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Abiotic factors as environmental pressures on protected natural ecosystems: A case study of the South-East Region, Republic of Moldova

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ABSTRACT: Republic of Moldova is characterized by a high diversity of natural landscapes, accompanied by pronounced vulnerability to environmental change and anthropogenic pressures. This study presents an integrated assessment of geo-ecosystem vulnerability and the cumulative impact of abiotic and anthropogenic factors on natural habitat status and biodiversity conservation. It focuses on the southeastern region of the country. The research is transdisciplinary, based on the integrated analysis of geological, geomorphological, hydrological, climatic, and pedological data, correlated with the structure of the National Ecological Network and the protected natural areas system, and complemented by GIS analysis and field observations. Land use is dominated by human activities, particularly agriculture and built-up areas, at the expense of natural vegetation, which is unevenly distributed and lacks ecological connectivity. Abiotic pressures and threats include slope and soil erosion, riverbank instability, and reservoir siltation, all amplified by hydromorphological alterations of the Dniester River and its tributaries. Climate analysis reveals rising mean annual temperatures and an increasing frequency of extreme events in the region. Consequently, 70% of the study area exhibits landscape instability, with 20% of the territory categorized as highly vulnerable to climate change, which underscores the urgent need for natural heritage conservation. The overlay of the most intense environmental pressures indicates that around 18% of the study area exhibits high vulnerability, unfortunately overlapping with some of the region's most valuable protected ecosystems. To address these challenges, the study provides practical recommendations for protected area management, including enhanced ecological connectivity, habitat restoration, and the integration of climate adaptation strategies into biodiversity conservation planning.

KEYWORDS: threats and pressure, natural habitats, biodiversity, climate change, ecosystem management

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1. INTRODUCTION

The natural ecosystems of the southeastern Republic of Moldova are characterized by high biodiversity and remarkable landscape complexity, determined by the region’s location at the junction of two major biogeographical regions (continental and steppe) and three distinct geo-botanical districts (the Downy Oak Forest District; the Bugeac Steppe District; and the southeastern Moldovan Steppe District)

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(Postolache, 2015). This area encompasses a wide range of forest, floodplain, and aquatic ecosystems of significant ecological, landscape, and conservation value, as reflected by the presence of various nationally and internationally protected natural areas, including the Lower Dniester International Wetland (Ramsar Site) and the Lower Dniester National Park. At the same time, these ecosystems are increasingly exposed to both anthropogenic and natural pressures, which affect their ecological functionality and reduce their capacity to adapt to ongoing environmental changes (Tărîță, 2024).

At the European scale, biodiversity is strongly influenced by human activity, and pressures on habitats and species remain high. Intensive agriculture, urban expansion, unsustainable forestry practices, pollution, and climate change are identified as the main drivers of ecosystem degradation (IPBES, 2019).

The relevance of this study stems from the need for a comprehensive understanding of the role of abiotic factors (soil, water, air, and relief) in maintaining the biodiversity conservation status and the ecosystem services provided by protected natural areas. The aim of this research is to characterize the abiotic components of the environment and assess their current and potential impacts on biodiversity under shifting environmental and climatic conditions, in order to substantiate effective management measures.

Methodologically, the study is based on the integrated analysis of pedological, hydrological, climatic, and geomorphological data, correlated with information on the protected natural areas network, using GIS tools and field observations. The article is structured as follows: the first section presents the natural and conservation framework of the study region, followed by the research methodology; the results and discussion section examines the vulnerability of abiotic components and their implications for biodiversity, while the conclusions synthesize the main findings and provide recommendations for the adaptive management of protected areas.

The originality of the study lies in the multidisciplinary integration of environmental components and their correlation with protected-area management, while its applied value is reflected in the formulation of adaptive management recommendations and integrated conservation policies relevant for strengthening resilience and maintaining long-term ecological functionality.

2. LITERATURE REVIEW

The specialized literature highlights the decisive role of abiotic factors (climate, relief, soil, water, geographical features) in defining the habitat characteristics, control biodiversity distribution, determine the resilience of protected ecosystems to climate change and human pressure and the services that they underpin (Iordache et al., 2026; Ardeleanu, 2025; Nardone et al., 2025; Da Gama, 2023; Sumuki, 2023; Kubacka et al., 2022; Slabbert, 2021; Maebe et al., 2019, etc.).

At the global level, assessments conducted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Bongaarts, 2019; IPBES, 2019) indicate that climate change, soil degradation, and land-use changes are major drivers of biodiversity loss. At the European level, the dominant pressures on habitats are primarily associated with intensive agriculture, land abandonment, urbanization, landscape fragmentation and climate change, processes that reduce ecological connectivity and diminish ecosystem services (EEA, 2026).

Conceptually, the classification of pressures and threats to ecosystems proposed by the International Union for Conservation of Nature provides a standardized framework for assessing the impact of natural and anthropogenic factors on protected areas (IUCN - Threats Classification Scheme, 2022). At the same time, studies dedicated to protected area management emphasize their role in biodiversity conservation and the maintenance of ecosystem services, highlighting the need to integrate physico-geographical factors into conservation planning (Dudley, 2008).

At the national level, research conducted by Postolache (2015) and Ursu (2011) underscores the relationship between natural factors and ecosystem structure, while studies on physico-geographical and climatic regionalization (Boboc, 2021; Nedealcov et al., 2013) emphasize the influence of physico-geographical conditions on the distribution and stability of ecosystems. Numerous recent studies address the particularities of individual abiotic factors, both at the scale of the entire national territory and for specific physico-geographical units, as reflected in the national atlas series. Recent investigations (Nedealcov, 2020; Atlas: Schimbările climatice și starea actuală a peisajelor, 2021; Donica et al., 2025; Cojocari & Donica, 2025) further indicate a high level of ecosystem vulnerability in southeastern Moldova, exacerbated by intensifying anthropogenic pressures and climatic aridification. Nevertheless, comprehensive assessments of territorial vulnerability to these cumulative environmental stressors, particularly those identifying dominant threats, remain notably scarce. (Bunduc, 2021).

However, most studies analyze environmental components separately, without a systematic integration of abiotic factors in relation to protected areas. Research explicitly correlating physico-geographical conditions with ecosystem vulnerability within an integrated spatial analysis remains limited. In this context, the present study proposes an integrated approach that correlates abiotic factors with ecosystem vulnerability (pressure and threats) contributing to the development of adaptive conservation measures in protected areas of southeastern Moldova.

3. RESEARCH METHODS

Study area: this research focuses on the lower sector of the Dniester River, encompassing both riverbanks, and covering an area of 3224.88 km^2. On the right bank, the administrative districts of Căușeni and Ștefan Vodă are examined, while on the left bank the area is bounded by the Slobozia district and the administrative border between the Republic of Moldova and Ukraine. The region is characterized by considerable physical-geographical diversity and a notable concentration of protected natural areas. At the same time, it is subject to significant abiotic and anthropogenic pressures, which underlines the relevance of the study for assessing the vulnerability of geo-eco-systems.

Materials and methods: the research is based on the hypothesis that abiotic factors, together with biotic and anthropogenic drivers, represent key determinants of ecosystem vulnerability in the southeastern part of the Republic of Moldova. It is assumed that the effects of abiotic pressures and threats are intensified by extensive agricultural land use, hydromorphological alterations of the Dniester River, and the increasing impacts of climate change. Protected natural areas are considered particularly sensitive to these pressures because the conservation status of their ecosystems depends largely on the stability of the physical environment.

The methodological approach combined classical geographical analysis with Geographic Information System (GIS)-based spatial modelling to identify, classify and integrate the principal abiotic factors influencing ecosystem vulnerability. Geological, geomorphological, pedological and hydrographic maps were integrated with climatic and hydrological data, satellite imagery, Digital Elevation Model (DEM) data and field observations. Spatial analyses were performed using ArcGIS Pro and QGIS software.

The spatial database included geological, geomorphological, pedological, hydrographic and protected-area datasets obtained from national cartographic sources, together with climatic observations provided by the State Hydrometeorological Service of the Republic of Moldova. The climatic dataset consisted of multiannual records of annual and monthly air temperature and precipitation covering the period 1980–2020, corresponding to the standard climatic reference period recommended by the IPCC for climate analyses. A Digital Elevation Model with a spatial resolution of 10 m served as the basis for deriving topographic parameters, including elevation, slope gradient and slope aspect. All spatial datasets were standardized to the WGS 1984 geographic datum and projected into the UTM Zone 35N coordinate reference system to ensure spatial compatibility throughout the analysis.

Prior to spatial analysis, analogue geological, geomorphological and pedological maps were georeferenced using common control points, digitized into vector format and converted into raster datasets with a spatial resolution corresponding to the DEM. Raster datasets with different original resolutions were resampled to a common 10 m grid to ensure spatial comparability during overlay analysis. Climatic observations from meteorological stations were spatially interpolated using inverse distance weighting (IDW) interpolation to generate continuous temperature and precipitation surfaces for the study area. These raster layers were subsequently used to calculate the spatial distribution of climatic aridity.

The selected abiotic indicators included lithology, relief characteristics (elevation, slope and aspect), soil properties, hydrographic conditions and climatic aridity. Each indicator was processed individually and transformed into a standardized raster layer suitable for multicriteria analysis. Continuous variables were classified according to either internationally accepted threshold values or the statistical distribution of observations within the study area, depending on the availability of established classification schemes. Thus, the De Martonne aridity index was classified according to the thresholds proposed by Pelin (2016) and Hrnjak (2014), whereas variables lacking internationally accepted thresholds were classified using natural breaks (Jenks) to preserve the spatial variability of environmental conditions. Categorical variables, including lithological and pedological units, were grouped according to their relative susceptibility to erosion, geomorphological instability and drought.

