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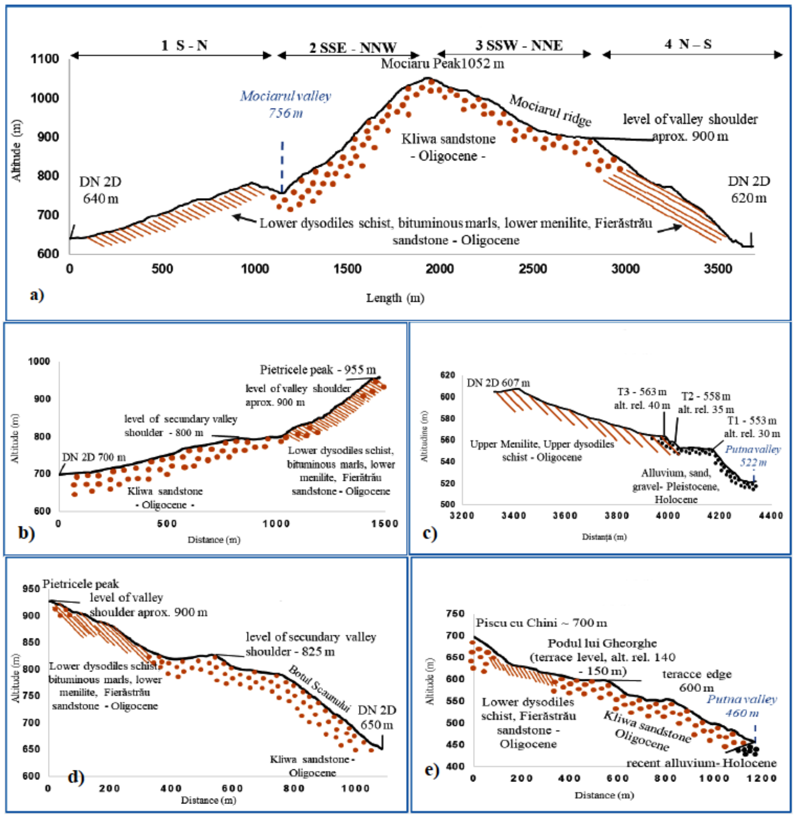

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Volume 16 / Numéro 33
Été 2026
ISSN et ISSN-L: 2247 – 2290

Cinq Continents
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Cinq Continents
Volume 16, Numéro 33
Été 2026

Cinq Continents est une revue indexée dans les bases de données internationales (BDI) et nationales

Les auteurs se sont engagés de l'originalité des résultats d'études.

ISSN et ISSN–L: 2247 – 2290

Cinq Continents
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Été 2026

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ISSN et ISSN–L: 2247 – 2290

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REVUE ROUMAINE DE GEOGRAPHIE

Volume 16 / Numéro 33
Été 2026
ISSN : 2247 - 2290
p. 5-29

Living Lab as a participatory framework for improving lake eutrophication mitigation policy

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Sommaire :

Citer ce document :

SÎRODOEV, I., PARASCHIV, M., CRACU, G.-M., SCHVAB, A., ALBU, A.-N., NICULESCU, R., MAMUT, E. 2026. Living Lab as a participatory framework for improving lake eutrophication mitigation policy. Cinq Continents 16 (33): 5-29.

Living Lab as a participatory framework for improving lake eutrophication mitigation policy

