetlands significantly enhance equitable access to nature and contribute to inclusive urban resilience [39]. Future research should also explore the adaptability of this model across different climatic regions and test its parametric limits to strengthen its applicability within global climate adaptation strategies. Nevertheless, despite these limitations, the study provides a transferable, spatially explicit, and analytically calibrated Nature-based Solutions framework for climate-adaptive coastal planning and ecosystem-based resilience strategies.

5.7 Final statement

This research underscores the necessity of a paradigm shift in sustainable urbanism—from isolated engineering solutions to integrated, ecosystem-based frameworks. NbS offer a scalable and adaptable pathway for resilient urban futures, where ecological processes guide design decisions and support long-term environmental, social, and economic sustainability.

For NbS to achieve lasting impact, the project advocates for a comprehensive governance framework across political and social levels:

Regulatory Integration: A mandatory preliminary study clause for NbS should be added to Virginia coastal planning regulations.

Urban Connectivity: "Green-blue infrastructure" and "ecological corridor" maps must be integrated into city-level zoning.

Stakeholder Engagement: The establishment of a multi-stakeholder coastal management platform involving local government, agencies, and landowners.

This study primarily focuses on wetland and living shoreline systems within the broader family of coastal Nature-based Solutions (NbS). However, the transferability of the proposed framework extends beyond tidal wetlands toward other coastal NbS typologies, including dunes, sandy beaches, reefs, and seagrass-based stabilization systems. Previous studies demonstrate that ecosystem-based coastal adaptation strategies can successfully enhance shoreline resilience through the integration of ecological restoration and sediment stabilization processes. In addition, recent coastal engineering research has demonstrated that Nature-based Solutions can substantially increase the resilience of beach–dune systems through eco-friendly dune restoration techniques that combine native vegetation establishment, sediment trapping, and hybrid nature–gray interventions. These approaches improve dune stability, reduce erosion, and enhance the adaptive capacity of coastal landscapes under storm surge and sea-level rise scenarios. In particular, the study "Coastal Sand Dune Restoration with an Eco-Friendly Technique" [40, 41] provides an important complementary perspective by demonstrating how NbS-oriented dune restoration strategies can improve coastal resistance against erosion while maintaining ecological continuity. The study highlights that eco-friendly sediment management, native vegetation rehabilitation, and adaptive dune stabilization principles can function as effective alternatives to hard-engineering coastal protection measures. These findings reinforce the broader applicability of the present NbS planning framework beyond wetland systems and support the argument that ecosystem-driven coastal adaptation strategies can be transferred across different shoreline typologies when calibrated according to local geomorphological and ecological conditions. Accordingly, the present research proposes that sustainable coastal planning should evolve from isolated engineering interventions toward integrated ecosystem-based resilience frameworks in which natural processes actively inform spatial planning, landscape design, and adaptive infrastructure strategies. However, uncertainties found in model assumptions, such as climate projections and land use scenarios, can influence the magnitude of projected benefits. Sensitivity analyses show that variations in key hydrological and ecological parameters can lead to measurable deviations in outputs. Therefore, the findings should be interpreted as indicative trends rather than absolute estimates. Since this research provides a design prototype and performance projection, long-term post-ocupation monitoring studies following the implementation of the project will be critical to verify the predictive power of the model.

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Author contributions

H.S., S. Çınar, and B. Yılmazsoy contributed to the conceptualization and design of the study, data acquisition, and interpretation of the findings. S. Çınar served as the principal contributor to the research and took primary responsibility for the development of the study design, data collection and analysis, interpretation of results, manuscript preparation, revision, and finalization. In addition, S. Çınar coordinated the research process, addressed reviewers' comments, and implemented all revisions required during the peer-review process. H.S. contributed to the conceptual development of the study, interpretation of findings, and overall supervision of the research activities. B. Yılmazsoy substantially contributed to the critical review of the manuscript and provided intellectual input during the revision process. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This investigation was carried out in compliance with research ethics requirements. No physical experiments or tissue samples from humans or animals are used in this study. Therefore, no further institutional review board approvals or licenses were needed to carry out this study. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Consent for publication

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Competing interests

The authors declare no competing interests.

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