To ensure the integration of heterogeneous variables within a common analytical framework, all indicator layers were reclassified onto a three-level ordinal vulnerability scale ranging from 1 (very low vulnerability) to 3 (very high vulnerability). The standardized raster layers were subsequently integrated using the Weighted Overlay procedure implemented in ArcGIS. Equal weights were assigned to all abiotic indicators because the objective of the study was to evaluate their cumulative contribution to ecosystem vulnerability without prioritizing any single environmental component. The resulting raster represented the cumulative abiotic vulnerability index for the study area.

Data interpretation focused on analysing the spatial relationships between the cumulative vulnerability index and the distribution of protected natural areas. Overlay analysis enabled the identification of sectors where multiple abiotic pressures coincide and where protected ecosystems are potentially exposed to a higher degree of environmental degradation.

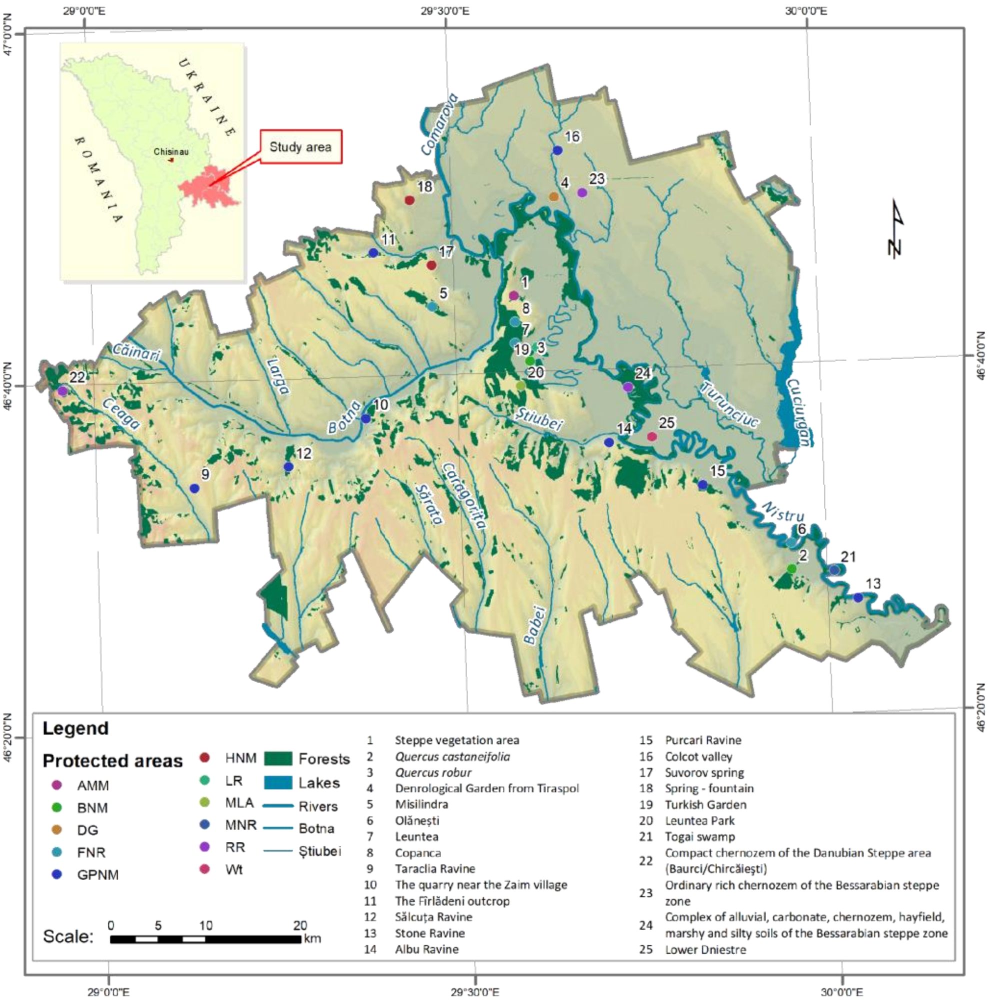
Climatic aridity was evaluated using the De Martonne aridity index (De Martonne, 1926), calculated according to the equation: $IM = P/(T + 10)$, where P represents annual precipitation (mm) and T is the annual mean air temperature (°C). The constant value of 10 was introduced to avoid negative values under low-temperature conditions. Monthly aridity was calculated using the modified equation: $IM = (12 \times P)/(T + 10)$, where P and T represent monthly precipitation and mean monthly temperature, respectively. Multiplication of monthly precipitation by 12 allows direct comparison between monthly and annual index values. According to Pelin (2016), values below 25 characterize steppe conditions, values between 25 and 30 correspond to forest-steppe environments, whereas values exceeding 30 indicate forest environments. The classification proposed by Hrnjak et al. (2014) for southeastern Europe was additionally used to evaluate the spatial variability of climatic aridity and its implications for ecosystem vulnerability.

The assessment of environmental pressures and threats was performed through thematic overlay analysis based on the standardized classification developed by the International Union for Conservation of Nature (IUCN, 2022). Particular attention was given to threat categories directly associated with abiotic processes, including natural system modifications, geological hazards, hydromorphological alterations and climate change. The spatial coincidence between these pressures and the cumulative abiotic vulnerability index allowed the identification of protected areas where natural ecosystems are most exposed to ongoing or potential environmental degradation. The resulting vulnerability patterns were finally compared with field observations collected during the survey period to verify the spatial consistency of the GIS-derived outputs.

4. RESULTS

4.1. The system of natural protected areas in the southeastern Republic of Moldova

The total protected natural area in the country is 189385.9 ha (approximately 5.61% of the country's territory). The national objective is to extend the protected area to 8% of the territory by 2030. The regulatory framework is mainly based on Low no. 1538/1998 on the fund of state-protected natural areas, with 12 categories. Seven categories are aligned with the IUCN classifications, three categories are established at the local level (Dendrological Gardens, Zoo Gardens, monuments of landscape architecture) and two categories are designed based on international instruments (Biosphere Reserve, Wetlands). The southeastern part of the Republic of Moldova, the Lower Dniester region, is known for the variety of natural ecosystems (essential for the protection of an impressive number of rare plant and animal species), developed at the confluence of the Dniester River, strongly meandering on a low plain relief, as well as for the heterogeneity of abiotic factors in the territory (Potențialul ecologic al componentelor de mediu din zona Nistrului Inferior, 2024). Through systems of protected areas - vital for biodiversity conservation - is possible to counteract environmental degradation, conserve threatened species and protect fragile ecosystems (Dudley, 2008). In the studied territory, these areas provide essential ecosystem services, function as nature-based solutions for addressing climate change, and preserve both natural and cultural heritage. Thus, in the south eastern side of the country, natural forest, floodplain, and aquatic landscapes dominate the lower course of the river and represent outstanding natural values for the region (Figure 1). These landscapes are protected under the wetland category Lower Dniester Ramsar Site (No. 1316 on the Ramsar List of Wetlands of International Importance), covering an area of approximately 60 thousand hectares.



AMM - Areas with Multifunctional management, representative sectors with steppe vegetation	LR - Landscape Reservation
FNR - Forest Nature Reserve	Wt- Wetland
MNR - Mixed Nature Reserve	MLA - Monument of Landscape Architecture
BNM- Botanical Nature Monument, secular trees	RR - Resource Reservation
DG - Dendrological Garden	GPNM - Geological and Paleontological Natural Monument
	HNM - Hydrological Natural Monument

Figure 1. Typology and distribution of natural protected areas in the study area.
Source: Created by the authors (2026).

Forest landscapes dominated by natural fundamental stands with native species, such as pedunculate oak (*Quercus robur*), downy oak (*Quercus pubescens*), poplar, willow, and elm, together with numerous rare species of flora and fauna, are protected through Forest Natural Reserves, including

"Copanca" Forest Natural Reserve, "Leuntea" Forest Natural Reserve, and "Olănești" Forest Natural Reserve. Natural landscapes with unique geo-ecosystem values are protected through the "Grădina Turcească" Landscape Reserve (224 ha), while landscape architecture heritage is represented by "Leuntea Park" Landscape Architecture Monument (21 ha). At the same time, natural landscapes with distinctive physical-geographical values are protected through Geological and Paleontological Natural Monuments, including "Vâlceaua Colcot" Geological and Paleontological Natural Monument (16 ha), "Râpa Taraclia" Geological and Paleontological Natural Monument (12 ha), "Fârlădeni Outcrop" Geological Natural Monument (5 ha), and "Purcari Ravine" Geological Natural Monument (5 ha); as well as Resource Reserves that maintain a favorable conservation status of local natural resources, such as "Danube Steppe Compact Chernozem" Resource Reserve (Baurci/Chircăiești, 5 ha) and "Bessarabian Steppe Typical Chernozem" Resource Reserve (2 ha). Most protected areas serve as core zones of the National Ecological Network and the pan-European Emerald Network (https://emerald.eea.europa.eu/). Furthermore, the establishment of the "Lower Dniester" National Park in 2022, covering approximately 62 thousand hectares, further highlights the ecological, aesthetic, and cultural-historical importance of the natural complexes within the lower floodplain of the Dniester River.

