



# Geoheritage Potential of Karacabey Floodplain Forest (Türkiye): A Layered Assessment of Paleoecological and Geochemical Archives

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## Abstract

This study aims to evaluate the geoheritage potential of the Karacabey Floodplain Forest (Longoz), located in the Marmara Region of Türkiye, through paleoecological and geochemical archive data. As the largest floodplain forest in the country, Karacabey Longoz represents a typical delta–lagoon–flooded forest system and stands out as a rare wetland ecosystem that chronologically records both natural and anthropogenic processes in its stratified sediments. A 24 cm sediment core extracted from Poyraz Lagoon was analyzed for pollen content, revealing ~250-year vegetation and climate change record from a paleoenvironmental perspective. Surface sediment samples from Dalyan Lagoon were examined for heavy metal concentrations and environmental risk indices, indicating significant pollution pressure from industrial and agricultural sources. Using the layered assessment framework developed by Semeniuk and Semeniuk (*Hydrobiologia*, 708(1), 45–67, 2013), (*Australian Journal of Earth Sciences*, 66 (6), 2019) for wetland geoheritage evaluation, the site was qualitatively analyzed across five criteria: representativeness, rarity, diversity, archival value, and conservation potential. Findings demonstrate that Karacabey Longoz should be preserved not only for its biological diversity but also as a geoheritage archive documenting environmental and cultural transformations.

**Keywords** Geoheritage · Biosite · Floodplain forest ecosystem · Paleoecological archive · Heavy metal analysis · Wetland management

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## Introduction

### The Concepts of Geoheritage and Biosite

The concept of natural heritage has long been addressed primarily along the axis of biological diversity, while geological and geomorphological elements have remained relatively in the background. However, the preservation of geological formations that represent the evolution of the Earth and record past environmental conditions is of great importance. Indeed, under the term geoheritage, it has been emphasized that geoheritage elements possessing scientific, aesthetic, or educational value for society should be preserved (Gray 2013, 2019; Claudino-Sales 2021; Kaur 2022; Herrera-Franco et al. 2022; Drinia et al. 2023). Within this framework, rocks, fossils, landforms, stratigraphic records, and paleoecological archives are evaluated as geoheritage (geodiversity) (Ruban 2010; Pal and Albert 2021; Crisp et al. 2021; Claudino-Sales 2021; Santos and Mansur 2024) and its conservation (geoconservation) (Burek and Prosser 2008; Anougmar et al. 2024) have become an important

component of contemporary nature conservation studies (Kaur 2022; Kubalíková 2023). In recent years, the focus of geoheritage research has expanded from terrestrial rocks and landforms to environments such as wetlands, coastal areas, and lagoon systems (Salvadeo et al. 2025). Although the geological and geomorphological heritage elements of wetlands are often overlooked, these environments hold significant potential for the development of geotourism and its outreach to broader audiences (Coratza et al. 2019). Especially in systems such as swamps, lakes, and floodplain forests (longoz), accumulated sediment layers are understood to be strong natural archives that reflect climate–sea level changes, paleoenvironmental variations, and human influences, since they are better preserved than those in continental areas (Semeniuk and Semeniuk 2004, 2005, 2006, 2013, 2019; Hein et al. 2016; Coratza et al. 2019; Pal and Albert 2021). For this reason, it has been revealed that in the conservation of wetlands, geoheritage archive value should also be taken into account in addition to biological values.

Areas where geoheritage elements coexist with living ecosystems represent the intersection of geological, geomorphological and biological heritage. In this context, the study brings forward the concept of biosite. Within a geopark, geological and geomorphological elements are categorized as geosites, while biological elements are categorized as biosites (Sulistiyowati et al. 2022; Santos and Mansur 2024). A biosite is a term that can be used to emphasize that a given area harbors both biological and geoheritage values simultaneously (Sulistiyowati et al. 2022). In the case of the Karacabey Floodplain Forest, biological and geoheritage values are intertwined: the sediment layers store the records of both natural and human-induced processes spanning centuries (Agostinho et al. 2000, 2004). This characteristic renders the floodplain forest a multidimensional site not only for scientists but also for educators, students, and nature enthusiasts. Although the term “biosite” is sometimes used in the literature solely to emphasize biological significance, in this study the concept of biosite is proposed as a conceptual innovation from a geo-bio heritage perspective.

### The Aim and Significance of the Study

The floodplain (longoz) forests observed in the Marmara and Black Sea regions of Turkey are rare ecosystems periodically subjected to flooding and possess unique geological, geomorphological and ecological values. The main floodplain forests in Turkey that remain largely preserved are the İğneada, Acarlar, and Karacabey floodplain forests. Located within the boundaries of the Karacabey district of Bursa Province, in the delta of the Susurluk (Kocasu) River, the Karacabey Floodplain Forest is the largest floodplain

forest in terms of surface area (Figs. 1 and 2). This wetland, which encompasses freshwater lakes, reed swamps, seasonal floodplain forests, and coastal dune habitats, hosts approximately 300 bird species and is recognized as a center of biodiversity of international importance. Moreover, the Karacabey Floodplain Forest includes Turkey’s only natural linden (*Tilia* sp.) forest and is notable for containing one of the world’s few extensive linden forests. The formation and sedimentary structure of the floodplain ecosystem is a product of river–sea interaction, where alluvial processes have created a layered environmental archive. In the soil and peat layers, traces of climatic and anthropogenic events from the recent geological past have been preserved.

