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Bayesian Belief Network for ecosystem service assessment in estuarian geomorphology

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Abstract

The diverse ecosystems of estuaries function as critical elements for shaping geomorphological patterns and delivering ecosystem services (ES). Rapid urbanization together with tourism developmental activities modified land use patterns which consequently transformed geomorphological structures and disrupted ecosystem processes. The analysis of geomorphology and land use changes in Vietnam's estuarine ecosystem assessment relies on Bayesian Belief Network (BBN) modeling. Through detailed geomorphological mapping, identified six types which include alluvial land, young sand dunes, mature sand dunes, fore-sand dunes, shallow water areas, and deep water areas. During three decades the cultural ES values expanded as regulating ES diminished in areas witnessing major land use modifications involving mangrove forest conversions into agricultural territory and aquaculture operations. Two scenarios opposing were developed evaluate the trade-offs between: "Urbanization and tourism development" and "Preservation of natural landscapes". Geomorphic stability faces extreme risks from urbanization development patterns while regulating ES values decrease substantially, increasing vulnerability. The protection of natural landscapes through conservation produces stable geomorphological patterns while enhancing regulating ES values together with improved resilience. This research highlights the fundamental importance of geomorphology for sustainable development while helping managers create land use policies for estuaries that achieve economic growth alongside ecological protection.

Keywords: Geomorphology, Estuary, Wetland, Tourism, Urbanization, Scenario.

1. Introduction

Shallow areas, tidal flats, mangrove forests, barrages and river deltas, which are important morphological components of estuaries (Michael E. Meadows et al., 2016; Olav Slaymaker et al.,

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2009)not only define the landforms but also support key ecosystem processes (Field et al., 2016; Smyth et al., 2022; Urban & Daniels, 2006). These geometries of land morphology affect sediment dispersion and water regimes (Olav Slaymaker et al., 2009), as well as ecological conditions and thereby support diverse, complex ecosystems that directly undergird human endeavors (Fox et al., 2020; Hunter, 2011; Thornbush, 2015). For example, the Ganges-Brahmaputra Delta of South Asia and the Mekong Delta of Vietnam, are not only densely populated areas but also sources of resources for crop production, fishing, and trading (Nicholls et al., 2018; Vũ Trung Tạng, 2020).

Common ecosystem services associated with estuarine geomorphic features include water supply, flood regulation due to the water storage potential of tidal flats and mangrove forests in the process of erosion control through sediment structures and vegetation for species support (Barbier et al., 2011; Weinstein, 2008). The application of these geomorphic systems also improves cultural (Panizza & Piacente, 2009), tourism, and recreational potentials (Alahuhta et al., 2018), creating tremendous economic returns worth trillions of USD per year (Grasso et al., 1998; Ramsar Regional Centre – East Asia (RRC-EA), 2020). Geomorphology-indicator is one of the important bases for determining the indices of ecosystem services and for future urban construction, infrastructure, and tourism (Hunter, 2011),(Field et al., 2016). Estuaries are the special geomorphic features that support life while playing a major role in the economy and the environment globally (Anthony et al., 2015; Barbier & Acreman, 1997; Diefenderfer et al., 2021; Van Ree et al., 2017)

River delta regions are subject to serious geomorphological hazards (erosion, abnormal sediment deposition, and river flow changes) occasioned by urbanization and climate change. Sea levels are rising, as are the risks of widespread flooding and coastal erosion (S. Díaz et al., 2019),(John et al., 2018; Prasad & Kumar, 2014; Warrick et al., 2024). According to the General Department of Disaster Prevention and Control (2023), the Mekong Delta loses 300–500 hectares of land annually to erosion, sand mining, and sea level rise of 3.5 mm/year. There are also incredible losses of more than 60 per cent of mangrove forests in the Mekong Delta, both over these past decades and upon the country as a whole, where natural buffers to coastal erosion and a decrease in saltwater intrusion have been lost (Anthony et al., 2015; Yuen et al., 2024). As in the Mississippi Delta (USA), over the past century, some 5,000 km² of land has disappeared to rising sea levels caused by human interference (Jordan, 2014; Presley et al., 1998). Not only do these changes further degrade critical ecosystems such as mangroves, wetlands, and floodplains, but they also diminish their ability to regulate floods, sequester carbon, and support biodiversity (Cazenave & Cozannet, 2014a). Extreme weather events and disasters are doubling economic losses to vulnerable regions every decade (Hoàng Văn Thắng, 2015; Nguyễn Văn Công, 2012; Quante et al., 2024), wrecking livelihoods and destroying environments for millions of people around the world (Cazenave & Cozannet, 2014; Nguyễn Văn Công, 2012; Nyberg et al., 2006).

Given these challenges, the assessment of ecosystem services (ES) at geomorphological units is crucial for sustainable management and planning (Barbier & Acreman, 1997; Boerema & Meire, 2017; Camacho-Valdez et al., 2014; Citation, 2005). Since the assessment of ecosystem services in geomorphological units requires various tools, their strengths and limitations are discussed. Services are simulated and quantified using predictive models such as InVEST, ARIES, and SWAT. The ARIES model required substantially more time and expertise to assess independent ecosystem service models (Waage, 2014). The InVEST model can be run at different spatial scales and extents, but spatial relationships among landscape components are oversimplified in the models (Nemec &

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Raudsepp-Hearne, 2013a). However, SWAT is most applicable to aquatic ecosystems than to non-aquatic systems (Garcia, 2023). Visualization of policy decisions based on ES maps using GIS spatial tools offers visual insights (Burkhard & Maes, 2017; Nemec & Raudsepp-Hearne, 2013; Sherrouse et al., 2011), but they are highly data-dependent and cannot represent changes across time.

The study aims to evaluate the relationships between ecosystem services across six geomorphological types in estuarine regions using the Bayesian Belief Network (BBN) model. Section 2.1 describes how the BBN model integrates ecological, social, and economic data to conduct scenario analysis and support decision-making processes. Section 2.2 focuses on the application of the BBN model in a matrix approach to assess trade-offs and various scenarios, aiding policymakers and environmental managers. The model proves vital in estuarine regions like Vietnam, where livelihoods are closely linked to geomorphological units vulnerable to natural hazards. By evaluating ecosystem services within these geomorphological types, the BBN model supports adaptive management strategies. Through systematic assessment and scenario generation, this research demonstrates the model's effectiveness in promoting rational resource use, enhancing resiliency, and advancing sustainable development goals in estuarine areas.

2. Material and methods

2.1. Case study

The various shapes of Vietnamese estuaries create different natural environments and deliver important services throughout the country. The Ba Lat estuary functions as the north's largest outlet of the Red River through its role in Thai Binh and Nam Dinh provinces. Both natural and human activity affects how fluvial and marine forces shape this coastline. The sandy and clayey sections of Red River deposits create natural landing spots for tidal action that develop along a wide stretch of mangrove trees. Mangrove forests that stretch 40 km defend this coastline by reducing coastal erosion and shielding areas from storms through the features formed by fluvial and marine geomorphic processes. At the Ba Lat estuary the fishing and shrimp farming industry brings in 20,000 tons of produce yearly which creates an ecosystem service value of VND 300 billion annually. This system responds clearly to weather patterns and stream variations which affect erosion and sediment movement so managers must address these challenges sustainably.

The Thu Bon River estuary in Quang Nam province shows how steep mountain slopes drive quicksand movement within the central Vietnam coastline. Estuaries in this area develop as coastal zones connect with rivers due to natural alignment between rivers and coastal forces. Their terrain responds quickly to seasonal flood water and flash floods that modify how sediment and nutrients distribute across the geomorphology. These small estuaries support local fisheries and agriculture alongside flood protection functions. Their behavior demonstrates that landforms and environmental benefits go together. The Hau River estuary in the Mekong Delta shows advanced fluvial and tidal interaction across its south faces. The estuary area shows strong sediment movement which pushes sand from the land at 0.15 meters per year while delivering 0.1 meters of sediments to the coastline each year. Two major river exits Tran De and Dinh An exist within the Cu Lao Dung district's fault zone and along sediment distribution patterns. The delta's natural geomorphic development created vast wetlands and mangrove forests which deliver clean water to society while preserving ecosystems and defending shorelines. Aquaculture companies in this area make USD 2,100 in ecosystem profits every year from one hectare. The changing landscape of this estuary needs planning agencies to

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consider how they will protect its environment while developing new areas. This analysis shows how changes in landforms and environment create essential services for Vietnam's coastal freshwater areas.

The different types of estuarial geomorphology in Viet Nam develop when tidal and coastal forces influence rivers and coastal sand formations. Estuaries show four basic types of landforms: alluvial areas build farmland and aquaculture platforms while young and mature sand dunes appear from coastal winds and waves, and fore dunes help stop beach erosion. Also, shallow and deep-water spaces serve as homes for plant and animal communities like seagrass habitats coral reef farms and water farms. The natural landforms of estuaries form the basis for establishing both their environmental systems and human activities.