4.2. Physical-geographical characteristics of the study area in the formation of local natural ecosystems

Physical and geographical characteristics define an ecosystem's capacity to support life, and their alteration (through pollution, fragmentation, climate change or other human activities) leads to biodiversity loss, affecting species distribution, abundance, and adaptation. Such studies are essential for understanding how the physical-geographical structure of a territory influences ecosystem stability and their resilience to environmental changes (Gray, 2013; Barron & Gordon, 2013). For example, geodiverse areas comprise a mosaic of microclimatic refugia that are buffered from regional climate change, and therefore, these areas can provide species with a range of suitable microclimates, i.e., local climatic conditions (Määttänen, 2024).

4.2.1. Physico-geographical regionalization

The southeastern region of the Republic of Moldova is part of the Southern Moldavian Plain, characterized by a gently undulating lowland relief with low altitudes and gentle slopes (Boboc, 2021).

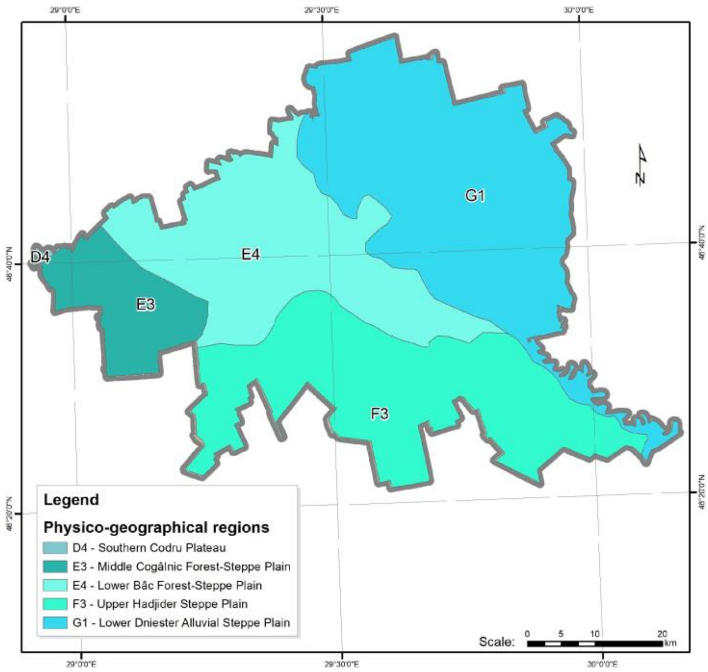


Figure 2. Physico-geographical regions.
Source: Boboc N., 2019, created by the authors (2026).

From the perspective of physico-geographical subregionalization, the territory belongs to the following units: the Middle Cogâlnic Silvosteppe Plain (E3), the Lower Bâc Silvosteppe Plain (E4), the Upper Hadjider Steppe Plain (F3), and the Lower Dniester Alluvial Steppe Plain (G1) (Figure 2).

This arrangement gives the region *a transitional character between silvosteppe and true steppe zones*, with predominately smooth surfaces and wide interfluves, locally fragmented by valleys and alluvial floodplains, which host specific ecosystems.

4.2.2. Geological and lithological structure

The geological structure of the study region includes Neogene and Quaternary formations. The Neogene system is represented by the Bessarabian substage of the Miocene and the Akchagylian and Kimmerian stages of the Pliocene (Figure 3).

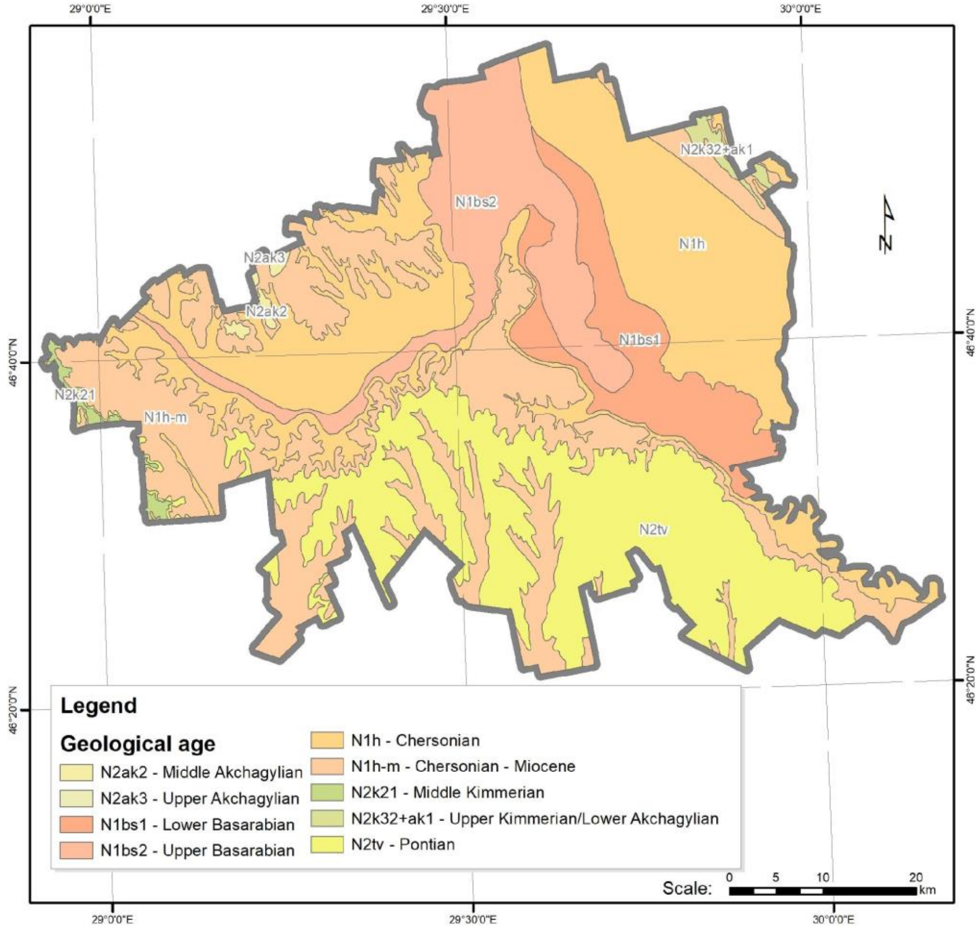


Figure 3. Distribution of geological formations.
Source: Created by the authors (2026).

The Bessarabian substage covers 2 subdivisions: 1) the lower unit (N1bs1) consists of sands, silts, clays, and reef limestones (about 8.1% of the territory), occurring mainly within the floodplain and lower terraces of the Dniester River; 2) the upper unit (N1bs2), predominantly composed of fine-grained, light gray sands, sometimes interbedded with silts, clays, and limestones, extends over more than 11.5% of the area, found in the floodplains of the Botna River and in the upper sector of the lower Dniester River. The lithological structure of these geological formations favors erosion processes and landslides, particularly during periods of heavy precipitation. As a result, geomorphological hazards pose a threat to the stability of floodplain ecosystems and to the species that depend on them.

The Khersonian (N1h) and Khersonian–Meotian (N1h–m) formations occur on and represent the most widespread geological formations in the area (approximately 29.6% of the region). They predominate in the northern sector, on the right slopes of the Botna River and the Dniester River and shaping the floodplains of several small rivers: the Ceaga River, Sărata River, Babei River, and Stiubei

River. These formations play an important role in the development of agricultural lands and floodplain ecosystems. However, the respective areas are highly vulnerable to erosion and deluvial processes, especially during periods of heavy precipitation, posing a significant risk to the biodiversity.

Pontian deposits (N_2tv) cover approximately 22.7% of the region. This area represents a zone of major ecological importance, where sand and clay deposits play an essential role in soil fertility and in the formation of freshwater ecosystems. Although these deposits are relatively stable from a geological perspective, they remain vulnerable to erosion risks, particularly during prolonged drought periods, which affect both the hydrological regime of the Dniester River and the stability of floodplain ecosystems.

Deposits of the Kimmerian - the lower horizon (N_2k21) and the upper horizon (N_2k32+ak1)stage are represented by alluvium, sands, pebbles.

As geodiversity is the abiotic counterpart to biodiversity, and together these two components form the dynamics of nature that we aim to conserve, it will taken into account that Bessarabian lithological structures - the most exposed to erosion and deluvial processes- serve as geological base to the most valuable protected natural ecosystems in the region. In addition, the presence of unique and representative geological features in the region, protected through four areas, designated as Geological and Paleontological Natural Monuments, highlights the need for further studies on the territory's vulnerability to environmental changes, as well as for the development of appropriate conservation and protection measures.

4.2.3. Relief features

Altitudinal characteristics

Environmental heterogeneity dictates habitat variability and ecosystem resilience. Topographic variety, such as slopes, aspects, and elevation, creates diverse microclimates and refugia niches for different species (Berca, 2000; Keppel et al., 2012). In the studied region, the analysis of the data indicated that the average altitude is 84.8 m and the maximum altitude reaches 257.5 m in the western extremity (Figure 4).