Scientific studies conducted in recent years in the Karacabey Floodplain Forest have highlighted the importance of this geoheritage archive. For example, heavy metal analyses performed on surface sediment samples taken from the Dalyan and Poyraz lagoons revealed that the region has been exposed to significant levels of anthropogenic pollution. In particular, the accumulation of cadmium (Cd) and mercury (Hg) posed a medium level of ecological risk at certain stations, while the toxic risk values associated with metals such as nickel (Ni), chromium (Cr), and arsenic (As) reached critical levels for human health (Aykır et al. 2023). On the other hand, pollen analysis conducted on a 24-cm sediment core obtained from the Poyraz Lagoon illuminated the vegetation and climate history of the floodplain forest and its surroundings over the last ~250 years. This palynological record showed that since the 1850s, tree species characteristic of floodplain forests such as *Fraxinus* (ash), *Alnus* (alder), and *Ulmus* (elm) had markedly increased in cover, while the proportions of *Castanea* (chestnut), *Olea* (olive), and certain herbaceous pollen types (*Chenopodiaceae*, *Poaceae*) indicative of human influence had also risen. Thus, it became evident that the floodplain ecosystem recorded both natural changes and human-induced transformations in a stratified manner (Karlıoğlu et al., 2024).

These findings demonstrate that the Karacabey Floodplain Forest holds a unique archival value not only from a biological perspective but also from a geological and geomorphological perspective. However, this value has not yet been evaluated within a geoheritage framework. Therefore, the primary aim of this study is to assess, through a holistic method, the geoheritage potential of the paleoecological and geochemical archives contained within the Karacabey Floodplain Forest. In this regard, the layered analytical approach proposed in the literature for wetland ecosystems by Semeniuk and Semeniuk (2013) and Semeniuk and Semeniuk (2019) has been integrated (Table 1).

This has been adapted from the geoecological system approach developed by Semeniuk and colleagues in the



Fig. 1 Location map of study area

Fig. 2 East to west view of the Karacabey Floodplain Forest, with the lagoons clearly visible in the upper right corner



Swan Coastal Plain. In the Karacabey Floodplain Forest, morphology–hydrology–stratigraphy–palynology components were considered together, and selected biosites (Poyraz, Dalyan) were evaluated as representative units.

No quantitative scoring was carried out; instead, criteria such as representativeness, rarity, diversity, archival value, and management/conservation potential were interpreted through a qualitative hierarchy (Tables 2 and 3).

**Table 1** Data used in determining the geoheritage values of wetland ecosystems (adapted from Semeniuk and Semeniuk 2019)

Criteria	Indicators	Justification for Geosite Evaluation	Evidence/Data Source
Representativeness			
Rarity			
Diversity			
Archival Value			
Management and Conservation Potential			

The indicator and justification fields are intentionally left blank at this stage. They are context-specific and are elaborated in the Results section, where the evaluative framework is applied to the floodplain wetland case study. This format was adopted to emphasize the methodological structure rather than pre-emptively filling evaluative details

Specifically, two data sources with geoheritage significance within the floodplain were considered: (1) a sediment core with pollen analysis obtained from the Poyraz Lagoon (a paleoecological archive), and (2) surface sediment samples taken from the Dalyan Lagoons, together with the results of heavy metal and risk analyses (a geochemical archive). These data sources were qualitatively examined using Semeniuk's (2019) approach to evaluate the integrative characteristics of the floodplain ecosystem. Thus, the geo-bio heritage value of the Karacabey Floodplain Forest was analyzed multidimensionally, encompassing both the observable surface features and the archival properties hidden within sedimentary layers. The results aim to contribute to the recognition of wetlands as geoheritage and to provide a scientific foundation for decision-makers to preserve floodplain forests such as Karacabey not only for their biological significance but also for their geoheritage archival value.

## Materials and Methods

### Study Area

The Karacabey Floodplain Forest is located within the boundaries of Bursa Province, on the southern coast of the Sea of Marmara, on the delta of the Susurluk (Kocasu) River (Figs. 1 and 2).

The floodplain forest and associated wetlands form a complex system in which interactions between freshwater and saltwater are observed. In the region, various geomorphological units coexist, including seasonally flooded forests (floodplain forests), two lagoon lakes (Dalyan and Poyraz), freshwater swamps, and coastal dunes (Figs. 3, 4, 5, 6, 7, 8, 9, 10 and 11).

A pronounced seasonal hydrological cycle is observed, characterized by rising water levels due to spring

precipitation and river flooding, and receding waters during the summer months. The alluvial plain where the floodplain forest has developed is surrounded by extensive agricultural lands and settlements, which exert pressures on the wetland through agricultural drainage, pollution, and land-use changes (Figs. 2, 9, 10 and 12). Accordingly, the Karacabey Floodplain Forest is regarded as a natural heritage site of national importance, as it represents one of the rare wetland ecosystems in which ecological, geological and geomorphological processes are interwoven.