Figure 1. The location of three chosen large estuaries for ecosystem service assessment in Vietnam

Source: Research area maps:Powered by Esri; field photographs by the authors.

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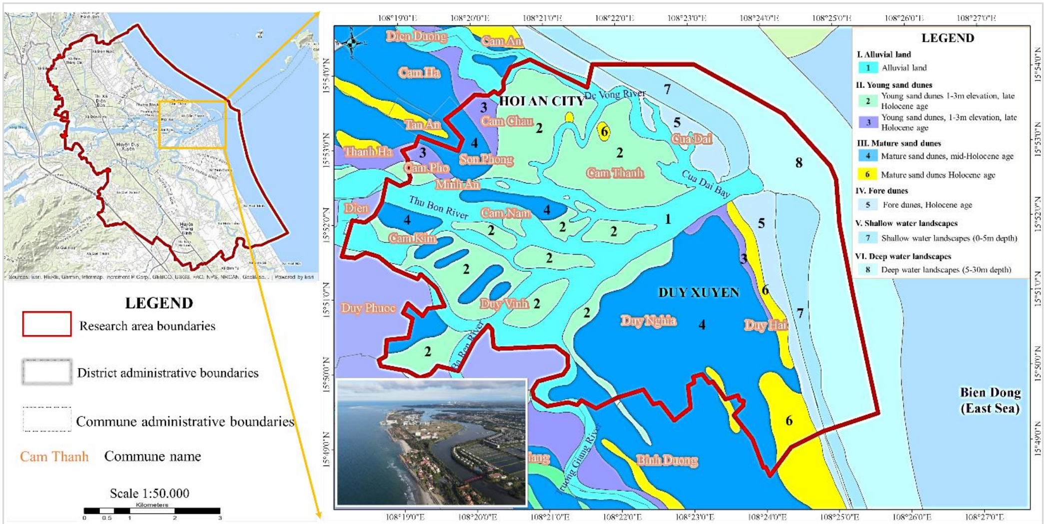

Figure 2. Geomorphological units for ecosystem service assessment in Thu Bon estuary

Source: Research area map: Powered by Esri; Geomorphological units map edited from the outputs of the research project "Scientific basis for the establishment and management solutions of coastal protection corridors in Viet Nam" (KC.09.17/16-20).

The Thu Bon estuary in central Vietnam presents diverse geological formations that make it a perfect research subject. Six primary geomorphological types have been identified here: The area contains alluvial land formations and mature sand dunes alongside young sand dunes and fore dunes in areas under 5m and 30m of water depth. Every geomorphological type in an estuary determines its physical setting and controls both natural ecosystems and how people use that space. The fertile farmlands and fish-breeding ponds in Thu Bon estuary exist alongside mangrove coconut forests which protect the shoreline and support regional wildlife. Human activities shape the sand dune shape of the estuary through this unique geomorphological system. Young sand dunes moving from shallow water to deep river areas influence the way we use residential areas and coastal tourism spaces. Both shallow and deep-water zones support aquatic farming activities while protecting seagrass and coral reefs demonstrating their importance to our environment. These special features were recorded as a UNESCO World Cultural Heritage Site and a component of the 2009-approved Cu Lao Cham - Hoi An Biosphere Reserve, with Thu Bon estuary serving as its buffer zone. Despite the region's ecological and cultural significance, its growth is regrettably being hampered by seaside tourism and fast urbanization. A total of 112.5 hectares of important wetland habitats were lost between 2004 and 2016, including 34.6 hectares of seagrass beds, 0.8 hectares of coral reefs, and 77.1 hectares of mangroves (Nguyễn Văn Thảo et al., 2013)(Hoàng Văn Thắng, 2015; Vinh et al., 2012). Erosion, flooding, and habitat degradation are also threats to the area. In late 2021, heavy flooding in Tam Ky damaged almost 3,000 dwellings. The multiple changes in Thu Bon estuary geomorphology create exceptional research setting to study how land development affects ecosystems and human development in similar coastal areas.

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2.2. Methodology

The study used the BBN model to assess ecosystem services in estuarine geomorphological units, following four basic steps. Literature analysis and initial field work were conducted to identify geomorphological units, land use/ecosystem types and associated ecosystem services. Geomorphological types were identified through expert mapping methods and applied to the study area. The service matrix, constructed using expert knowledge, was fed into a regression model (Generalized Linear Model + Structural Equation Model) to examine ecosystem service linkages. The results are summarized in Appendix 5 and linked to the BBN model. In the third step, semi-quantitative ES values for geomorphological units were calculated using the BBN model, integrating ALOS satellite image data extracted over the past 30 years. As a final step, ES values for geomorphological units were evaluated for regional planning and disaster scenario projections up to 2030. Input data will include regional "land use planning" and "climate change scenarios". Figure 3 provides a separate representation of this process.

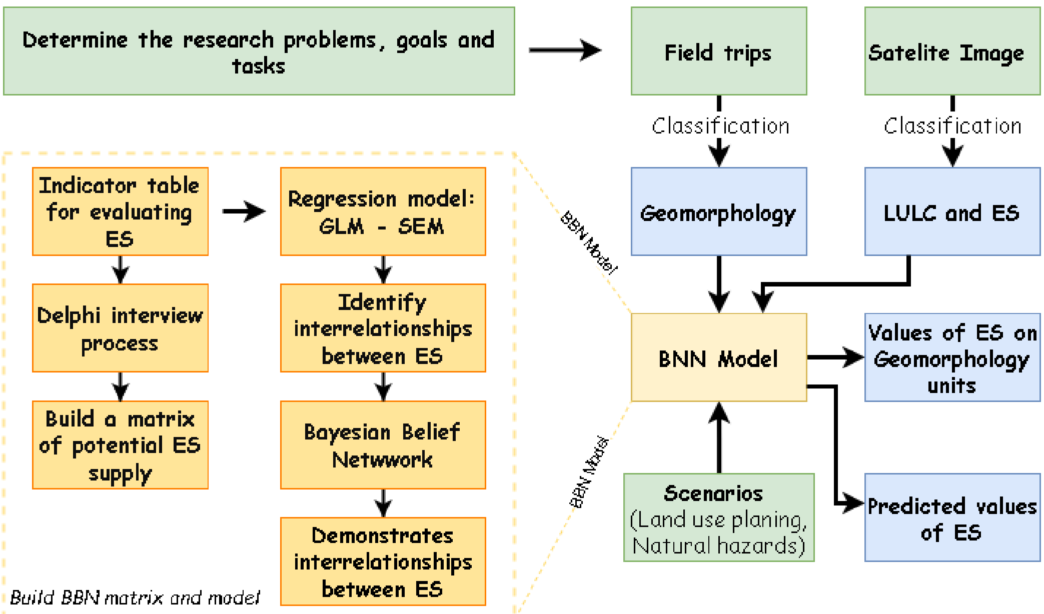

Figure 3. The contents of the study to assess ecosystem services in estuarial geomorphology

2.2.1. Database for model development

The model database was created by categorizing geomorphological units and ecosystem types alongside land use/land cover (LULC) types to delineate their corresponding ecosystem services (ES). Fieldwork undertaken in 2024, along with published sources, facilitated the categorization of two principal datasets: (1) map of six geomorphological units: mature sand dunes; alluvial land; fore dunes; young sand dunes; shallow water zone (0-5m depth); and deep water zone (5-30m depth); and (2) map of two primary ecosystem categories: terrestrial ecosystems (including agricultural land, sand dunes, raised beaches, and residential areas) and wetland ecosystems (comprising tidal alluvial flats and sands, mangroves, and aquaculture areas). They significantly contrast with upland

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geomorphological features, recognized for their high biodiversity, and are characterized by low-lying and often inundated terrain (wetland ecosystems).

The research employed remote sensing data, geomorphology, and ecosystem maps spanning 30 years to evaluate the geographical distribution of geomorphological units, ecosystems, and land use/land cover types. Monthly surveillance of recent alterations in the Thu Bon estuary over the previous five years was conducted utilizing Google Earth Professional imagery, complemented by a 30-year historical analysis employing the highest resolution ALOS satellite pictures alongside 30m x 30m resolution images. The research utilize geospatial data from Landsat and Sentinel 1and 2, employing a geospatial data-driven random forest technique to produce a dense, complete dataset for Vietnam. A classification system with 18 categories was employed, reflecting the complexity and geomorphological diversity of the estuary, with an accuracy range of 78% to 85%.