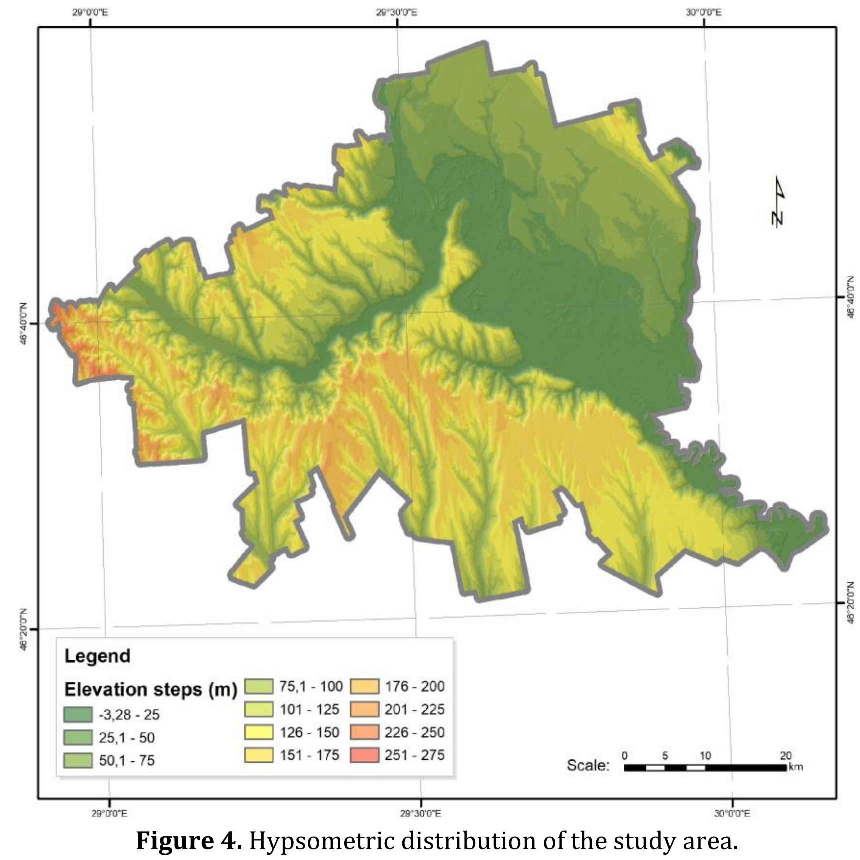


Figure 4. Hypsometric distribution of the study area.
Source: Created by the author (2026).

The percentage analysis of hypsometric levels (Figure 4) highlights a pronounced altimetric asymmetry, determined by the high proportion of surfaces located below 100 m altitude. More than 55% of the region's surface corresponds to the floodplains and lower valleys of the Dniester River and its tributaries. The lowest elevations are found in the Dniester River floodplain (an area known as the region with the lowest altitudes in the country, with negative elevations). A relatively high proportion, exceeding 44%, corresponds to the hypsometric level between 100 and 200 m.

Slope

The analysis of relief characteristics represents an essential tool for identifying areas susceptible to active geomorphological processes (such as erosion and landslides), correlating altitudinal distribution with landscape types, and assessing the ecological stability of landscapes, with direct implications for biodiversity. Slope represents a fundamental morphometric parameter of relief, as it reflects the geological structure, the geomorphological evolution stage, and the types of both present and past land-shaping processes (Patriche, 2005). Slope controls processes such as water erosion and landslides, influences the solar radiation regime, soil formation and continuity, vegetation distribution, and patterns of land use (Bănică, 2006). In this study, slope gradient values were classified into five categories (classes) based on morpho-dynamic criteria adapted to local and regional conditions, in order to highlight areas with high susceptibility to environmental degradation processes.

The analysis of slope gradients in the southeastern region of the Republic of Moldova-highlights the predominance of gentle slopes, under 2°, which cover more than 54% of the total area. These surfaces are primarily located in the floodplains of rivers traversing the region, as well as in the upper parts of slopes, at the interface with interfluve ridges. Slopes ranging from 2–5° also occupy a significant proportion, approximately 28%, while slopes of 5–7° account for just over 9% of the total area.

Slopes within the 7–10° range cover about 6.33% of the territory and generally correspond to moderately inclined surfaces, including river terraces, transition zones between floodplain and slope, gently inclined slopes, and the junctions between interfluve ridges and slopes. Slopes of 10–15° make up approximately 2.27% of the total area and mark the threshold at which linear erosion processes become active, favoring the development of rill networks, gullies, and ravines. Slopes greater than 15° are virtually absent in the study area. Areas with gentle slopes, coinciding with floodplains and river terraces, encompass the most important floodplain ecosystems and protected wetlands, but they are also exposed to erosion and instability under intense precipitation events, representing sensitive zones susceptible to environmental pressures and threats.

The distribution of slopes by aspect (the angle between the north direction and the slope direction, measured clockwise) in southeastern Moldova is heterogeneous, resulting in a mosaic of relatively small surface units (Budui, 2002). The largest proportions are recorded for east-facing slopes (17.8%), characterized by cooler and semi-shaded conditions, followed by southwest-facing slopes (16.8%), west-facing slopes (14.2%), and south- and southeast-facing slopes (both 11%). The smallest proportions occur on northwest-facing slopes (6%) and north-facing slopes (7%). Overall, the cumulative share of sunny and semi-sunny slopes (53.7%) is comparable to that of shaded and semi-shaded slopes (46.3%), indicating a relatively balanced distribution of microclimatic conditions at the regional level. This aspect structure locally controls moisture availability, soil stability, and vegetation distribution, thereby directly influencing the sensitivity of protected natural ecosystems to climatic and anthropogenic pressures (Patriche, 2005).

Thus, the relief characteristics and local microclimate have created favorable conditions for the development of natural vegetation communities: floodplain vegetation on Dniester meadows, steppe vegetation and thermophilous sub-Mediterranean forests on fields (Postolache, 2015).

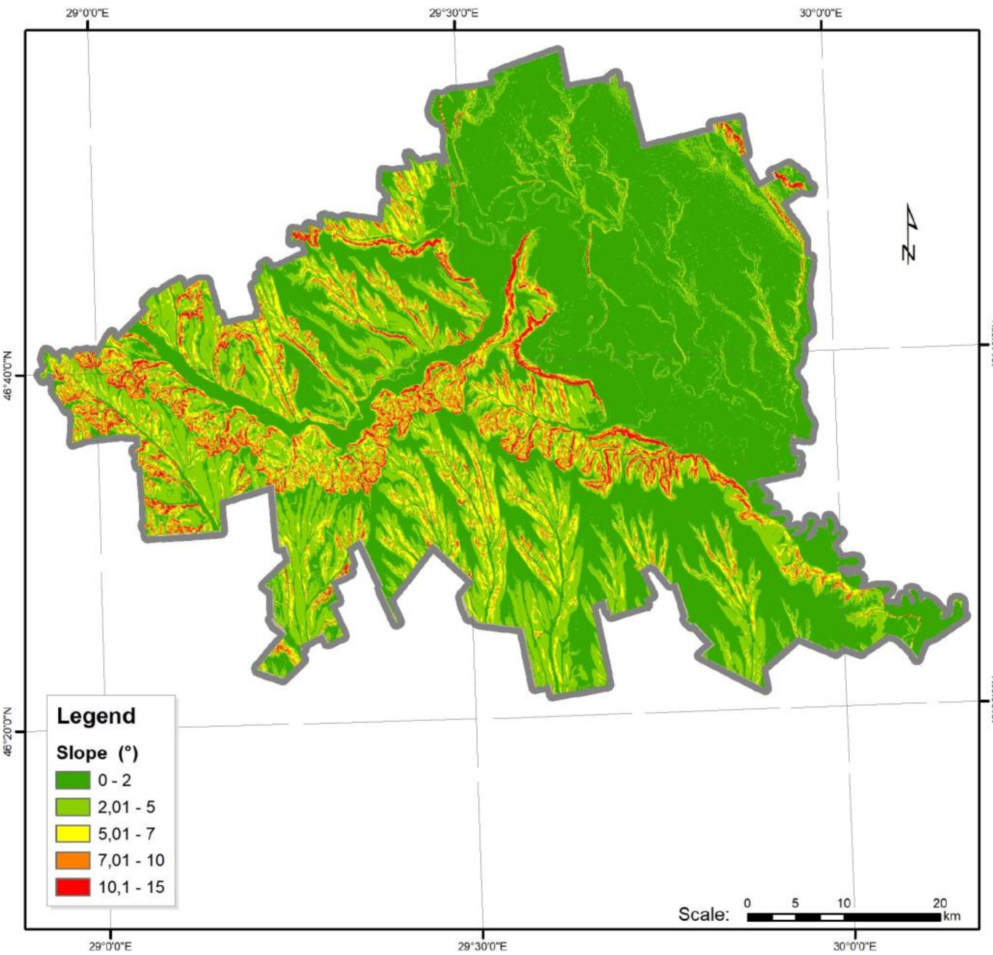


Figure 5. Slope on the terrain.
Source: Created by the authors (2026).

Soil cover

The diversity of natural pedogenetic factors in the southeastern region of the Republic of Moldova, particularly lithological conditions, climatic regime, and relief morphology, has led to the development of a complex and varied soil cover (Figure 6).

Against the general backdrop of steppe and forest-steppe landscapes, characteristic of the south east of the country, automorphic soils of the chernozem class predominate, complemented by hydromorphic and halomorphic soils, which are distributed in an insular pattern within depression and floodplain areas.

Automorphic soils constitute the dominant pedogenetic background of the region, covering well over half of the total area (approximately 70%) and developing extensively on loess and loessoid-deluvial deposits under conditions of favorable natural drainage and a relatively balanced hydric regime. Within this group, chernozems occupy a central position: the carbonate chernozem is the most widespread in the southern and southeastern parts; leached chernozem occurs on interfluve plateaus and gently sloping hillsides; typical chernozem is distributed across the central and northern areas; and vertic chernozem appears sporadically in low-lying depressions. Overall, the chernozems of south-eastern Moldova are almost entirely integrated into the agricultural cycle, used for arable fields, vineyards, and orchards. Intensive exploitation has locally led to the degradation of soil aggregate structure and a reduction in organic matter content, particularly on lands exposed to erosion and deep plowing (Ursu, 2011).