## Data and Analyses

### Paleoecological Data (Core and Pollen Analyses)

In order to shed light on the recent past of the floodplain ecosystem, a paleoecological study was carried out on the shore of the Poyraz Lagoon, and its results were used (Karlioğlu et al., 2024). The upper 24 cm of a sediment core retrieved from the bottom of the lagoon was analyzed. AMS radiocarbon dating of a sample taken from the lowest organic layer of the core yielded a calibrated age of  $\sim 238 \pm 24$  BP (approximately 1712 CE), indicating that the core represents the accumulation of the last  $\sim 240$  years. Samples were taken at 4 cm intervals along the core; pollen extractions were performed using standard palynological techniques, and at least 250 terrestrial pollen grains were counted under a microscope for each level. The resulting pollen diagrams were interpreted to reveal the temporal changes in the composition of regional vegetation. Changes in the relative proportions of arboreal pollen (e.g., *Fraxinus*, *Alnus*, *Ulmus*) versus herbaceous/reed and agricultural plant pollen were examined according to the stratigraphically defined zones in the vertical profile (Karlioğlu et al., 2024). In this way, the climatic and vegetational dynamics of the floodplain during the last few centuries, as well as transformations induced by human influence, were reconstructed from a paleoenvironmental perspective.

The palynological record in question parallels a similar approach applied by Semeniuk (2013, 2019) in the wetlands of the Swan Coastal Plain in Australia, where Holocene climate and environmental changes were interpreted through the combined analysis of stratigraphic, pollen, and radiocarbon data. Similarly, the pollen data obtained from the Karacabey Floodplain were evaluated together with their stratigraphic positions and datings, thereby enabling a holistic analysis of both the natural development of the floodplain and the impacts of human activity.

Accordingly, pollen records from the last 250 years in the Poyraz Lagoon indicate that the regional vegetation has been consistently dominated by floodplain species such as *Fraxinus* sp., *Alnus* sp., *Corylus* sp.,

**Table 2** Integrated evaluation of the Karacabey floodplain (Poyraz and Dalyan Lagoons) based on the Semeniuk (2019) wetland geoheritage approach (Semeniuk & Semeniuk,2019)

Criteria	Indicators	Poyraz Lagoon (Evaluation+Justification)	Dalyan Lagoon (Evaluation+Justification)	Evidence/Data Source
Representativeness	Typical morphology of delta–lagoon–floodplain system; stratigraphic continuity; presence of pollen zones; consistency with present hydrology	HIGH – Poyraz represents a typical example of the delta–lagoon–floodplain system in Karacabey. Clear stratification and pollen zones were observed in the core; forest and reed components are consistent with present hydrodynamics.	MODERATE–HIGH – Dalyan well represents lagoon morphology; however, since it is represented only by surface sediments, stratigraphic continuity and direct record of the past are limited.	Poyraz: core (24 cm), pollen diagram; Dalyan: surface sediment, morphological observations.
Rarity	Frequency of lagoon + floodplain forest association in the Marmara region; number of similar types	HIGH – The lagoon–floodplain forest association is rare in the Marmara region; Poyraz clearly exhibits this combination.	HIGH – Dalyan is also part of the same rare combination; coastal lagoon and reed zones are distinctive.	Regional literature and maps; field observations.
Diversity	Geomorphic subunits (lagoon mirror, coastal ridge, reedbed, alluvial surface, channel); hydrological zones (fresh/brackish); pollen diversity	HIGH – Coexistence of lagoon mirror + reedbeds + floodplain forest; arboreal pollen (AP) and non-arboreal pollen (NAP) taxa together in pollen record. Seasonal hydrological zonation is distinct.	MODERATE–HIGH – Lagoon and reedbed diversity is high; however, stratigraphic/palynological diversity record is short-term (surface).	Poyraz: pollen sequence and stratigraphic record; Dalyan: habitat observations, surface sediment.
Archival Value	Continuity of record (core length); chronology (AMS 14 C); clarity of pollen zone boundaries; distinguishability of human/climate signals	MODERATE–HIGH – ~24 cm core, AMS age at lowest level (~238 ± 24 BP). Clear increases in anthropogenic indicators and changes in forest taxa at upper levels; strong record focused on last few centuries rather than Holocene scale.	LOW–MODERATE – Only surface sediments are available, thus long-term archival value is limited; valuable as a short-term indicator of present conditions.	Poyraz: AMS dating, pollen zones; Dalyan: heavy metal/ecological risk as indicator of present conditions.
Management and Conservation Potential	Conservation status; human pressure (agriculture, drainage, tourism, industry); accessibility and monitoring capacity	MODERATE – Partial protection and nature conservation rules exist; however, agricultural and industrial pressures and potential hydrological interventions remain.	MODERATE – Similar pressures exist in Dalyan; tourism/recreation and coastal land-use pressures increase management needs.	Local legislation and monitoring data; heavy metal/ecological risk findings (indicator of current pressures).

*Carpinus* sp., and *Quercus cerris*. During the period AD 1710–1847, ash, alder, and deciduous oak exhibited high pollen percentages, and these taxa continued to persist during AD 1847–2021, reflecting increasingly moist conditions. The pronounced rise of *Fraxinus* sp., *Alnus* sp., and *Ulmus* sp. in the modern period demonstrates a strengthening of floodplain forest dynamics. The region’s Csa climate type and semi-humid character

align well with these findings. Comparisons with records from Lake Mert support a similar regional trend in the development of floodplain (longoz) forests. The increase in anthropogenic indicator taxa such as *Castanea* sp., *Olea* sp., Poaceae, and Chenopodiaceae during the AD 1847–2021 interval points to the growing influence of agricultural and settlement activities on the ecosystem after AD 1850 (Karlıoğlu et al., 2024).