2.2.2. Development of the BBN Model

The Bayesian Belief Network (BBN) is a probabilistic model based on Bayes' theorem and artificial intelligence, intended to illustrate cause-and-effect linkages within a system or dataset. It comprises two essential components: Directed Acyclic Graphs (DAGs): These graphs depict the causal links, along with the dependency and independence of variables. DAG consists of an organized collection of nodes (or variables) linked by directed edges. Nodes signify random variables with associated probability distributions, and edges indicate weighted causal linkages among the nodes (Barton et al., 2008; Landuyt et al., 2013; McCann et al., 2006; Nyberg et al., 2006b). Directed arrows signify the statistical dependencies of nodes, with edges directed from parent nodes to child nodes. Every child node possesses a conditional probability tables (CPTs), which is based on the values of its parent nodes. CPTs measure the strength of connections between nodes and articulate the probability of each node's potential states depending on the states of its parent nodes. The amalgamation of DAGs and CPTs establishes a causal framework that underpins the construction of an operational BBN. The likelihood of each node is dictated by the interactions and dependencies established in the model. This systematic methodology enables BBN to accurately represent intricate systems by encapsulating their probabilistic causal relationships. The probability distributions were established based on expert input and historical data validation. Sensitivity analysis was performed to ensure the robustness of the model predictions. The Bayes' theorem can be formulated as:

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)}$$ (Dang et al., 2019).

In which, "B" is the parent node (cause factor), and "A" is the child node (effect factor).

However, the development of suitable indicators is critical to the implementation of the BBN model for evaluating ecosystem services within estuarine geomorphological and ecological frameworks. The indicators work as quantifiable metrics for system's desirable attributes. In order to assess ecological values efficiently, the indicators chosen should be strategic, important and accessible. This research, based on the distinct geomorphological and ecological characteristics of the estuarine area and consistent with the Common International Classification of Ecosystem Services (CICES) framework, found 17 types of ecosystem services categorized into three primary groups: providing, regulating and cultural services.

These ES kinds were aligned into a matrix to which the BBN model was applied, and thus nodes within the network could be identified. The Delphi interview was used to enhance the matrix

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by multiple feedback from specialists. Experts evaluated the availability and distribution of ecosystem services within a wide variety of geomorphological and biological units, alluvial land, dunes, mangroves, and aquaculture zones. The process culminated with consensus when asking each feedback iteration because of this.

Consultants were 21 academic and research organization specialists in urban planning, agriculture, forestry, geomorphology, culture studies, and ecology. In ecosystem service matrices they were integrated into ecosystem services associated with land use targets or with coastal and estuarine networks of services for each land use category. In the event such differences occur, the evaluators may suggest alterations including changing land use classifications or correcting omissions. Values in a 20-40% variance range were averaged into final matrices. Additional conversations were held to reach a consensus for discrepancies greater than 40%. The ES evaluation was conducted in an iterative and collaborative way so that the output captured the geomorphological and biological changes in the estuarine area as fully as possible *(Appendix 1)*.

The matrix which resulted from this was then put into the R programming environment (R-Studio 4.3 application) and reviewed along with scientists. The model for the interrelationship of ecosystem services is shown in figure 4. Based on these finding a Bayesian Belief Network (BBN) was constructed using the Netica program. It shows the relationships between ecosystem services, quantifies their values, and analyzes their patterns of distribution across geomorphological and biological units of sand dunes, alluvial flats, mangroves and aquaculture zones. The ecosystem service (ES) values for each ecosystem or land use/land cover (LULC) type were computed using the formula:

$$\sum \text{ES} = \sum Ee.El$$

The magnitude of the potential provision of the ecosystem service Ee, and the magnitude of the land use and land cover type El. The aggregate ES value is evaluated service values. Model outputs are provided in relative units rather than absolute measurement units, since the input data are computed as % proportions on 5 scale levels. This calculation and methodology was used in Sections 3.3 and 3.4 on ES values that used matrix table weights. The methodology ensures that the contribution of different geomorphology units to ecosystem services are fully investigated geomorphologically and ecologically together.

2.2.3. Matrix for the assessment of the ability to provide ecosystem services of different ecosystem types in the estuary

The matrix assesses changes of values of variables associated with ecological and geomorphological units over a long time period. Nevertheless, the study does not attempt to quantify specific variables, or employ quantitative techniques. Potential capacity is referred to by qualitative adjectives “high,” “medium,” and “low”. This method allows opportunities to identify variables that influence the development of geomorphology and Ecosystem Services (ES) group(s) of which those geomorphologys are part.

On a scale of 0 to 100, the ability of each type of ecosystem-from mangroves and shallow or deep-water s to alluvial flats and sand dunes-to deliver particular services is evaluated into five levels: Less than 20: Deficits in capacity to deliver this ecosystem service. 30-40: Limited ability to supply;

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Average supply capacity: 50-60; 70-80: High capacity for supply; Over 90: High capacity for supply. In fact, no ecosystem approaches a maximum capacity (value = 100) or arrives at a situation in which there is no ability to provide services (value = 0). This scale reflects the inherent complexity and heterogeneity of ecological and geomorphological processes underlying the provision of ecosystem services on varying geomorphological types.

2.3. Scenario development

The development of scenarios is an essential function of the BBN model. The Thu Bon estuary, with its complex and sensitive geomorphology, is under great pressure from urban development, tourism and the impacts of climate change. According to the Hoi An City Strategic Plan from 2020 to 2030, rice growing land, natural forest land and of forest land will be transformed into non agricultural land uses. Hoi An City is thus envisaged to become an exceptionally intelligent metropolis with 40 percent of urbanization by 2030 (according to Quang Nam Province's 2030 orientation). Consequently, in accordance with the planning, the study formulates two scenarios to evaluate future land-use impacts on estuarine ecosystem services: (1) Urbanisation and tourism development and (2) preservation of natural landscapes. The two scenarios were built by reallotment of area ratio among different LULC categories to assess the impact of future policies on ES. Data were specified in accordance with Dece of the province of Quang Nam’s general planning and the issued data were verified against of the LULC area of 2020 (Table 1).

Table 1. Changes of types of geomorphology and land use/ land cover in the two scenarios until 2030

LULC	Urbanization and tourism development	Preservation of natural landscapes
Residential/Urban and tourism	Expand by +400 ha	Remained stable
Beach	Narrow -10 ha	Expanded +10 ha
Forest	Reduce -250 ha	Increase +150 ha
Agricultural	Reduce by -150 ha	Increase by +50 ha
Aquaculture	Expand by +50 ha	Stabilize or reduce by -50 ha
Water surface of river and sea	Narrow by -50 ha	Remained stable

- Scenario 1: The scenario involves developing socio-economic development goals and expanding tourism in the region through urbanization. Enhance the image of the Thu Bon estuary as a sea and island tourism destination. Through the conversion of agricultural, forest, and barren land, expand 400 hectares of residential/urban and tourism land. Forest area is reduced by about 40%, that is, more than 250 hectares compared to 2024. Part of the coastal forest is used to create a tourist area; part of the forest around the residential area is converted into urban or non-agricultural land; the rest is due to natural degradation of protective forests in the alluvial plain. Narrowing the water surface of river and sea increases the aquaculture area by 50 hectares. In addition, the scenario also reduces 10 hectares of beach area due to annual erosion and beach renovation for tourism development.

- Scenario 2: Under this scenario, the stability of the geomorphology and ecology of the estuary are maintained while minimizing the negative impacts of the development of the economy-society. Maintain a stable residential/urban and tourism area (compared to the urbanization growth rate of the region (Hoi An city's urbanization rate is 74.5% (2021)), and limit uncontrolled expansion. 50 hectares of agricultural land increases through the restoration of rice-growing areas and traditional farming land. It increases forest area by 20 percent (150 hectares recover to replant mangroves and river/sea protection forests to protect river banks and prevent erosion). The aquaculture remains sensed stable or lowers 50 hectares, restrains uncontrolled advance, and water contamination. Maintain the Water surface of river and sea, enhance flow management, and promote freshwater conservation. In addition, 10 hectares (about Cua Dai beach) of the beach area is expanded to protect the coastal area and attract tourists.

3. Results

3.1. Statistical analysis of interdependence as a basis for BBN parameterization

The provisioning ecosystem services (ES) are closely linked to geomorphological and ecological factors, such as soil properties, hydrological conditions, flora and fauna systems, terrain features (elevation and slope), and climate. These factors determine both ecosystem spatial configuration and temporal characteristics as well as their capacity to offer ES. The trading relationships between different service groups and their interactions within service groups ultimately get shaped by geomorphological features in the system. R-Studio presents the connection between 17 types of ecosystem services through a matrix that uses positive or negative values between -1 to +1 to demonstrate the relationships as depicted in Figure 4. The matrix R-Studio illustrates enhancing mutual relationships through red lines but trade-offs through blue ones with no correlation having a value of zero.