However, there are also small protected areas of chernozems - Resource Reserves (RR), within the study area (RR "Compact Chernozem of the Danube Steppe region", covering 5 ha; and RR "Typical Fat Chernozem of the Bessarabian Steppe region", covering 2 ha), which underscores the importance of studying factors affecting protected areas.

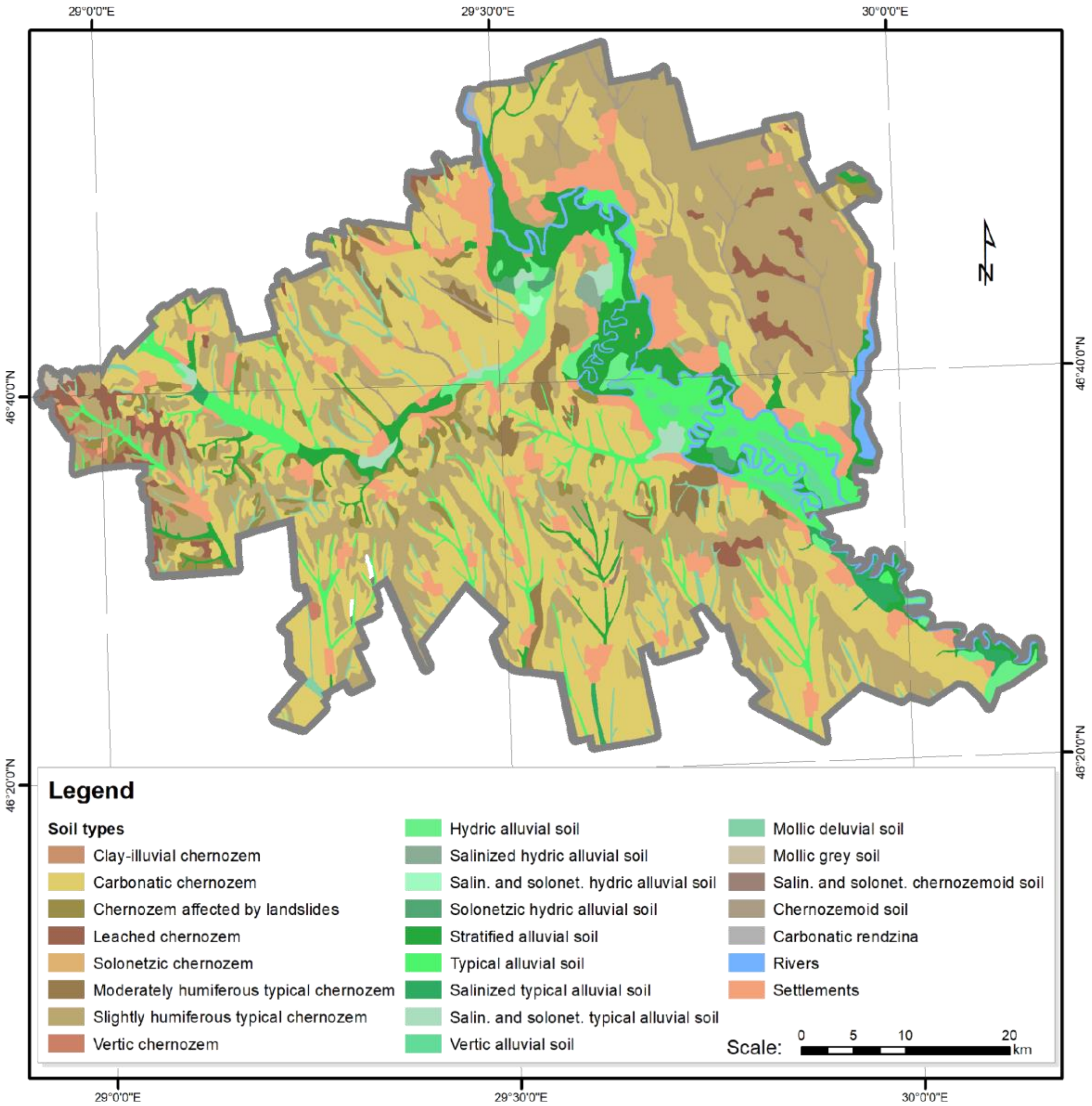


Figure 6. Spatial distribution of soil subtypes.
Source: Created by the authors (2026).

Hydromorphic soils have a limited distribution, developing primarily in the floodplain of the Dniester River and smaller tributaries, in local depressions where water temporarily accumulates, the groundwater table is high, and natural drainage is insufficient. In the transition zones between slopes and floodplains, deluvial soils have developed through the accumulation of eroded material. The alluvial soils of the Dniester and its tributaries are distinguished by clear stratification and high natural fertility and are frequently used for vegetable and fodder crops where the risk of flooding is controlled. (Ursu, 2011).

In the southeastern region of the Republic of Moldova, the more arid climate, combined with slope, soil texture, and human pressures (deforestation, deep plowing, monocultures), exacerbates the phenomenon of land degradation (IPBES, 2019).

For the study area, the degradation pattern indicates a predominantly stable pedological background: 48% of the soils are uneroded, complemented by the floodplains (21%) – areas that are relatively little affected by erosion but subject to hydromorphic risks. Nevertheless, erosion impacts approximately 20% of the territory (12% slight, 6% moderate, 2% severe), while landslides cover 11%, with localized high impacts on the slopes (Figure 7). Slopes affected by erosion, however, provide favorable conditions for steppe vegetation, which has established herbaceous plant communities due to the local topo-climatic conditions and the fact that these slopes are excluded from agricultural use.

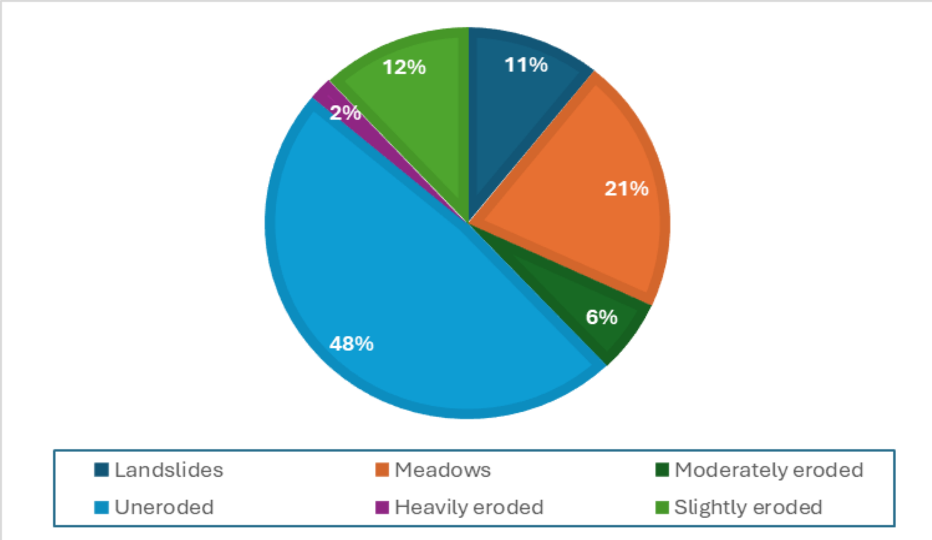


Figure 7. Soil erosion categories.

Hydrographic network

The Dniester River is the most important water source in the region. The average multiannual water volume of the Dniester River is about 9.2 km³, varying between 6 km³ in dry years with a moisture deficit and 12 km³, values reached in years rich in water resources. The multiannual average of the flow at the Bender hydrological station (the closest to the study region) in the years 1980-2022 was 272 m³ /s, which falls within the limits of 4.68-6.49 l/s, and the runoff layer amounted to values of 148-205 mm. In the last 10 years, however, a decrease in the average flow by 17 m³ /s has been recorded, which can be explained by the consequences of climate change and damming of riverbeds. It is likely that the decrease in runoff in recent years is part of a new cycle of low water levels, which began in 2011.

The main supply sources for the river are snow and rain, with groundwater playing a much smaller role. Most precipitation falls as rain showers and only 10% falls as snow. A high water level is recorded in spring due to snowmelt (40-50% of the annual runoff). In the summer season, with the torrential rains, the levels of rivers, especially small ones, can rise considerably, sometimes causing major floods. (Nistru River Basin Management Plan, 2025).

The hydrographic network in the studied region has a total length of approximately 869,4 km, comprising a complex system of interconnected watercourses and river segments. Due to its geographical location, morphometric and hydrological characteristics, the region's hydrographic network is part of the Dniester and Black Sea drainage basins. Thus, the network encompasses the lower segment of the Dniester River, along with the Colcotov–Cuciurgan and Iagorlacul Uscat–Comarova sub-basins located on the left bank of the Dniester, as well as the Nistrul Vechi–Știubei–Liman and Botna sub-basins on the right bank, At the same time, the network includes several secondary rivers - Căplani, Babei, Caragorița, Sărata, and Ceaga - which are part of the Prut–Danube–Black Sea hydrological district (Figure 8).

According to data (The National Geospatial Data Fund of the Republic of Moldova), approximately 89 water reservoirs have been identified in the southeastern region of the country. In terms of origin, all these reservoirs are anthropogenic, created either by damming watercourses or by establishing artificial basins. Among them, the largest is the Cuciurgan reservoir, with a surface area of approximately 25,01 km², followed by the Crasnoe reservoir, covering around 2,4 km². The remaining reservoirs are smaller than 1 km², with the smallest measuring only 0,0026 km². In total, the water surface area of all reservoirs in the region amounts to approximately 40,4 km², highlighting a significant density of artificial water bodies within the regional hydrographic network.