**Table 3** Evaluation of the Karacabey floodplain forest according to Semeniuk and Semeniuk (2019) approach

Criterion	Evaluation	Explanation
Representativeness	High	The Poyraz and Dalyan lagoons represent the Karacabey area well as a typical delta–lagoon–floodplain system in the Marmara Region.
Rarity	High	The coexistence of floodplain forests and lagoons is represented by only a very limited number of examples in Turkey.
Diversity	High	Lagoons, reedbeds, floodplain forests, and deltaic depositional surfaces coexist, providing ecological and geomorphological diversity.
Archival Value	Moderate–High	The pollen records obtained from the Poyraz core reflect the environmental changes of the last ~250 years. Although shorter in duration compared to the Swan examples, it constitutes a strong archive.
Management and Conservation Potential	Moderate	The site has partial protection status, but agricultural, industrial, and tourism pressures continue. Conservation strategies need to be strengthened.

**Fig. 3** Entrance of the Karacabey Floodplain Forest

**Geochemical and Risk Data (Sediment Analyses and Heavy Metals)** To understand the current environmental status of the floodplain and the anthropogenic pressures to which it is exposed, sediment pollution data obtained from the Dalyan and Poyraz lagoons were examined (Aykır et al. 2023). Eighteen surface sediment samples (0–5 cm) were collected from the Dalyan Lagoon, and a short sediment core extending to a depth of 40 cm was extracted from the Poyraz Lagoon. Concentrations of potentially toxic elements (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, etc.) were analyzed in the collected samples using inductively coupled plasma mass spectrometry (ICP-MS). In order to obtain clues about

**Fig. 4** View of the section where the Susurluk River, the freshwater source of the Karacabey Floodplain Forest, flows into the Sea of Marmara**Fig. 5** Karacabey Longoz Forest contains every shade of green

the transport and accumulation processes in sediments, total organic carbon (TOC), carbonate percentage, and chlorophyll degradation products (pigments) were also measured. The heavy metal concentrations obtained were interpreted using various environmental risk indices to assess sediment quality and pollution levels. For example, the Modified Ecological Risk Index (mPER) and the Ecological Contamination Index (ECI), which consider the enrichment and toxicity potential of each element relative to its background value, were calculated. Similarly, the Hazard Quotient (HQ) and Lifetime Cancer Risk (LCR) values were calculated to evaluate the possible impacts of accumulated pollutants in sediments on human health. The scales used in the evaluation of the data are provided in Supplementary Data 1. These geochemical analysis results were recently published by Aykır et al. (2023), showing that the Dalyan and Poyraz



**Fig. 6** Wetlands of various sizes can be seen in the Karacabey longoz forest area



**Fig. 7** Rich biological diversity observed in the floodplain area



**Fig. 8** Rich biological diversity observed in the floodplain area



**Fig. 9** Animal husbandry is widely practiced in the floodplain area, with small ruminants visible in the photograph



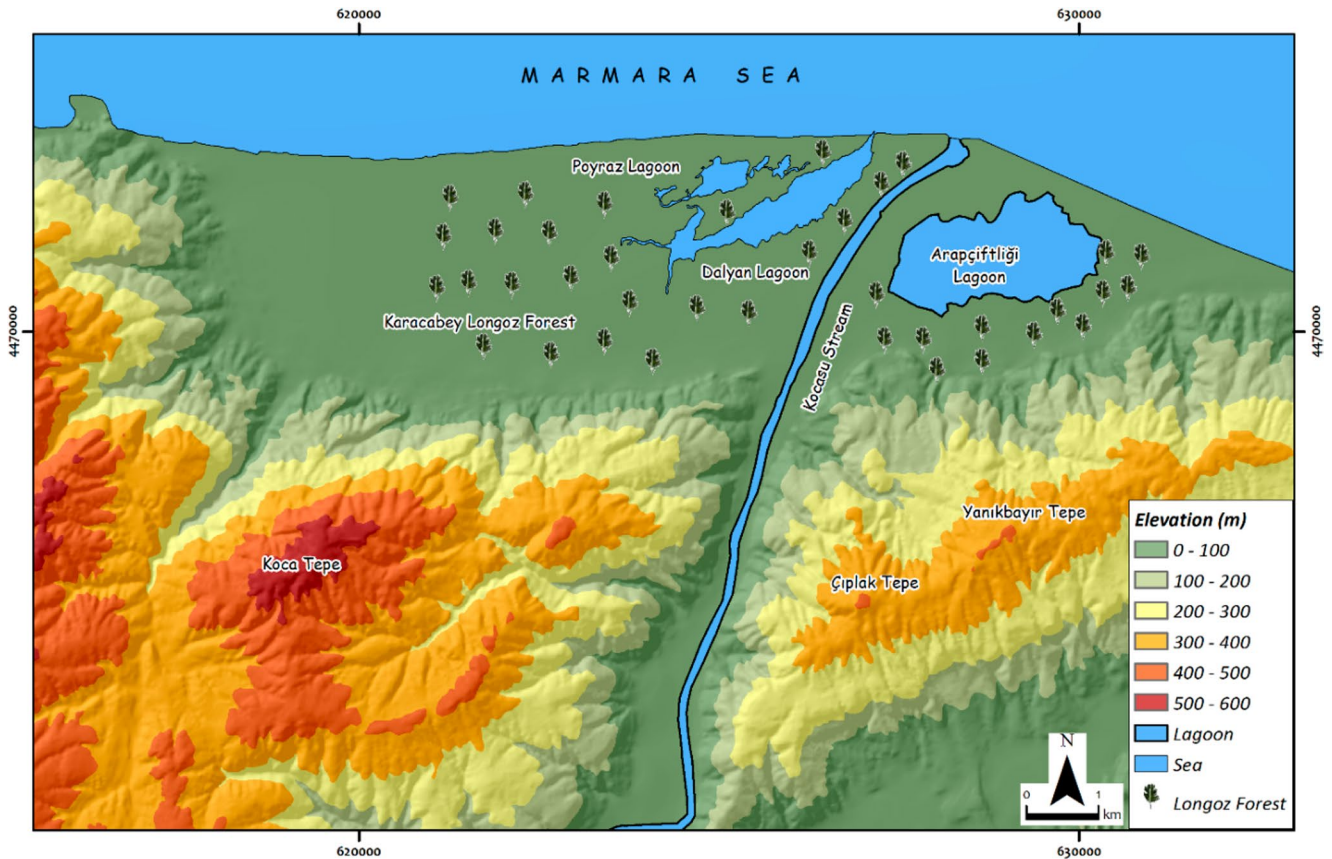
**Fig. 10** Cattle breeding activities continuing in the floodplain forest