The research divided ES correlations into three separate groups (N1, N2 and N3) which represent provisioning ES and regulating ES and cultural ES. The cluster analysis method identified distinct groups which demonstrate different ranges of service dependence relationships. The regulating and cultural ES groups (N2 and N3) demonstrate stronger positive interdependency among their variables yet provisioning ES variables (N1) present weaker interdependencies. Within the regulatory ES variables set (flood regulation and erosion regulation) there exists a strong complementation between them whereas the cultural ES variables set (natural heritage and landscape aesthetics) produces high positive correlation measures within N3.

The provisioning ES group consisting of fish and other seafood and timber and crops and livestock demonstrates overall negative relationships with other ES types in the environmental service field. Cultural environmental service variables demonstrate a strong negative relationship with Livestock and Timber (-0.8 to -0.9) while containing a weaker negative correlation with the regulating environmental service group (-0.4 to -0.7). The natural phenomenon of geomorphological shows evidence of trade-offs because provisioning ES expansion leads to decreased functionality of regulating and cultural ES. Among provisioning ES the variable “minerals” demonstrates distinct characteristics that set it apart from others. The positive correlation between mining operations and

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cultural ES (natural heritage and knowledge service) outweighs their destructive effects on regulating ES processes such as air quality regulation and flood regulation (-0.8 and -0.5).

The procedure of riverbed sand removal demonstrates how geomorphological activities lead to economic conflicts. The negative correlation score is high because mining affects sediment flow and generates riverbank erosion while creating saltwater contamination in the aquifers and air pollution which reduces the capacity of the ecosystem to regulate ecological services. The research shows that geomorphological processes determine ES relationships in geomorphologic regions that have experienced major human-induced ecosystem disturbances. The current need emerges for land use integration that establishes equilibrium between economic growth and ecosystem protection so as to minimize flood regulation and coastal resilience diminishment.

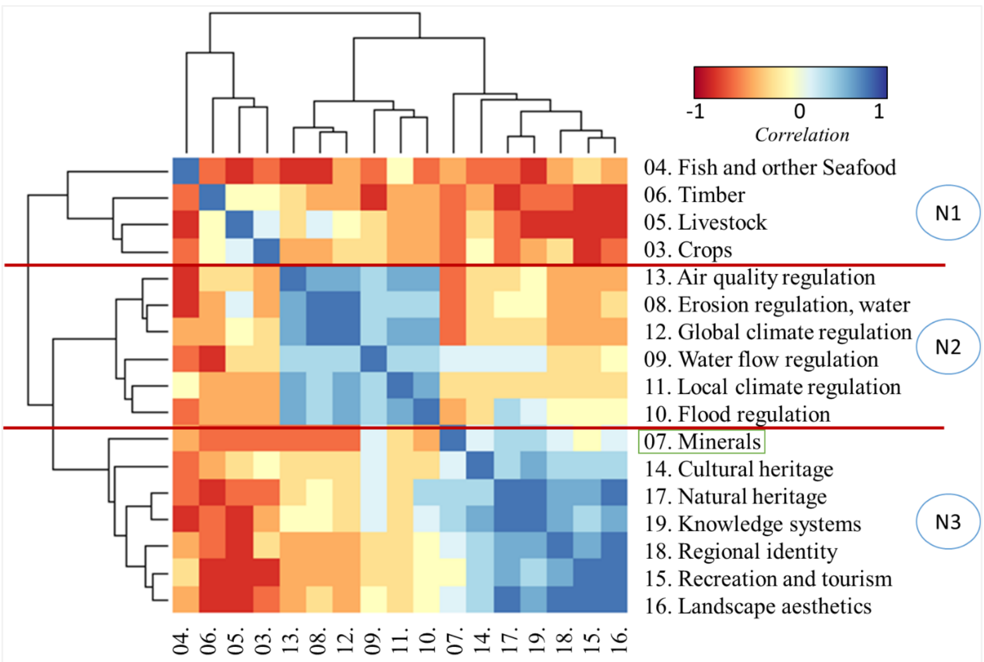

Figure 4. The relationship between ecosystem services on geomorphology in the Thu Bon estuary.

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3.2. SEM model for BBN development

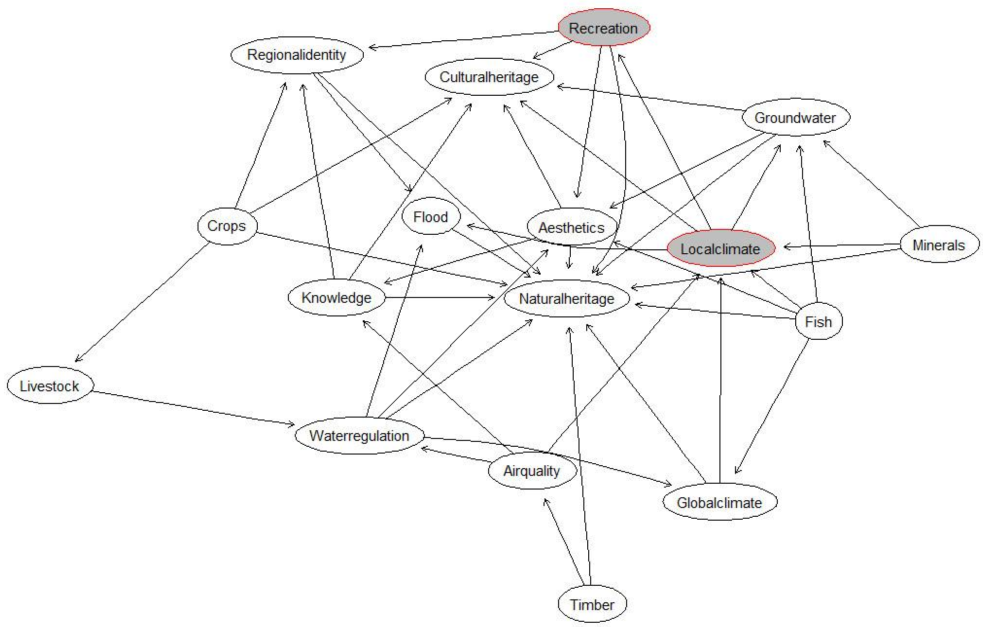

Figure 5. The SEM model to set up a BBN for assessing esturian ecosystem service

The figure featuring an SEM model displays an elaborate structure demonstrating the incoming and outgoing connections between environmental, natural and sociocultural determinants. Natural resources “Groundwater,” “Minerals,” “Fish,” and “Timber” show relationships with five environmental factors including “Localclimate,” “Globalclimate,” “Flood,” “Waterregulation,” and “Airquality.” Besides natural heritage and regional identity the model connects sociocultural elements with recreational activities alongside aesthetics and cultural traditions. The model demonstrates multiple causal relationships where “Localclimate” receives influence from both “Globalclimate” as well as “Flood” and “Naturalheritage” but simultaneously affects “Recreation” and “Airquality.” Within the model network graph “Crops” and “Livestock” serve as intermediate elements to connect with water resources and climate variables. The model features arrows which depict the theory-based relations that exist between different variables in the network. Through this model researchers can view the intricate associations that exist between both environmental and societal networking mechanisms. The interactive system mapping technique assists in showing both important elements alongside their interaction dynamics which enables identification of central problem areas aimed at sustainable solution development. Building a BBN network starts with the SEM model structure which demonstrates important causal relationships between variables.

3.3. BBN network in for assessing relations between ecosystem services in different geomorphological types

Figure 6 presents a BBN model of the relationship between geomorphological types and ecosystem services (ES). The box “1. Geomorphology” types lists six types of landforms, including alluvial landforms, fluvial-marsh landforms, marine-wind landforms, dune landforms, shallow water landforms (0-5m depth), and deep water landforms (5-30m depth), each with an equal weight of

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16.7%. These landforms are linked to the land use/land cover classes in the box "2. Land use/land covers", each with a weight of 6.25%.

Ecosystem services are classified into three main groups: Provisioning ES, Regulating ES, and Cultural ES. These services are represented in different colored boxes and relate to a variety of elements such as minerals, crops, livestock, timber, fisheries, cultural heritage, natural heritage, tourism, climate regulation, groundwater recharge, flood regulation, and erosion control. Each service has bars representing the percentages of different levels of the associated elements. "2. Land use/land covers" in the figure illustrates in detail the types of land use and land cover associated with the terrain types listed in the previous section. These classes include symbols such as ODT, KDL, ONT, CDG, BCS, DCS, LUC, LNK, RPT, NTS, SON, ESD, NSB, ALS, BWS, DWS (*Appendix 2)*, each accounting for 6.67%.These symbols may represent specific types of land use, such as cropland, forestland, urban areas, or agricultural land.