Thus, in the region, the natural ecosystems functioning, the natural habitats maintenance and biodiversity conservation, mainly specific to wetlands and bird areas are directly formed and supported by the supply of the Dniester River with water and nutrients.

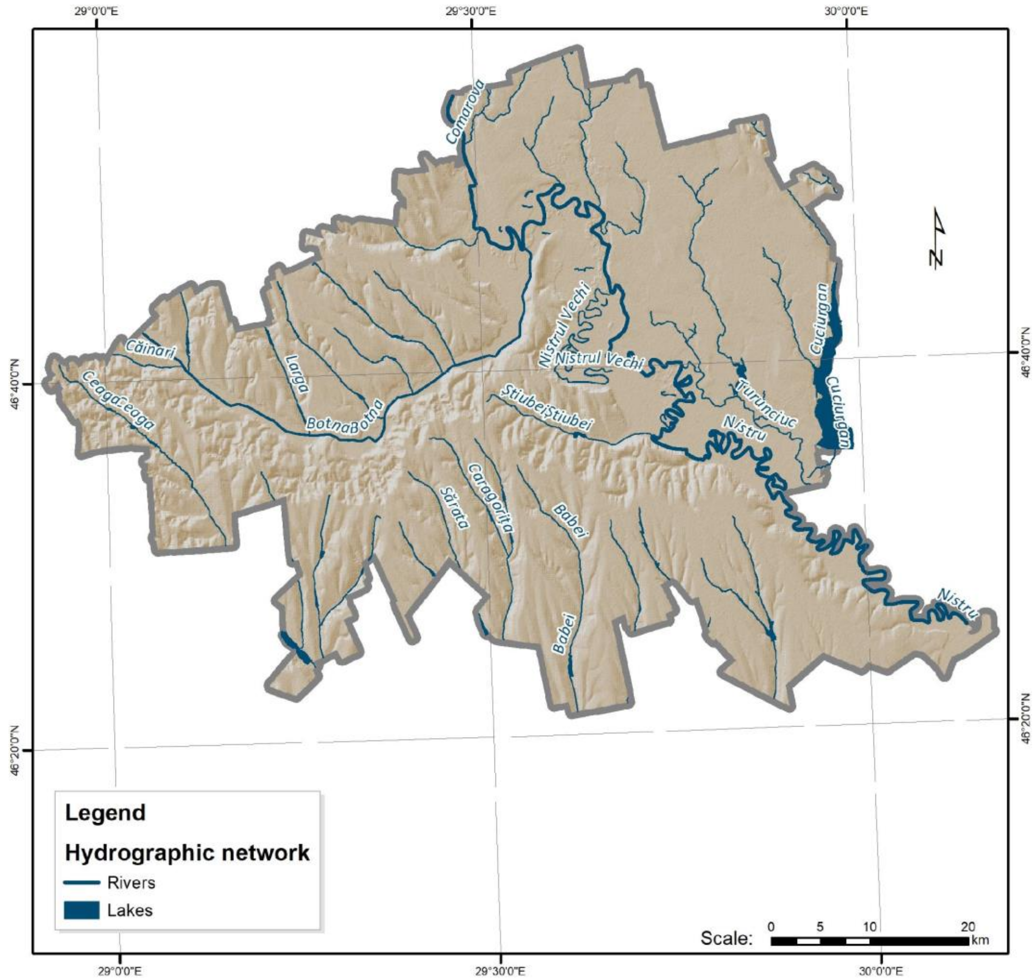


Figure 8. Hydrographic network.
Source: Created by the authors (2026).

Climatic characteristics

From the perspective of climatic regionalization, the Republic of Moldova territory is situated within a temperate continental climate zone. In the southern part of the country, this climate is further influenced by the proximity of the Black Sea, as well as by the air masses advection, originating from the Mediterranean region. The specific features of the general atmospheric circulation in the central and south-eastern part of Europe, together with the "openness" of the territory towards the Black Sea, represent the main factors that induce noticeable local variations in atmospheric dynamics, with direct effects on the thermal regime and precipitation patterns (Nedealcov, 2013).

The relief fragmentation degree exerts a direct influence on the spatial distribution of the thermal regime, through the effects induced by altitude and slope aspect. An analysis of data from the scientific literature indicates that the multi-annual average temperatures (1991–2020) recorded in the southeastern region of the Republic of Moldova (10.0–11.9°C) exceed, in quantitative terms, the national multi-annual average (10.8°C). In temporal terms, the coldest month of the year – January - records average temperatures of −1.8°C in the study area, which is 0.5°C higher than the national average (−2.3°C) (Atlas Republica Moldova: Factorii naturali și antropici de risc, 2020). For the warmest month – July - a similar difference is observed between the national average (21.8°C) and the values recorded in the southeastern part of the country (23.1°C), indicating a thermal surplus (Atlas: Factorii abiotici de mediu și securitatea ecologică, 2023).

The absolute annual maximum air temperature (1991–2020) indicates average peak values of 36.0°C in the southeastern part of the Republic of Moldova, compared to the national average of 35.1°C. From a temporal perspective, this parameter, recorded at the Ștefan Vodă Meteorological Station, shows high values, ranging from 31.7°C (in 2004) to an absolute maximum of +41.1°C recorded in 2007. The upward linear trend (+1.8°C per decade) reflects the general tendency toward increasing aridity in the region.

The absolute annual minimum air temperature (1991–2020) indicates, for the southeastern part of the Republic of Moldova, minimum values of −18.2°C, compared to the national average of −18.5°C. From a temporal perspective, this parameter, recorded at the Ștefan Vodă Meteorological Station, shows low values ranging from −25.3°C (in 2006) to −8.3°C (in 2020). The slightly increasing linear trend (+0.6°C per decade), although barely perceptible, aligns with the general trend of increasing aridity and ongoing climate change in the region (Cojocari, 2025).

For the study region, the average annual precipitation amounts to approximately 510 mm, which is about 30 mm lower than the national average of the Republic of Moldova. Recent climatic studies project significant changes in both the mean annual temperature and the average annual precipitation for the tree vegetation period (April - October) in the southeastern part of the country, with a particular emphasis on the summer months (June - August), which are characterized by high air temperatures and low precipitation input (Raileanu, 2021).

Land use structure

The land use structure in the southeastern region of the Republic of Moldova reveals a clearly dominant agricultural profile, reflecting the region's traditional economic orientation and the high degree of its soil resources utilization. The total analyzed area exhibits a differentiated distribution among agricultural lands, forested areas, pastures, wetlands, water bodies, and built-up areas (Figure 9).

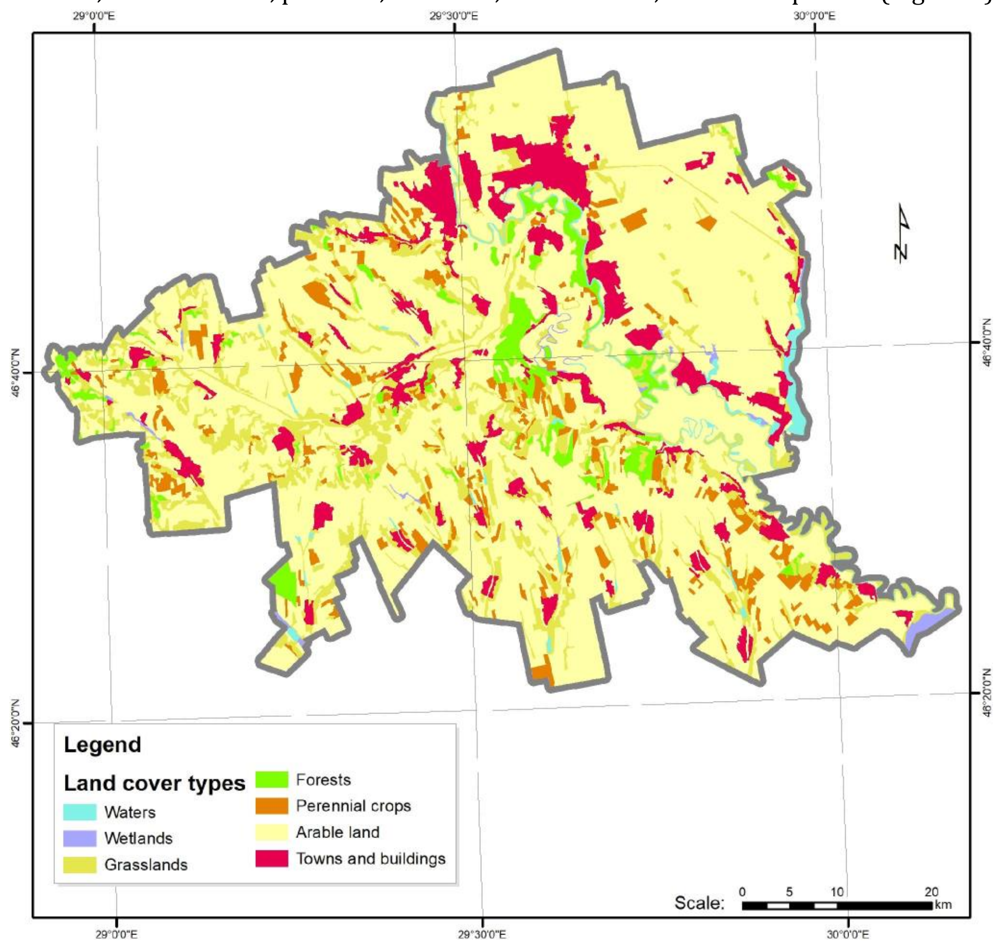


Figure 9. Land use categories.
Source: Created by the authors (2026), Corine Land Cover, 2023.