lagoons carry a medium level of ecological risk particularly due to Cd and Hg accumulation, and that carcinogenic risks associated with some metals, especially Ni, exceeded acceptable thresholds. Consequently, critical information was obtained regarding the level of pollution in the floodplain and its implications for both the ecosystem and public health. These data directly contributed to the “conservation priority” criterion in our evaluation, quantitatively revealing the extent of threats and risks in the region.

**Evaluation Method**

**Semeniuk and Semeniuk (2013, 2019) Approach – Geo-bio Heritage of Wetlands**

The approach developed by Semeniuk and Semeniuk (2013, 2019), particularly for the wetlands of the Swan Coastal Plain in Australia, emphasizes not only individual geological



**Fig. 11** Elevation levels map of study area. Study area is located on the delta plain formed where the Susurluk River flows into the Sea of Marmara

formations but also the holistic functioning of the ecosystem and its layered archival capacity when evaluating the geoheritage value of wetland ecosystems. In this method, a swamp/floodplain area is examined in dimensions such as geomorphological unit characteristics, hydrological regime, biotic components, ecosystem functionality, and the continuity of human impacts. In other words, the value of wetlands as paleoenvironmental archives is assessed together with current ecosystem dynamics and human-interactive processes (Tables 1, 2 and 3).

In this study, based on Semeniuk and Semeniuk (2019), the attributes of the floodplain ecosystem considered important from the perspective of geoheritage were addressed under three headings: ecosystem archival depth (capacity for creating layered stratigraphic and geochemical records), ecosystem functionality (status of hydrological and ecological processes), and geo-cultural interaction (interaction between natural processes and human activities).

### Rationale for Methodological Choice

Although Brillha's (2016) quantitative, score-based framework has proven effective in geoheritage site comparisons, its application to floodplain wetlands may lead to conceptual

inconsistencies. Wetland systems are characterized by dynamic hydrological regimes, morphological variability, and ecological processes that cannot be adequately captured through static scoring. In contrast, Semeniuk's (2019) qualitative, process-oriented model directly addresses wetland morphology and hydrodynamics, offering a more context-specific and functionally coherent approach. For this reason, Brillha's framework was not applied in the present study.

### Results

The concept of a "biosite," due to its ability to represent key examples of biological diversity, ecosystem processes, and habitat continuity, can serve as an important tool that can be integrated into geotourism planning, wetland conservation strategies, and geotourism education in Turkey. Identifying biosites within geoparks supports a holistic "geo-bio heritage" approach by enabling the recognition of ecological values alongside geoheritage elements. In sensitive habitats such as floodplain forests, lagoon systems, and coastal wetlands, the designation of biosites can guide management plans in terms of ecological carrying capacity, habitat connectivity, and species conservation priorities. In