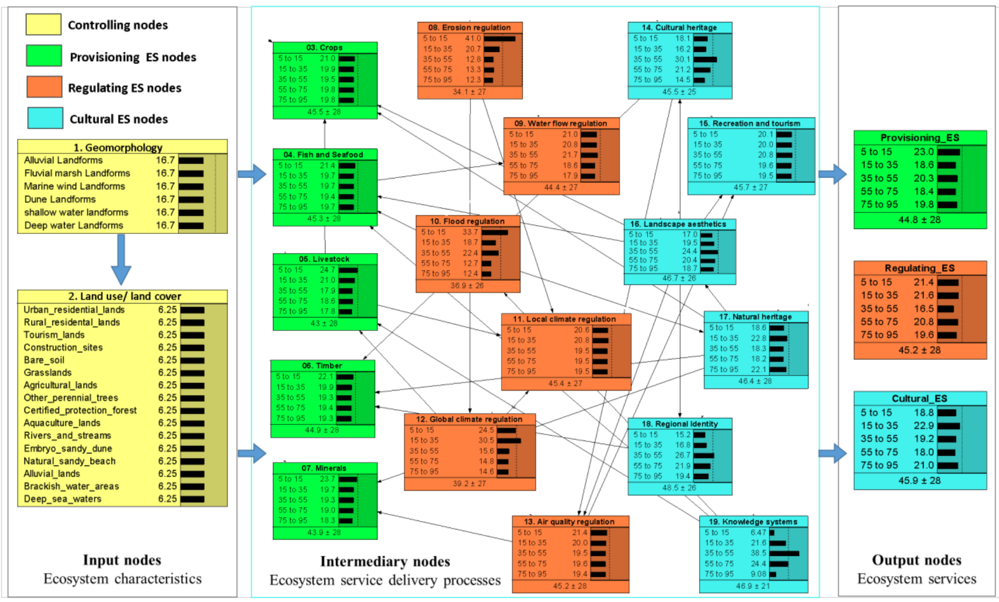

Figure 6. Bayesian network to evaluate ecosystem services in six estuarial landforms

These land use classes act as an intermediary, connecting geomorphological types to ecosystem services (ES). They reflect how topographic features and land uses affect the ability to provide different ecosystem services. For example, land uses such as agriculture or forests can affect groundwater regulation or erosion control, which are important elements of regulating services. These land use classes also facilitate deeper analysis of the interaction between humans and nature, allowing for the assessment of the impacts of land use changes on ecosystem services, such as food provision, climate protection, and cultural preservation. By combining information about topography and land use classes, the model helps identify and predict changes in ecosystem services over time and under different scenarios. At the bottom of the figure, a summary of provisioning, regulating, and cultural services is shown for land use scenarios (LULC) from 1990 to 2020, including two different scenarios. Changes in ecosystem services over time and predicted trade-offs are also shown. The

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figure shows the interactions between terrain types and ecosystem services, along with changes over time due to different land use scenarios.

3.4. Testing model for valuating ecosystem services of estuarial landforms in Vietnam

The developed BBN model was used to value estuarial ecosystem services across geomorphological units in Vietnam over the past 30 years. In the middle part of Vietnam, ES values across geomorphological units can be divided into three distinct periods: Values showed minimal fluctuations during the first period (1991-2001) of little human impact. Second, there was a second period (2002-2015) that exhibited large fluctuations, at least during part of this period, seeming to be influenced by urbanization. The second period had the rest of the periods. In this period, the trends demonstrated that the stabilization of ES values, with fewer variations, were gradually in tune with the evolution of the urban development in research areas.

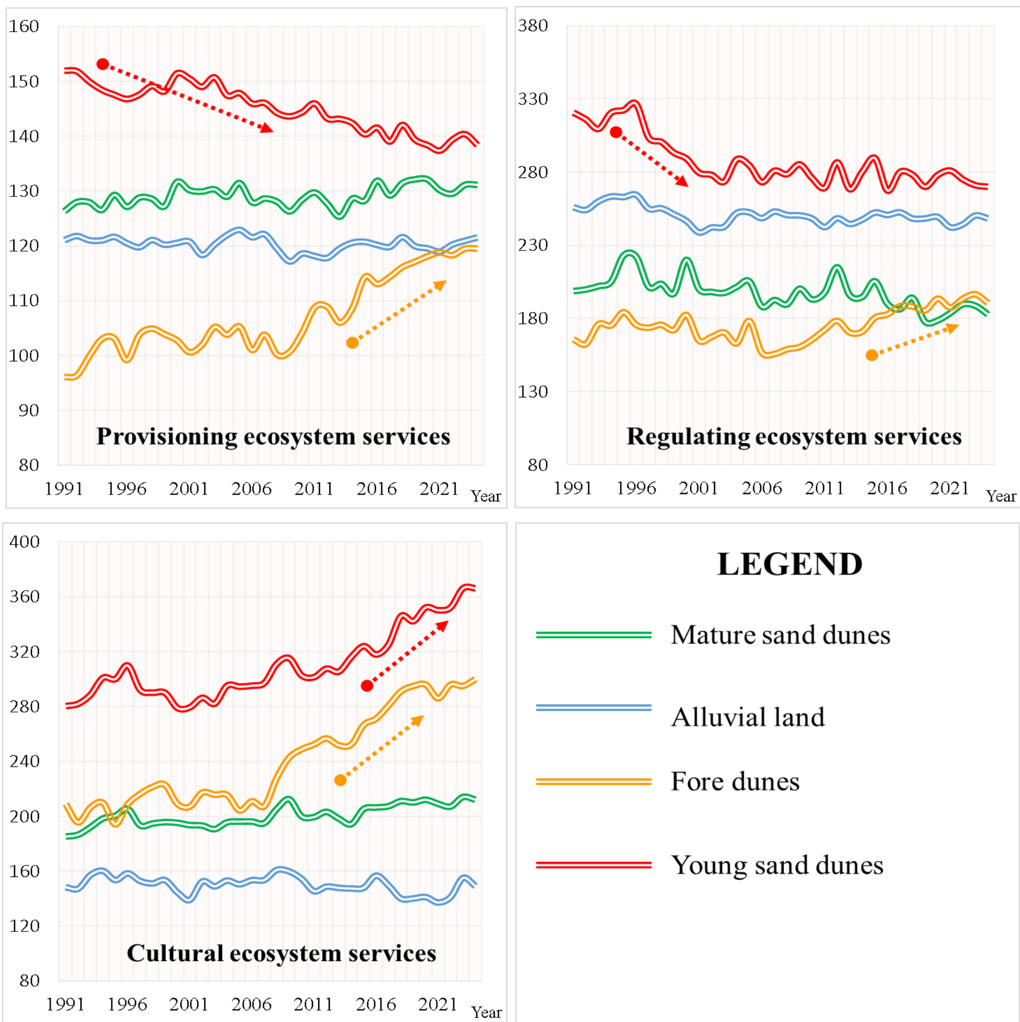

Figure 7. Total value ecosystem services of different estuarial landforms in middle part of Vietnam

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Overall, the values of the three ES groups have been relatively stable, only fluctuating in certain years. Across six geomorphological groups, ecosystem services valued increased from 3,146 points in 1991 to 3,319 points in 2024, a 3% increase. In 2001 this value was as low as 3,089 points and in 2024 as high as 3,319 points. The areas of the geomorphological groups vary: Alluvial land (1,587ha), fore dunes (344 ha), young sand dunes (1,865 ha), mature sand dunes (1,520 ha). Despite little change in areas, the value of services varied markedly across geomorhophycal groups because of changes in land use and functions of the ecosystems.

The highest value is found in the "young sand dunes," which has increased from 714 points to 777points. The second in value is the "alluvial land," which fluctuates between 728 and 781 points over the years. Fisheries and tourism in the Thu Bon estuary area are particularly valuable due to the alluvial soil. A decreasing trend can be observed in this group from 1991 to 2001, recovering in the period 2002-2011 and gradually decreasing in the third cycle. The "young sand dunes" mainly provide agricultural services; the regulating services decrease as the terrain becomes urbanized, and the cultural values increase as tourism develops. The fluctuations become more evident every year. As urbanization gradually develops in Hoi An, people change the land use purpose in Cam Thanh ward; residents gradually reclaim and build on stable sand dunes on the river, such as Cam Nam ward, Cam An, and Duy Vinh commune. From a land still covered with green, the transition to tiled-roof houses makes the regulatory value gradually decrease and cultural services begin to increase for tourism and service development. Along with that, the area for growing agricultural crops such as rice and vegetables is clearly planned with more regional space than in previous years, but the value tends to decrease. In 1992, the Cam Thanh commune area was mainly agricultural ecosystems, aquaculture, and the tidal creek system was still thick, but now (2020), the agricultural and aquatic land has partly changed into residential areas. The impacts of waves, wind, and coastal tourism have been shown to have significant value fluctuations in the "fore dunes". However, "fore dunes" had low value in the early years, but recently, due to the change in purpose, cultural services have increased, leading to higher ecosystem service values in the area. This terrain does not provide many services (about 95-105 points) because the area of aquaculture north of Cua Dai ward was converted to construction land in the period of 2009-2011. "Fore dunes" are affected by nature and humans, so there are clear fluctuations divided into 2 cycles; the rate of value increase is rapid. However, this terrain has gradually become stable. "Mature sand dunes" are relatively low and stable for 30 years for their service values.Stable but low service values ranging from 445–450 points were attributed to erosion and sediment accumulation in other geomorphological groups such as shallow water zone and deep water zone.