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Le Living Lab comme cadre participatif pour améliorer les politiques d'atténuation de l'eutrophisation des lacs. L'eutrophisation demeure l'une des pressions les plus persistantes et les plus complexes affectant les écosystèmes lacustres. Bien que les mécanismes de l'eutrophisation soient bien étudiés, de nombreuses stratégies de restauration des lacs continuent de rencontrer des difficultés de mise en œuvre, car l'eutrophisation n'est pas seulement un problème écologique, mais aussi un problème social, institutionnel et d'aménagement. Les apports en nutriments proviennent généralement de sources multiples, notamment l'agriculture, les eaux usées, le ruissellement urbain, l'aménagement des rives, les infrastructures touristiques et les charges internes provenant des sédiments. Par conséquent, les stratégies visant à réduire l'eutrophisation nécessitent une coordination entre différents secteurs, échelles et groupes de parties prenantes. Ce manuscrit soutient que l'approche du Living Lab peut constituer un cadre participatif utile pour l'élaboration de stratégies et de plans visant à réduire l'eutrophisation et les proliférations algales dans les lacs. Le Living Lab est compris comme un environnement multi-acteurs, co-créatif et itératif, dans lequel sont combinées les connaissances scientifiques, l'expérience locale, la responsabilité institutionnelle et l'apprentissage social. L'article examine l'importance de l'eutrophisation pour la santé des lacs, la nécessité d'approches participatives dans la gouvernance lacustre, la structure possible d'un Living Lab conçu pour traiter l'eutrophisation, ainsi que les défis théoriques et méthodologiques associés à une telle approche. L'argument central est que le principal avantage de cette approche réside dans une architecture participative organisée, grâce à laquelle le diagnostic scientifique peut être traduit en stratégies socialement légitimes, adaptatives et applicables.

Mots-clés : eutrophisation, planification participative, co-création, gouvernance lacustre, gestion adaptative, Siutghiol, Constanța.

Living Lab as a participatory framework for improving lake eutrophication mitigation policy. Eutrophication remains one of the most persistent and complex pressures affecting lake ecosystems. Although its mechanisms are well studied, many lake restoration strategies continue to face implementation difficulties because eutrophication is not only an ecological problem but also a social, institutional, and planning problem. Nutrient inputs usually originate from multiple sources, including agriculture, wastewater, urban runoff, shoreline development, tourism infrastructure, and internal sediment loading. Consequently, strategies to reduce eutrophication require coordination across sectors, scales, and stakeholder groups. We argue that the Living Lab approach can provide a useful participatory framework for developing strategies and plans to reduce eutrophication and algal blooms in lakes. The Living Lab is understood as a multi-actor, co-creative, and iterative environment in which scientific knowledge, local experience, institutional responsibility, and social learning are combined. The article discusses the importance of eutrophication for healthy lakes, the need for participatory approaches in lake governance, the possible structure of a Living Lab designed to address eutrophication, and the theoretical and methodological challenges associated with such an approach. The central argument is that the main advantage of this approach is in organised participatory architecture through which scientific diagnosis can be translated into socially legitimate, adaptive, and implementable strategies.

Keywords: eutrophication, participatory planning, co-creation, lake governance, adaptive management, Siutghiol, Constanța.

1. INTRODUCTION

Lakes are among the most valuable components of inland and coastal landscapes (Popa et al., 2023). They support biodiversity, regulate local hydrological and bio-geochemical processes, provide cultural and recreational services, sustain fisheries and tourism, and contribute to the identity of many communities (Popa et al., 2020). Their ecological condition is therefore not a narrow environmental concern but a broader question of territorial quality, public health, local development, and social well-being (Walker et al., 2013; Cheval et al., 2020). Healthy lakes depend on maintaining water clarity, oxygen balance, nutrient equilibrium, aquatic vegetation, functional food webs, and resilience to disturbance (Pavelescu et al., 2014). When these conditions are disturbed, the degradation of lake ecosystems can rapidly become visible through declining water quality, unpleasant odours, fish mortality, algal scums, bathing restrictions, loss of landscape attractiveness, and conflicts among users (Skolka, 2024).

Among the pressures affecting lakes, eutrophication remains one of the most widespread and difficult to manage (Popa et al., 2023). Eutrophication is generally defined as the enrichment of aquatic systems with nutrients, especially phosphorus and nitrogen, resulting in increased primary production and often in excessive algal or cyanobacterial growth (Popa et al., 2023). The process can occur naturally over long timescales. However, the current environmental concern is primarily related to cultural or anthropogenic eutrophication, in which human activities accelerate nutrient inputs beyond the assimilative capacity of the lake ecosystem (Smith et al., 1999; Schindler, 2006). The consequences are well documented: loss of water transparency, changes in phytoplankton composition, expansion of cyanobacteria, reduction of submerged macrophytes, oxygen depletion, release of nutrients from sediments, alteration of trophic relationships, and decline in the ecological and social value of lakes (Carpenter et al., 1998; Scheffer et al., 1993; Søndergaard et al., 2003).