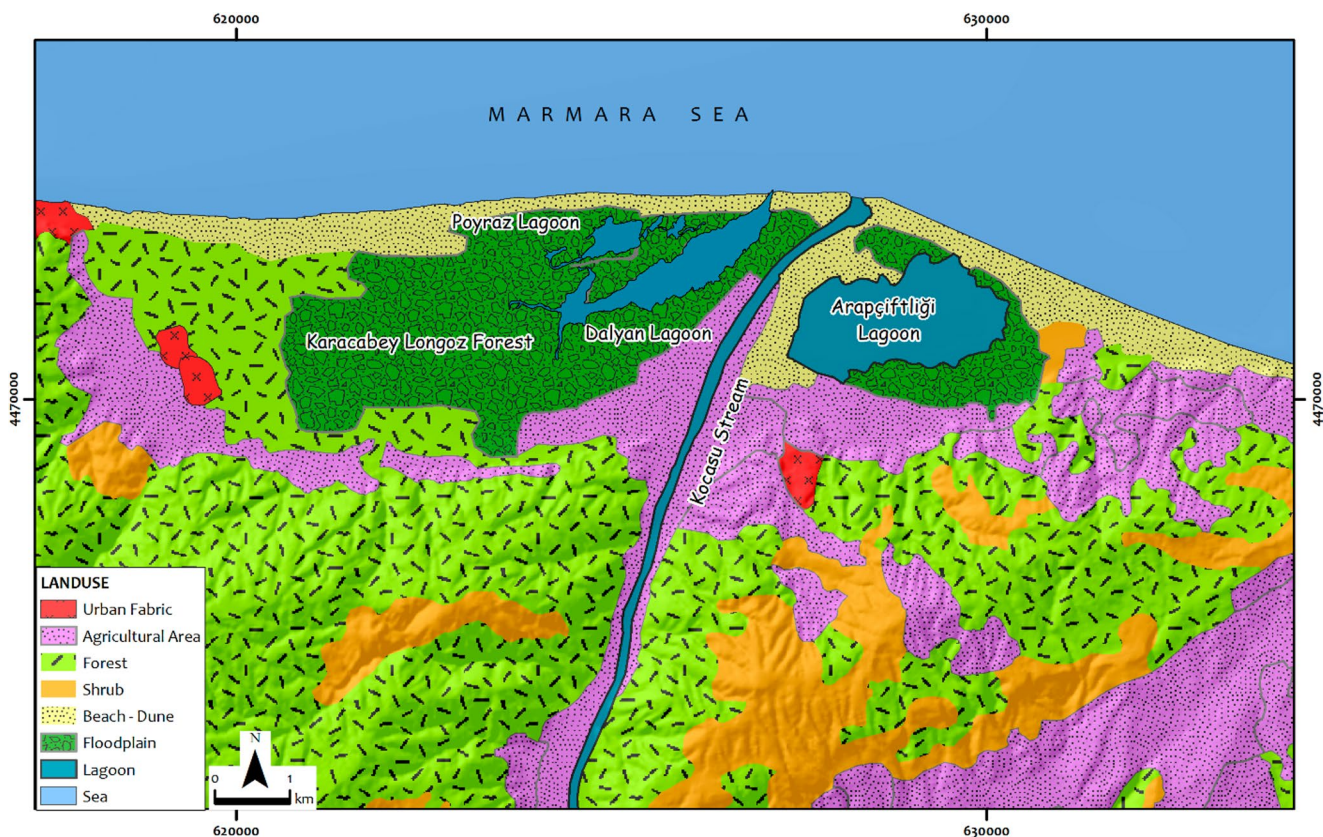


Fig. 12 Landuse map of study area

the context of educational geotourism, biosites offer exemplary field areas where students and visitors can observe the simultaneous functioning of geological, geomorphological and biological processes, thereby strengthening field-based, interdisciplinary learning. Thus, the biosite approach can play a strategic guiding role for geopark management, wetland conservation, and interdisciplinary environmental education (Semeniuk and Semeniuk 2013, 2019; Brilha 2016).

**Biosite 1: Poyraz Lagoon (Core – Palynological Archive)**

**Paleoenvironmental Record and Significance** The pollen-analyzed sediment core obtained from the Poyraz Lagoon has stratigraphically recorded the environmental changes of the floodplain forest and its surroundings over the past several centuries. The high proportions of flood-tolerant tree pollen (particularly *Alnus* sp. and *Fraxinus* sp.) within the core layers indicate that, in the past as well, the floodplain forest represented a water-saturated swamp ecosystem similar to its present condition.

The findings reveal that the floodplain has functioned as a continuous stratigraphic data carrier, showing that no radical change occurred in the ecosystem over centuries and that the natural structure has been preserved. On the other

hand, relative changes in pollen composition shed light on regional environmental fluctuations. For example, decreases in *Pinus* sp. (pine) pollen percentages and increases in the steppe plant *Artemisia* sp. pollen suggest that there were past phases of reduced climatic humidity and relative aridification. Such paleoecological evidence supports Semeniuk’s emphasis on the role of wetlands as paleo-climate archives (Semeniuk 2013, 2019).

In conclusion, the Poyraz Lagoon core represents a highly valuable archive containing biological indicators of climate change (in the form of pollen records) and constitutes an important element of geoheritage with both high scientific and educational significance (Tables 2 and 3).

**Biosite 2: Dalyan Lagoon (Surface Sediment – Heavy Metal and Risk Analysis)**

**Geochemical Record and Significance** The geochemical findings of the floodplain ecosystem make a significant contribution to its geoheritage value by revealing the recent anthropogenic impacts and environmental risks in the region. Analyses of sediment samples from the Dalyan and Poyraz lagoons demonstrated that pollution originating from industrial and agricultural activities has left a stratigraphic imprint in the sedimentary layers (Aykir et al.