3.5. Scenario results

The two scenarios of land use/land cover data were put into the BBN model. This showed how geomorphology (solid foundation) affects and responds to land use changes in the Thu Bon estuary by 2030 (Figure 8). Geomorphology is not only a natural factor shaping landscape forms but also a physical foundation that plays a central role in maintaining ecosystem function in the face of impacts from economic development and urbanization. The results show that the correlation between land use and geomorphological change reflects opposite impact trends.

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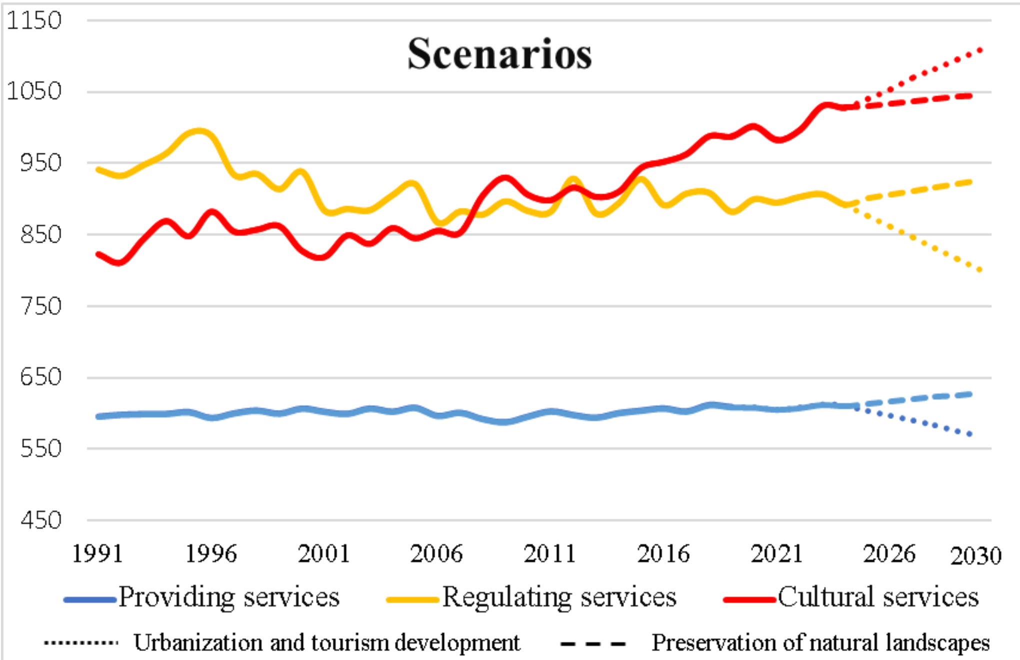

Figure 8. Fluctuation of ecosystem services in estuarial geomorphology in "Urbanization and tourism development" and "Preservation of natural landscapes"

Scenario 1, with a focus on urbanization and tourism development, results in a significant increase in regional cultural ES values with a rapid decline in regulated ES values by 2030. The dramatic land use/land cover places direct pressure on the geomorphic, altering natural structures and functions, especially young sand dunes and foredunes. Increased built-up areas and reduced forest cover weaken sediment storage capacity and reduce flow stability, leading to increased erosion risk in coastal dunes. The loss of natural cover also severely degrades riverine fore dunes, which are sensitive geomorphic units. Young sand dunes and foredunes are vulnerable to saltwater intrusion in areas outside the belt. Furthermore, when sea level rise during storms combines with tidal forces, water levels in coastal plains reach 150-200 cm, leading to the risk of flooding of all geomorphology units. In contrast, Scenario 2 emphasizes the conservation of natural landscapes, minimizing geomorphological risks, and enhancing resilience to the pressures of climate change and economic development. Limiting uncontrolled urban expansion and restoring mangrove forests significantly increases regulating ES values, surpassing cultural ES values. Geomorphology, in this scenario, retains its stable foundation role, supporting surrounding ecosystems to maintain regulating ecosystem services such as young sand dunes and foredunes. Increasing forest cover and reducing unsustainable exploitation also provide opportunities for the gradual restoration of sensitive geomorphic systems, especially riverine alluvial plains and coastal areas, contributing to increased resilience to climate change pressures.

The correlation between geomorphology and land use change in both scenarios shows that land use decisions not only impact the land surface but also directly influence the structure and function of the solid geomorphic foundation. Scenario 1 illustrates how urbanization and short-term economic development can cause significant damage to geomorphology, weakening natural defense functions, leading to increased risk of natural disasters and erosion. Scenario 2, in contrast, demonstrates that conservation and sustainable management of geomorphology can mitigate the impacts of climate change while maintaining long-term ecological values and stability for both nature and people. Geomorphology, as a solid foundation, cannot be separated from land use strategies, since any change in land use will directly reflect on its stability and function.

4. Discussion

4.1. Relations between Geomorphology and ES

The study proved that how an estuary's physical shape shapes its function particularly by protecting against floods and managing water flow while cleaning up water. The natural river features of lagoons and floodplains along with canals slow water movement to prevent flooding in nearby areas. The coastal systems naturally clean water before it enters the ocean by eliminating pollution at its water stage. Flooded areas of maritime estuaries absorb and store carbon which helps fight climate change. Our research confirms geomorphology provides multiple ecosystem benefits by shielding the environment and creating better neighborhoods.

The research outcomes demonstrated that estuaries benefit from natural landforms which make both fresh water accessible and deliver necessary ecological services to the community. Natural water environments with habitats in wetlands and floodplains support aquatic animals and deliver important food supplies to people living nearby. Aquatic life thrives in wetlands close to coastal areas and estuaries which expands both fishery resources and boosts the aquaculture sector. Geomorphic features control how people get and use freshwater to meet household requirements and farm irrigation. Research evidence shows geomorphologic systems require preservation to maintain the benefits they offer resource supply systems in estuarine environments.

The results demonstrate how estuarine shapes determine environmental advantages by providing amenities that make scenic views plus places to live. The different landforms of beaches marshes and mangrove areas serve multiple purposes by capturing tourist interest and hosting important cultural sports and entertainment events. The locations support tourist activities which boost regional economy and motivate people to protect our natural environment. Cultural practices rooted in estuarine geography include celebration and ritual ceremonies of local people with their coastal water environments. Our research shows that adjustments in the land forms of this region directly interact with the local cultural elements and impact their ability to preserve and develop these cultural services.

4.2. Challenges and Opportunities of BBN Model in Geomorphology and ES Research

Geomorphic and ES researchers use BBN models to study how geomorphic features get affected by land use patterns and the services ecosystems provide. This research uses BBN to identify how geographic elements and ecological processes influence the delivery of ecosystem services. BBN merges multiple types of data into its analysis while managing the imprecise aspects of information. Researchers use BBN modeling to analyze how topographic features and land use changes interact with geomorphological processes to influence how ecosystems deliver services such as climate control and biodiversity protection. The BBN model analyzes how terrain types and geomorphic processes modify over time affect the delivery of ecosystem services. The way geomorphic processes impact coastal erosion or water levels controls both drinking water quality and defense against

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flooding alongside shaping tourism destinations. By showing how different elements affect each other through the BBN model it helps predict changes to ecosystem services as part of geographical factor modifications. This model aids decision-making in sustainable estuarine management by showing how linked ecosystem services rely on geomorphic processes. This framework shows us how changed land uses result in specific effects from mining operations or development on our ecosystems. Our model reviews possible treatments to protect and enhance environmental services of critical ecological spots.

The BBN proves its worth for linking geomorphological science with ES evaluations when essential data is limited. BBN successfully manages limited data by combining scientific knowledge with measurements to analyze ecosystem controls in different estuarial types in Vietnam. Our assessment system uses online maps of land use at multiple administrative levels and scientist input alongside statistical information. The data processing aspects of BBN remain easy to use in adaptive management and allow validation with both new information and acquired data. Regularly adding new knowledge to our data system lets BBN respond faster to environmental changes while opening new doors for interdisciplinary research between geomorphologists and ecosystem service experts. Building systems from this model proves hard because it requires handling subjective data and has restricted program connection functions. Our efforts need to improve both BBN data sources and public knowledge about this model as we work to expand its use across multiple fields.