According to cartographic and statistical data, arable land represents the principal component of the functional structure, covering 216142 hectares, which accounts for approximately 67.5% of the total area. This highlights a pronounced agricultural specialization, primarily focused on the cultivation of cereals and industrial crops, supported by the high fertility of chernozem soils, to the detriment of sectors with natural vegetation, which are unevenly distributed.

Pastures occupy a significant share, amounting to 41952.5 hectares (13.1%), and are primarily distributed on hilly slopes and in areas characterized by vertic or partially hydromorphic soils. In addition to their importance for grazing, these lands also fulfill an essential ecological role, acting as buffer zones against erosion, landslides, and soil loss.

Perennial crops, particularly vineyards and orchards, cover 17519.3 hectares (5.5%) and are distributed in a mosaic pattern across the region, where topoclimatic conditions are favorable for perennial species.

The forest fund, although more limited in extent compared to other regions, covers 11142.7 hectares (3.5%) and represents an essential component for the ecological stability of the landscape. Forests are distributed in a fragmented manner, particularly on slopes prone to erosion and in the vicinity of watercourses, contributing to the regulation of the hydrological regime and air temperature.

Settlements and built-up areas total 29150.3 hectares (9.1%), being concentrated around administrative centers and along major transport corridors (Chișinău - Căușeni - Ștefan Vodă - Palanca). Their expansion reflects a process of gradual urbanization, still below the national average in terms of density.

Water surfaces, totaling 4740.45 hectares (1.5%) - including the Dniester River and reservoirs - play a crucial role in regulating the hydrological regime and maintaining biodiversity. At the same time, wetlands, covering 1703.63 hectares (0.5%), are associated with floodplains and low-lying depressions, where water stagnation and hydric soils frequently occur.

5. DISCUSSION

Threats represent one of the most important concepts in conservation practice. Direct threats include current or future human activities that are the immediate cause of ecosystem degradation and loss, or of species population decline. They also encompass major stressors within natural systems whose dynamics have been altered by the effects of present or historical human actions (IUCN Red List of Threatened Species, 2022).

Direct threats constitute the critical interface through which human socio-economic systems impact and modify natural systems and are, therefore, the direct or indirect target of many conservation actions. It is important to note that the IUCN classification lists only human activities and stressors that may pose threats to conservation targets; it does not describe the actors or the targets themselves. Furthermore, this classification does not explicitly aim to include methods for assessing the magnitude (scope and severity) of a given threat.

The analysis of threats affecting protected areas in the southeastern region of the Republic of Moldova identified climate change as one of the most significant threats within the category of abiotic factors, followed by the category of Natural System Management and Modifications.

5.1. Climate change

The vulnerability of protected ecosystems to climate change can be quantified through the calculation and interpretation of eco-climatic indices (Hrnjak, 2014). Recent studies on the territorial aridity degree, expressed by the De Martonne Aridity Index (IM), indicate that the southeastern part of the country is predominantly classified within semi-humid conditions (approximately 60% of the territory), with IM values 24.0-28.0 units, followed by Mediterranean-type conditions (IM values between 21.8–24.0 units), covering about 40% of the studied area (Cojocari, & Donica, 2025).

The suitability for the development of specific vegetation formations, depending on IM values, places the study area within two distinct subtypes: (a) IM values between 20–25 units, indicating conditions favorable for the development of tall-grass steppe, and (b) IM values between 25–30 units, indicating conditions favorable for forest-steppe/silvosteppe development. Consequently, protected forest ecosystems in the region are of increased importance for maintaining ecological stability.

A comparison between the multiannual IM values (1980–2020) and literature data on forest vulnerability to aridity indicates that forest ecosystems in the southeastern region fall into two vulnerability zones: (a) a zone of very high vulnerability (IM values below 25 units), covering approximately 20% of the study area, and (b) a zone of high vulnerability (IM values between 25–30 units), covering about 80% of the territory. Notably, most protected forest ecosystems in the region, such as FNR Copanca, FNR Leuntea, FNR Olănești, the eastern sector of the "Lower Dniester" National Park, among others - are located within the very high vulnerability zone (Donica, 2025).

5.2. Natural System Management & Modifications

A) Fire & Fire Management

The most exposed to this threat are forest ecosystems, predominantly found within the region's forest nature reserves, as well as vegetation in protected steppe sectors.

B) Dams & Water Management / Use.

Human activities alter or fragment aquatic habitats, modify water discharge and chemical composition, and/or lead to water scarcity or excess within ecosystems. Hydromorphological changes of the Dniester River and its tributaries are caused by the construction of dams and reservoirs along watercourses, which disrupt the longitudinal connectivity of rivers, as well as by flood protection dikes and irrigation channels that affect the lateral connectivity between the river and its floodplain. In the floodplain of the Nistru River, protective dikes are constructed in the lower course, at a distance of 20–100 m from the minor riverbed, with heights reaching up to 4 m. (HG. Nr. 814, 2017).

Other relevant pressure categories identified under the IUCN classification include:

5.3. Use of lands and waters

A) Residential, Commercial & Recreation Areas (urban areas, suburbs, villages, rural housing etc.).

Settlements and constructions in the region have a more pronounced impact on natural ecosystems located in the northeastern part of the studied area and along the valleys of local rivers, through conversion and degradation effects caused by their expansion and continuous presence. In the case of the consolidation and expansion of the human settlement system, particularly near the Dniester River, where most of the forest nature reserves are located, including the Lower Dniester Ramsar Site and the Lower Dniester National Park, a moderate threat to the natural ecosystems of the region is anticipated.

B) Agriculture & Aquaculture.

In the studied region, agricultural activities are dominant, reflecting the traditional economic profile of the area and the high level of utilization of soil resources. Intensive agricultural specialization, focused on cereal and industrial crop cultivation, leaves little room for natural vegetation. Agriculture and livestock farming, including expansion, intensification, or the agricultural practices employed, can impact the environment and also leave a spatial footprint through the facilities required for these activities.

A study on the ecological stability of landscapes (by K ecological stability coefficient) in the southeastern part of Moldova indicates that unstable landscapes cover approximately 70% of the study area, while stable landscapes account for only 30% of the territory (Angheluta, 2025). This spatial distribution highlights significant degradation of natural landscapes despite existing conservation efforts, primarily due to ongoing human pressures such as unsustainable management of forests, grasslands, and meadows, agricultural expansion, environmental pollution, land degradation, climate change, and low connectivity among elements of the National Ecological Network (Donica, 2025) -(Figure 10 and Figure 11).

Figure 10. Old branch of the Dniester River, drying up due to the aridification of the climate.
Source: Donica A., 2025.

Figure 11. Landslides, on the right slope of the Dniester River, stabilized by vegetation and agricultural lands on river meadow.
Source: Donica A., 2025.

5.4. Transportation, Service & Security Corridors

Transport corridors in the region (R28, R30, R52) exert specific pressures on biodiversity through habitat loss and fragmentation, including effects associated with their use (e.g., vehicle-caused mortality, restriction of species movement).

5.5. Natural Disasters

Geological Events

Landslides affect 10.7% of the studied territory, impacting the ecological stability of natural habitats located on slopes.

As a preventive analysis, we indicate that environmental pressures, such as climate change and the forecasted trend of climate aridification, land use patterns, and exogenous processes induced by this pressure, the dynamics of river waters and hydromorphological changes are considered abiotic factors with an obvious negative impact on the natural heritage in the southeast of the country (Table 1).

Table 1. Estimated intensity of some current/ongoing threats on protected ecosystems from the South-Eastern side of the Republic of Moldova.

IUCN Threats Class (version 4.0)		**Estimated intensity**
Level 1 Threat	**Level 2 Threats**	
A. Use of Lands & Waters		
1. Residential, Commercial & Recreation Areas	Residential Areas (urban areas, suburbs, villages, rural housing, vacation homes, shopping areas, offices, schools, hospitals, etc.)	1
	Commercial & Industrial Areas (stand-alone office parks, stand-alone shopping centers, manufacturing plants, sewage treatment plants, landfills, etc.)	1
	Recreation & Tourism Areas (visitor facilities in parks, campgrounds, football or other sports fields, cultural tourist attractions, cemeteries etc.)	1
2. Agriculture & Aquaculture	Annual & Perennial Non-Timber Crops (farms, household swidden plots, orchards, vineyards, mixed agroforestry systems, biofuel crops, haying practices that disturb nesting birds etc.)	2
	Wood Plantations (acacia plantations, pulp or fiber plantations, firewood lots, etc.)	1

	Terrestrial Animal Farming, Ranching & Herding (cattle feed lots, dairy farms, cattle ranching, chicken farms, goat, bee keeping, etc.)	1
3. Transportation, Service & Security Corridors	Roads, Trails & Railroads (highways, secondary roads, logging roads, biking trails, bridges & causeways, public transport systems, railroads, etc.)	0
	Utility & Service Lines (electrical & phone wires, aqueducts, powerlines etc.)	0
B. Use / Management of Species & Ecosystems		
1. Natural System Management & Modifications	Fire & Fire Management (fire suppression to protect homes, inappropriate fire management, building of fire breaks, escaped agricultural fires, arson, campfires, etc.)	1
	Dams & Water Management / Use (dam operations, levees and dikes, channelization, highway culverts, water catchment areas, snow fences, surface water withdrawals, groundwater pumping, artificial lakes, water treatment plants, etc.)	1-2
2. Natural Disasters	Geological Events (earthquakes, landslides, etc.)	1
	Severe Weather Events (rain/wind storms, hail storms, blizzards, dust storms, floods, etc.)	1
3. Climate Change	Changes in Temperature Regime (heat waves, cold spells, etc.)	2
	Changes in Precipitation & Hydrological Regimes (rainfall patterns, droughts, timing of rains, reduced snow accumulation, increased severity of floods, shrinkage or loss of lakes etc.)	2

Legend:
· **Level 0** (No threats, no impact); Does not pose a threat at this time.
· **Level 1** (Very low threat intensity, Low impact); Minor threat, at present, requiring monitoring but no specific management actions.
· **Level 2** (Moderate threat intensity, Medium impact); Moderate threat requiring specific management actions (to be included in the Protected Areas Management Plans).
· **Level 3** (High threat intensity, High impact); Major threat requiring intensive management actions (to be included in the Protected Areas Management Plans).
· **Level 4** (Very high / Maximum threat, Very high impact).