2023). In other words, the Karacabey Floodplain records not only natural processes but also the effects of human activities in chronological order within its sediments. This phenomenon constitutes a concrete example of Semeniuk's concept of geo-cultural interaction (Semeniuk et al., 2013, 2019), wherein anthropogenic signatures can be discerned within natural deposits. Indeed, the variations in heavy metal concentrations throughout the sediment depths reveal the historical trajectory of industrial and agricultural activities in the region. Furthermore, the risk indices calculated for sediment quality quantitatively express that certain parts of the floodplain ecosystem are exposed to serious levels of ecological stress.

For example, high Enrichment Factor (EF) values indicate excessive accumulation of certain metals compared to the natural background, while ecological risk indices such as the Modified Potential Ecological Risk Index (mPER) show that there is a risk of permanent damage to the ecosystem at some sites. Similarly, the calculated Lifetime Cancer Risk (LCR) values indicate that pollutants accumulated in the sediments may also pose a non-negligible threat to public health. All of these data demonstrate that the geochemical archive of the floodplain is a critical record documenting human-induced environmental changes for the future (Tables 2 and 3).

**Evaluation According To Semeniuk's Method (Ecosystem and Process Analysis)** Within the framework of Semeniuk's wetland-focused approach, the geoheritage value of the Karacabey Floodplain has been examined in three main dimensions: ecosystem depth, ecosystem functionality, and geo-cultural interaction. The layered archival depth of the floodplain ecosystem has been evaluated as high, since the sediments it accumulates are capable of recording both natural (climate, vegetation) and anthropogenic (pollution, land use) processes over the long term (Tables 2 and 3). Indeed, the soil and sediment layers of the floodplain possess the capacity to preserve both natural changes and human influences spanning centuries.

Ecosystem functionality, however, has been evaluated as partially degraded. The hydrological cycle of the floodplain, shaped by seasonal floods, is sensitive to external pressures; due to impacts such as agricultural drainage and pollution, it can be argued that the self-regulation capacity of the floodplain has begun to be constrained. For this reason, the functional state of the ecosystem has been rated at a moderate level (Tables 2 and 3).

In terms of geo-cultural interaction, the floodplain has been regarded as possessing very high value, since it represents an area where natural processes and human activities are intertwined. The fact that traces of industrial and

agricultural activities (e.g., metal accumulations) can be read in the sedimentary archive of the floodplain clearly demonstrates the interaction between geoheritage and cultural/human processes. This adds a distinctive dimension to the geoheritage value of the site and enhances its importance from both a scientific and historical perspective (Tables 2 and 3).

In this context, the mentioned geochemical sequences are directly associated with the scientific geoheritage category defined by Gray (2019), as the sedimentary and chemical records provide a unique geoscientific dataset that enables the high-resolution reconstruction of recent environmental processes and anthropogenic influences. Moreover, the ability to interpret anthropogenic signatures within sediments alongside natural depositional processes strengthens the cultural geoheritage dimension of the area by allowing environmental change to be traced in parallel with societal, economic, and technological practices. These records also fall within the scope of educational geoheritage, as the sedimentary archive serves as a field-based, interdisciplinary laboratory for the instruction of environmental geochemistry, geodiversity, ecosystem responses, and geo-cultural interactions. Finally, the stratigraphic continuity and natural integrity of the sedimentary structures within the floodplain forest, in accordance with Gray's definition of aesthetic geoheritage, constitute a geomorphological aesthetic value grounded in the legibility of geological processes and enhance the perceived heritage significance of the site.

## Discussion

This study conducted in the Karacabey Floodplain demonstrates that wetlands should be evaluated not only in terms of biological diversity but also with respect to their geoheritage potential. The pollen-analyzed sediment core obtained from the Poyraz Lagoon has provided a high-resolution paleoenvironmental record of the climatic and vegetational changes in the floodplain ecosystem over the past several centuries. This record is consistent with Semeniuk's approach to evaluating wetlands as paleo-climate archives. In particular, the continuity of pollen percentages of flood-tolerant tree species indicates that the natural structure of the floodplain has been preserved and that it presents an archive with stratigraphic continuity.

The geochemical data obtained from the Dalyan Lagoon, on the other hand, quantitatively revealed the recent anthropogenic pressures and environmental risks of the region. Heavy metal accumulations and risk indices demonstrated that the sedimentary layers of the floodplain bear the traces of human activities, thereby providing a high heritage value in terms of geo-cultural interaction. These findings support

Semeniuk's proposal that wetlands, where natural processes and human impacts are intertwined, should be included within the scope of geoheritage.

The evaluation of both biosites revealed that the Karacabey Floodplain possesses high geoheritage potential in terms of representativeness, rarity, and diversity, and medium-to-high potential in terms of archival value and conservation capacity. However, external pressures on ecosystem functionality (agricultural drainage, industrial pollution, tourism activities) threaten the self-regulation capacity of the floodplain. This indicates that conservation strategies should be restructured to encompass not only biological diversity but also the geological archival significance of the ecosystem.

In conclusion, evaluating wetlands such as the Karacabey Floodplain from a geoheritage perspective offers a new approach both scientifically and managerially. The conservation of such areas is critically important not only for current ecosystem services but also for transmitting environmental and cultural knowledge of the past to future generations.