5. Conclusions

The research creates an assessment index system with a Bayesian Belief Network model to examine how geomorphology interacts with land use/land cover and ecosystem services in estuarine regions. The BBN model resolves data uncertainty together with expert assessment by uniting traditional professional insights with modern computational tools. Vietnam's urbanization alongside tourism development has stressed geomorphology triggering both cultural ES value increases and regulatory ES value decreases while promoting development challenges conservation needs. When mangrove forests and natural land are replaced with urban developments and tourism complexes economic benefit arises however it destabilizes ecological systems which elevates flood and erosion threats in vulnerable zones. The findings emphasize the need for policy interventions that integrate geomorphological stability into land-use planning. The BBN model evaluation reveals that Thu Bon coastal protection forest restoration is an immediate necessity to maintain geomorphological stability while reducing potential disasters. The research shows how geomorphology contributes to sustainable land use planning by protecting ecosystem functioning while increasing landscapes' ability to resist climate change effects. The BBN model demonstrates utility for estuary research in Vietnam and presents universal applicability across the world.

Author contributions

Conceptualization: TDLN, QDB, KBD, THNH, MHN; Data curation: TDLN, PTT, CLN; Formal analysis: TDLN, KBD, TLG; Funding acquisition: QDB; Field surveys and sociological investigation: all authors; Expert interviews: KBD, TLG, MHN; Methodology: KBD, PTT, TLG; Project administration and supervision: KBD, THNH, MHN, QDB; Resources: all authors; Modeling:

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TDLN, KBD, PTT; Validation: CLN, QDB, PTT, NMH; Visualization: CLN, QDB, PTT; Writing (original draft preparation): TDLN, QDB, THNH; Writing (review and editing): all authors.

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Preprint. Discussion started: 30 December 2025

References

Alahuhta, J., Ala-Hulkko, T., Tukiainen, H., Purola, L., Akujärvi, A., Lampinen, R., & Hjort, J. (2018). The role of geodiversity in providing ecosystem services at broad scales. *Ecological Indicators*, *91*(March), 47–56. https://doi.org/10.1016/j.ecolind.2018.03.068

Anthony, E. J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., & Nguyen, V. L. (2015). Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports*, *5*, 1–12. https://doi.org/10.1038/srep14745

Barbier, E. B., & Acreman, M. (1997). *Economic valuation of wetlands: a guide for policy makers and planners*.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169–193. https://doi.org/10.1890/10-1510.1

Barton, D. N., Saloranta, T., Moe, S. J., Eggestad, H. O., & Kuikka, S. (2008). Bayesian belief networks as a meta-modelling tool in integrated river basin management - Pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. *Ecological Economics*, *66*(1), 91–104. https://doi.org/10.1016/j.ecolecon.2008.02.012

Boerema, A., & Meire, P. (2017). Management for estuarine ecosystem services: A review. *Ecological Engineering*, *98*, 172–182. https://doi.org/10.1016/j.ecoleng.2016.10.051

Burkhard, B., & Maes, J. (2017). *Mapping Ecosystem Serviecs*. https://doi.org/10.1016/b978-0-12-394396-5.00054-3

Camacho-Valdez, V., Ruiz-Luna, A., Ghermandi, A., Berlanga-Robles, C. A., & Nunes, P. A. L. D. (2014). Effects of Land Use Changes on the Ecosystem Service Values of Coastal Wetlands. *Environmental Management*, *54*(4), 852–864. https://doi.org/10.1007/s00267-014-0332-9

Cazenave, A., & Cozannet, G. Le. (2014). Sea level rise and its coastal impacts. *Earth's Future*, *2*(2), 15–34. https://doi.org/10.1002/2013ef000188

Citation, S. (2005). Valuing ecosystem services: Toward better environmental decision-making. In *Valuing Ecosystem Services: Toward Better Environmental Decision-Making*. https://doi.org/10.17226/11139

Nguyễn Văn Công. (2012). *Đánh giá tính dễ bị tổn thương do biến đổi khí hậu đối với sinh kế người dân các xã vùng đệm Vườn quốc gia Cát Bà*.

Dang, K. B., Windhorst, W., Burkhard, B., & Müller, F. (2019). A Bayesian Belief Network – Based approach to link ecosystem functions with rice provisioning ecosystem services. *Ecological Indicators*, *100*(April), 30–44. https://doi.org/10.1016/j.ecolind.2018.04.055

Diefenderfer, H. L., Steyer, G. D., Harwell, M. C., LoSchiavo, A. J., Neckles, H. A., Burdick, D. M., Johnson, G. E., Buenau, K. E., Trujillo, E., Callaway, J. C., Thom, R. M., Ganju, N. K., & Twilley, R. R. (2021). Applying cumulative effects to strategically advance large-scale ecosystem restoration. *Frontiers in Ecology and the Environment*, *19*(2), 108–117. https://doi.org/10.1002/fee.2274

Field, J. P., Breshears, D. D., Law, D. J., Villegas, J. C., López-Hoffman, L., Brooks, P. D., Chorover, J., & Pelletier, J. D. (2016). Understanding ecosystem services from a geosciences perspective. *Eos (United States)*, *97*(5), 10–11. https://doi.org/10.1029/2016eo043591

https://doi.org/10.5194/egusphere-2025-3519
Preprint. Discussion started: 30 December 2025

Fox, N., Graham, L. J., Eigenbrod, F., Bullock, J. M., & Parks, K. E. (2020). Incorporating geodiversity in ecosystem service decisions. *Ecosystems and People*, *16*(1), 151–159. https://doi.org/10.1080/26395916.2020.1758214

Garcia, X. (2023). Using the Soil and Water Assessment Tool (SWAT) to quantify the economic value of ecosystem services. *River*, *2*(2), 173–185. https://doi.org/10.1002/rvr2.47

Grasso, M., Hannon, B., Limburg, K., Naeem, S., Paruelo, J., Raskin, R. G., Sutton, P., & van den Belt, M. (1998). The value of ecosystem services: putting the issues in perspective. *Ecological Economics*, *25*(1), 67–72.

Hunter, S. (2011). *A geomorphological framework for providing ecosystem services in lowland rivers*.

John, S., Brew, D. S., & Cottle, R. (2018). Coastal ecology and geomorphology. In *Methods of Environmental and Social Impact Assessment* (Issue September 2017). https://doi.org/10.4324/9781315626932-7

Jordan, T. S. and F. (2014). *Effects of the Deep Horizon Oil Spill on Marsh Fishes in the Mississippi River Delta Tom*. 175–184.

Landuyt, D., Broekx, S., D'hondt, R., Engelen, G., Aertsens, J., & Goethals, P. L. M. (2013). A review of Bayesian belief networks in ecosystem service modelling. *Environmental Modelling and Software*, *46*, 1–11. https://doi.org/10.1016/j.envsoft.2013.03.011

McCann, R. K., Marcot, B. G., & Ellis, R. (2006). Bayesian belief networks: Applications in ecology and natural resource management. *Canadian Journal of Forest Research*, *36*(12), 3053–3062. https://doi.org/10.1139/X06-238

Michael E. Meadows, & Jiun-Chuan Lin. (2016). Geomorphology and Society. In *The SAGE Handbook of Geomorphology*. https://doi.org/10.1007/978-4-431-56000-5

Nemec, K. T., & Raudsepp-Hearne, C. (2013). The use of geographic information systems to map and assess ecosystem services. *Biodiversity and Conservation*, *22*(1), 1–15. https://doi.org/10.1007/s10531-012-0406-z

Nguyễn Văn Công. (2012). *Đánh giá tính dễ bị tổn thương do biến đổi khí hậu đối với sinh kế người dân các xã vùng đệm Vườn quốc gia Cát Bà*.

Nguyễn Văn Thảo, Đặng Văn Bào, Trần Đình Lân. (2013). Biến động phân bố các hệ sinh thái tiêu biểu vùng bờ biển Quảng Ninh. *Tạp Chí Khoa Học và Công Nghệ Biển*, *13*(4), 349–356.

Nicholls, R. J., Hutton, C. W., Hanson, S. E., Neil Adger, W., Rahman, M. M., & Salehin, M. (2018). Ecosystem services for well-being in deltas: Integrated assessment for policy analysis. *Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis*, 1–593. https://doi.org/10.1007/978-3-319-71093-8

Nyberg, J. B., Marcot, B. G., & Sulyma, R. (2006). *Using Bayesian belief networks in adaptive management*. *3116*, 3104–3116.

Olav Slaymaker, Thomas Spencer, & Christine Embleton-Hamann. (2009). *Geomorphology and Global Environmental Change*. Cambridge University Press, Cambridge, UK. https://doi.org/https://doi.org/10.1017/CBO9780511627057

Panizza, M., & Piacente, S. (2009). Cultural geomorphology and geodiversity. *Geomorphosites*, *January 2009*, 35–48.