By superimposing pressures and threats with impact on local biodiversity, we deduce that the most vulnerable natural ecosystems, especially to climate change and land use, are those located in low-altitude territories, in the Dniester River floodplain (below 50m), *where is presented a Mediterranean-type climate (according to the Martonne index) and ecologically unstable territory (according to* K_{eco}*index)* (Figure 12). We consider that in the researched region, 3 distinct vulnerability zones of natural ecosystems to the impact of the most intense environmental pressures, of abiotic origin (the impact of climate change, land use and land degradation through exogenous processes) can be distinguished, namely:

- areas with high vulnerability, where the semi-arid/Mediterranean climate and ecologically unstable landscapes persist (the area covers about 18% of the territory researched, with dominance in the physical-geographical subregion Lower Dniester aluvial steppe plan);
- areas with medium vulnerability, transitional one, where natural ecosystems are subject to the impact of environmental pressures, either through the dominance of the climate aridity impact, or through the dominance of the land use and land degradation through exogenous processes (the area covers about 62.7% of the researched territory, with dominance in the physical-geographical subregions Upper Hadjider steppe plan, Lower Bac forest steppe plan and Lower Dniester aluvial steppe plan);
- areas with low vulnerability, where the semi-humid climate prevails, and ecologically stable landscapes (the area covers about 19.3% of the territory, with dominance in the physical-geographical subregion Middle Cogalnic forest steppe plan and a part of Lower Bac forest steppe plan).

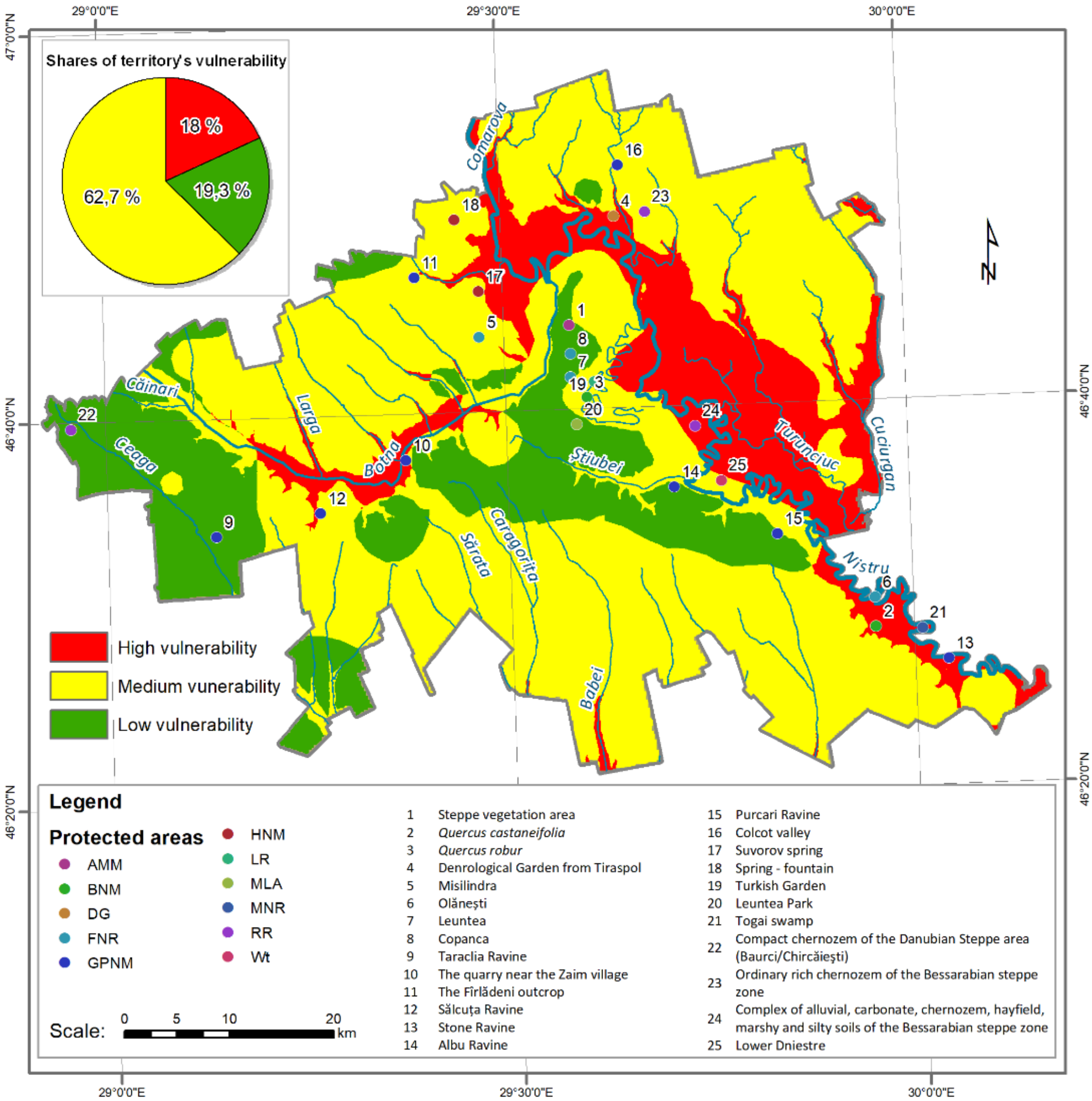


Figure 12. Territorial vulnerability under the impact of the most prevalent environmental pressures.

Source: Created by the authors.

Unfortunately, several protected areas that preserve valuable natural heritage fall within the high-vulnerability zone, including the Togai Swamp Nature Reserve, the Olanesti Scientific Reserve, and part of the Lower Dniester Ramsar Wetland.

Data included in this study, serve as basis for future analysis on flora and fauna populations from natural ecosystems. In analysis of the threats will take into account the timing, scope and severity of the threats. For each threat identified in this study, additional information is needed, mainly through direct field studies (during the growing season or specific periods of fauna activity), which would allow the severity of threats and their impact on habitats and local populations.

6. CONCLUSIONS

The present study analyzed threats predominantly induced by abiotic factors on protected natural ecosystems in the southeastern part of the Republic of Moldova, highlighting the important role of ecosystem stability and resilience. It is confirmed that physical-geographical characteristics define an ecosystem's capacity to sustain life, and their alteration (through pollution, fragmentation, climate change, or other human actions) induces biodiversity losses (distribution, abundance, and species adaptation).

Although Neogene and Quaternary formations in the region are relatively stable from a geological perspective, they remain vulnerable to erosion risks, especially during prolonged drought periods, which influence both the river's hydrological regime and the stability of floodplain ecosystems. Relief characteristics have led to the formation of areas susceptible to active geomorphological processes (erosion, landslides) and have determined the predominance of ecologically unstable landscapes. From a pedological perspective, the southeastern zone is characterized by the predominance of chernozems, intensively used for agriculture, which explains the high pressure on soil resources and their moderate degree of degradation. The land cover structure confirms the predominantly agricultural character of the region, with a high proportion of cultivated land, in contrast to the relatively limited areas occupied by forests, wetlands, and other natural elements that ensure ecological balance. This distribution increases the vulnerability of natural ecosystems to anthropogenic pressures, ecosystem fragmentation, and biodiversity loss, particularly in the vicinity of protected areas.

Climate change and associated risks are highlighted as the most intense threats to natural ecosystems in the region. Existing data clearly outline local climate aridization trends, which require the identification of appropriate and sustainable measures for conserving the natural heritage of the studied area. Hydromorphological changes of the Dniester River and its tributaries represent another factor threatening protected natural ecosystems, which are formed and sustained primarily through the river's supply of water and nutrients.

The cumulative impact of the dominant environmental pressures and threats in the region indicates that approximately 18% of the territory is characterized by high vulnerability to environmental change, while 19.3% falls within the low-vulnerability category, maintaining relatively stable ecosystem structure and functioning. The remaining territory is situated within a transitional zone of moderate vulnerability, where future ecosystem stability will largely depend on the intensity and direction of ongoing changes in abiotic factors across the region.

As a result, an integrated approach to geological, pedological, climatic, and anthropogenic factors is essential to ensure geo-ecosystem stability, biodiversity conservation, ecological connectivity and the appropriate management. We recommend this study in the development of management plans for protected areas in the region, including Emerald sites and Ramsar area, especially in identifying connections between geodiversity and biodiversity, pressure/ threats on local biodiversity and conservation measures.

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Use of AI tools declaration
The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions
All authors contributed equally to this work. All authors read and approved the final manuscript.

Conflicts of interest
The authors declare no conflict of interest.

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