### The Concept of Biosite: Its Place in the Literature and Conceptual Innovation

The integration of geoheritage and biological heritage concepts is a perspective that has only recently begun to be emphasized in literature. The classical approach in geoheritage studies defines conservation and value through the concept of "geosite," focusing entirely on abiotic elements (Gray 2013, 2019; Brilha 2016, 2018). However, the holistic value of ecosystems emerges from the interaction of biotic and abiotic components. As an increasing trend in scientific studies, it has been emphasized that geoheritage and bioheritage elements in terrestrial and aquatic environments should be addressed through a holistic approach (Coratza et al., 2019; Claudino-Sales 2021). Indeed, within the framework of geobiology, issues such as the influence of biological processes on geological records and their joint conservation have come to the fore.

Nevertheless, the use of the term "biosite" in the literature remains quite limited. In some sources, the expression "biosite" is used primarily to denote areas of biological importance. In this study, however, the concept of biosite has been conceptualized to define biological ecosystems that also contain geological and geomorphological archival value. In this sense, the biosite concept goes one step beyond the concept of geosite by addressing geoheritage within the context of living ecosystems. This perspective, which we seek to contribute to the literature, underscores the necessity of incorporating ecological context and human-interactive processes into geoheritage assessments. In the future, the "geo-bio heritage" or "biosite" approach may expand to

encompass the social and ecological dimensions of geoheritage, thereby making significant contributions to conservation efforts.

## Conclusion and Recommendations

This study has evaluated the geoheritage potential of the Karacabey Floodplain in light of paleoecological and geochemical data, revealing that wetlands should be considered not only for their biological significance but also as natural archives documenting stratigraphic and cultural processes. The pollen-analyzed sediment core obtained from the Poyraz Lagoon functions as a paleoenvironmental archive by recording, in high resolution, the climatic and vegetational changes of the floodplain ecosystem over the last ~250 years. The surface sediment samples collected from the Dalyan Lagoon, on the other hand, quantitatively revealed the recent anthropogenic pressures and environmental risks of the region, demonstrating that industrial and agricultural activities have left traces within the sedimentary layers.

Based on Semeniuk's wetland geoheritage approach, the evaluation determined that the Karacabey Floodplain holds high heritage value in terms of representativeness, rarity, and diversity, and medium-to-high value in terms of archival capacity and conservation potential. In particular, in the dimension of geo-cultural interaction, it possesses a unique value as an environmental archive in which natural processes and human activities are intertwined.

In this context, the conservation of wetlands such as the Karacabey Floodplain is critically important not only for sustaining ecological diversity but also for transmitting environmental and cultural knowledge of the past to future generations. The integration of a geoheritage perspective into wetland management strategies will contribute both to scientific understanding and to managerial decision-making processes.

**Official Protection and Inventory** Considering its geoheritage potential, the Karacabey Floodplain should be nominated for a geopark or a similar protection status. The geosites/biosites within the floodplain should be included in the national geoheritage inventory, and specific conservation regulations should be enacted for the area. In this way, the legal framework and resources for the area's preservation will be strengthened, providing long-term protection.

**Monitoring and Management** The sources of heavy metal pollution in the floodplain (industrial facilities, agricultural drainage, etc.) should be strictly controlled, and regular environmental monitoring programs should be implemented. Basin-scale remediation efforts should be planned to reduce

the accumulation of pollutant metals, particularly Cd, Hg, and Pb. Furthermore, the hydrological balance of the ecosystem should be maintained, minimizing interventions into the natural water regime of the floodplain (e.g., by controlling agricultural drainage channels).

**Education and Awareness** To benefit from the educational potential of the area, field education programs should be organized in cooperation with universities, schools, and non-governmental organizations. For visitors to the floodplain, informative panels should be prepared that present both the climate narrative revealed by pollen analysis and the environmental message conveyed by heavy metal accumulation. In this way, both local residents and visitors can be made more aware of the geological, geomorphological and ecological values of the floodplain.

**Sustainable Geotourism** Controlled eco-geotourism activities encompassing the floodplain forest and lagoons should be encouraged. For example, walking trails and bird/habitat observation points could be created along specific routes, and geo-tourism tours could be organized with expert guides. In this way, economic benefits could be provided to the local community while increasing awareness of geoheritage among visitors. The fundamental principle should be that geotourism activities remain at a scale that does not harm the ecosystem and are properly regulated.

**Dissemination of the Methodological Model** The geoheritage evaluation method applied in this study can also be adapted to other wetlands and similar ecosystems in Turkey. Other floodplain forests such as İğneada and Acarlar, as well as wetland ecosystems such as the Kızılırmak Delta, should be investigated in a similar manner to identify significant geoheritage areas at the national scale. Such evaluations will contribute to determining conservation priorities and provide decision-makers with a robust scientific foundation.

In conclusion, the Karacabey Floodplain is one of the unique areas where geological, geomorphological, and biological heritage values are intertwined. It illuminates the scientific community through its long-term natural archives while also reflecting contemporary environmental problems that offer instructive lessons for humanity. In these respects, the floodplain should be regarded not only as an ecosystem but also as a natural laboratory and archive; maximum effort must be devoted to ensuring its effective conservation, monitoring, and transmission to future generations.

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