Prasad, D. H., & Kumar, N. D. (2014). Coastal Erosion Studies—A Review. *International Journal of Geosciences*, *05*(03), 341–345. https://doi.org/10.4236/ijg.2014.53033

Presley, B., Wade, T., Santschi, P., & Baskaran, M. (1998). *Historical contamination of Mississippi River Delta, Tampa Bay, and Galveston Bay sediments. National status and trends program for marine environmental quality: March*.

Quante, L., Willner, S. N., Otto, C., & Levermann, A. (2024). Global economic impact of weather variability on the rich and the poor. *Nature Sustainability 2024*, *7*(November), 1–10. https://doi.org/10.1038/s41893-024-01430-7

Ramsar Regional Centre – East Asia (RRC-EA). (2020). Rapid Assessment of Wetland Ecosystem Services: A Practitioner's Guide. *Repubilc of Korea*, 44.

S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A, and C. N. Z. (eds.). (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

Sherrouse, B. C., Clement, J. M., & Semmens, D. J. (2011). A GIS application for assessing, mapping, and quantifying the social values of ecosystem services. *Applied Geography*, *31*(2), 748–760. https://doi.org/10.1016/j.apgeog.2010.08.002

Smyth, A. R., Reynolds, L. K., Barry, S. C., Stephens, N. C., & Patterson, J. T. (2022). *Ecosystem Services Provided by Living Shorelines*. 1–6.

Hoàng Văn Thắng. (2015). Đánh Đổi Các Dịch Vụ Hệ Sinh Thái Trong Bối Cảnh Biến Đổi Khí Hậu. *Kỷ Yếu Hội Thảo "Đa Dạng Sinh Học và Bảo Tồn,"* 3–13.

Thornbush, M. (2015). Geography, urban geomorphology and sustainability. *Area*, *47*(4), 350–353. https://doi.org/10.1111/area.12218

Urban, M. A., & Daniels, M. (2006). Introduction: Exploring the links between geomorphology and ecology. *Geomorphology*, *77*(3–4), 203–206. https://doi.org/10.1016/j.geomorph.2006.01.004

Van Ree, C. C. D. F., van Beukering, P. J. H., & Boekestijn, J. (2017). Geosystem services: A hidden link in ecosystem management. *Ecosystem Services*, *26*, 58–69. https://doi.org/10.1016/j.ecoser.2017.05.013

Vinh, V. D., Thi, C., & Trang, T. (2012). *Mô hình toán phục vụ đánh giá sức tải môi trường khu vực Vịnh Hạ Long - Bái Tử Long. January*.

Vũ Trung Tạng. (2020). Vùng cửa sông: Quy hoạch định hướng trên quan điểm hệ sinh thái. *Tạp Chí Phát Triển Khoa Học và Công Nghệ*, 9.

Waage, S. (2014). New business decision-making aids in an era of complexity, scrutiny, and uncertainty: Tools for identifying, assessing, and valuing ecosystem services. *Handbook on the Economics of Ecosystem Services and Biodiversity*, *May*, 546–565. https://doi.org/10.4337/9781781951514.00040

https://doi.org/10.5194/egusphere-2025-3519
Preprint. Discussion started: 30 December 2025

Warrick, J. A., Buscombe, D., Vos, K., Bryan, K. R., Castelle, B., Cooper, J. A. G., Harley, M. D., Jackson, D. W. T., Ludka, B. C., Masselink, G., Palmsten, M. L., Ruiz de Alegria-Arzaburu, A., Sénéchal, N., Sherwood, C. R., Short, A. D., Sogut, E., Splinter, K. D., Stephenson, W. J., Syvitski, J., & Young, A. P. (2024). Coastal shoreline change assessments at global scales. *Nature Communications*, *15*(1), 2023–2025. https://doi.org/10.1038/s41467-024-46608-x

Weinstein, M. P. (2008). Ecological restoration and estuarine management: Placing people in the coastal landscape. *Journal of Applied Ecology*, *45*(1), 296–304. https://doi.org/10.1111/j.1365-2664.2007.01355.x

Yuen, K. W., Park, E., Tran, D. D., Loc, H. H., Feng, L., Wang, J., Gruel, C. R., & Switzer, A. D. (2024). Extent of illegal sand mining in the Mekong Delta. *Communications Earth and Environment*, *5*(1), 1–13. https://doi.org/10.1038/s43247-023-01161-1

https://doi.org/10.5194/egusphere-2025-3519
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705 **Appendix A: Indicator table for assessing estuarine ecosystem services in Vietnam**

Ecosystem services		**Indicators**
Provisioning services	*Crops (human nutrition)*	Quantity of plants usable for human nutrition.
	Fish and Seafood	Quantity of seafood, algae useable for food, fish meal and fish oil.
	Livestock	Capability/ quantity of domestic animals useable for nutrition and related products (dairy, wool).
	Timber	The mass of wood useable for human purposes (e.g. construction,...)
	Minerals	Minerals extractable close from surface or above surface (e.g. sand for construction, lignite, gold, salts).
Regulating services	*Erosion regulation*	Protect and minimize disasters related to floods, storms, erosion,...
	Water flow regulation	Water cycle feature maintenance (e.g. water storage and buffer, natural drainage, irrigation and drought prevention).
	Flood regulation	Soil retention and the ability to prevent and mitigate soil erosion and landslides.
	Local climate regulation	Changes in local climate components like wind, precipitation, temperature, radiation due to ecosystem properties.
	Global climate regulation	Long-term storage of potential greenhouse gases in ecosystems.
	Air quality regulation	Capturing/filtering of dust, chemicals and gases from air.
Cultural services	Cultural heritage	Values that humans place on the maintenance of historically important (cultural) landscapes and forms of land use (cultural heritage).
	Recreation and tourism	Outdoor activities and tourism relating to the local environment or landscape, including forms of sports, leisure and outdoor pursuit.
	Landscape aesthetics	Visual quality of the landscape/ecosystems or parts of them influencing human well-being and the need to create something as well as the sense of beauty people obtain from looking at landscapes/ecosystems.
	Natural heritage	The existence value of nature and species themselves, beyond economic or direct human benefits.
	Regional identity	Ecosystem elements or processes contribute to a person's personal identity (sense of belonging) or strengthen people's group identity.
	Knowledge systems	Environmental education based on ecosystems/landscapes and knowledge in terms of traditional knowledge and specialist expertise arising from living in this particular environment.

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Appendix B: Matrix to evaluate the potential to provide ecosystem services (ES) of different estuarial ecosystems in Vietnam.

ES group	LULC	Residential					Forest		Agricultural		Wetland						
		ODT	ONT	KDL	CDG	BCS	RPT	LNK	LUC	DCS	NTS	SON	ESD	NSB	ALS	BWS	DWS
Provisioning	Crops (human nutrition)	30	50	5	5	5	5	5	90	40	10	5	5	5	5	5	5
	Fish & Seafood	5	20	5	5	5	10	5	5	5	90	40	5	5	5	60	90
	Livestock	20	40	5	5	20	10	10	10	80	5	5	5	5	5	5	5
	Timber	10	20	5	10	5	5	10	5	5	5	5	5	5	5	5	5
	Minerals	5	5	5	5	5	5	5	5	5	5	30	10	10	10	5	5
Regulating	Erosion regulation, water	20	10	20	10	5	90	70	20	70	5	20	5	20	5	5	5
	Water flow regulation	10	10	10	10	10	90	70	60	70	30	90	60	10	10	10	5
	Flood regulation	20	40	10	5	10	90	70	30	40	10	30	50	20	50	30	40
	Local climate regulation	20	30	10	5	10	90	90	40	40	30	70	20	5	5	40	70
	Global climate regulation	20	30	10	10	5	90	90	40	80	20	30	30	20	20	50	40
	Air quality regulation	10	30	10	5	20	90	80	20	20	10	10	10	5	5	5	5
Cultural	Cultural heritage	40	60	40	10	5	70	10	70	50	40	80	60	70	20	10	10
	Recreation & tourism	30	50	90	5	5	90	20	40	30	50	80	70	90	60	50	70
	Landscape aesthetics	30	40	80	5	5	90	20	50	30	40	90	70	70	70	50	50
	Natural heritage	20	40	40	5	5	90	20	30	40	20	80	80	70	70	30	30
	Regional identity	50	60	60	10	10	90	10	70	20	30	80	60	70	70	50	50
	Knowledge systems	40	40	40	10	5	90	30	40	20	30	80	60	60	60	10	10

In which: ODT: Urban residential lands; ONT: Rural residental lands; KDL: Tourism lands; CDG: Construction sites, industry and commerce; BCS: Bare soil; DCS: Grasslands; LUC: Agricultural lands; LNK: Other perennial trees; RPT: Mangroves/Certified protection forest; NTS: Aquaculture lands; SON: Rivers and streams; ESD: Embryo sandy dune; NSB: Natural sandy beach ; ALS: Alluvial lands; BWS: Brackish water areas; DWS: Deep sea waters.