The difficulty of eutrophication management derives from the fact that it is rarely produced by a single source or solved by a single technical intervention (Popa et al., 2023). Nutrients can enter lakes through agricultural runoff, wastewater discharges, stormwater systems, soil erosion, septic tanks, aquaculture, atmospheric deposition, and the remobilisation of legacy phosphorus stored in sediments (Popa et al., 2020). In many cases, external nutrient reduction is necessary but not sufficient for rapid ecological recovery, because internal feedback can maintain turbid, bloom-dominated states for long periods (Jeppesen et al., 2005; McCrackin et al., 2017). In addition, climate warming may intensify the risk of algal blooms by increasing water temperatures, strengthening stratification, altering hydrological regimes, and favouring cyanobacteria under certain conditions (Paerl, Otten, 2013). The result is a complex socio-ecological problem that requires both scientific understanding and coordinated governance.

Traditional approaches to eutrophication control have often been based on expert diagnosis, regulatory instruments, technical measures, and sectoral planning (Yan et al., 2024). However, the long-term success of lake restoration also depends on public legitimacy, stakeholder cooperation, institutional coordination, behavioural change, and the ability to adapt strategies as ecological responses unfold (Walker et al., 2013). This is why participatory approaches have become increasingly important in environmental management (Newig et al., 2023).

Participation can improve the quality of environmental decisions by integrating diverse forms of knowledge, increasing transparency, identifying conflicts early, and fostering ownership among actors expected to implement or to support management measures (Reed, 2008). At the same time, the literature on environmental governance shows that participatory processes vary considerably in quality and outcomes, and that poorly designed participation may remain symbolic, selective, or dominated by powerful actors (Koontz, Thomas, 2006; Newig, Fritsch, 2009).

In this context, the Living Lab approach offers a promising framework for developing strategies and plans to reduce lake eutrophication. Living Labs emerged in innovation studies and participatory design as real-life environments in which users, researchers, public authorities, companies, and other actors co-create, test, and evaluate solutions (Bergvall-Kåreborn, Ståhlbröst, 2009; Leminen et al., 2012; Hossain et al., 2019). More recently, Living Labs have been applied to sustainability transitions, urban governance, agroecosystems, and complex socio-ecological challenges (Voytenko et al., 2016; McCrory et al., 2020; McPhee et al., 2021). Their relevance for eutrophication lies in their ability to connect scientific monitoring, local knowledge, institutional responsibility, experimentation, and adaptive planning within a structured participatory process (Papadaki et al., 2026).

This study proposes and discusses the Living Lab as a participatory approach for developing strategies and plans to reduce the impacts of eutrophication processes in lakes. It aims to clarify: why eutrophication matters for healthy lakes; why participatory approaches are important in addressing this problem; how a Living Lab for eutrophication could be structured; and what theoretical and methodological challenges should be considered when designing such an instrument to address this issue.

2. EUTROPHICATION IMPACT

Lake health should be understood as the capacity of its ecosystem to maintain ecological structure, functional processes, biodiversity, water quality, and resilience under natural and anthropogenic pressures (Popa et al., 2023). In this sense, eutrophication is one of the most important threats to healthy lakes because it simultaneously affects several components of ecosystem integrity (Paraschiv et al., 2013).

The first and most direct effect of eutrophication is an increase in primary production due to excessive nutrient availability (Popa et al., 2023). In many freshwater systems, phosphorus has historically been identified as a key limiting nutrient, although nitrogen also plays an important role in many contexts and it can influence algal community composition and bloom dynamics (Schindler, 2006; Conley et al., 2009). When nutrient inputs exceed ecological thresholds, phytoplankton biomass increases, water transparency decreases, and the underwater light climate deteriorates (Florescu et al., 2022). Reduced light availability affects submerged aquatic vegetation, which is essential for habitat complexity, sediment stabilisation, nutrient uptake, and the maintenance of clearer-water conditions (Matsuzaki et al., 2021).

This process is especially important in shallow lakes, where interactions between sediments, aquatic vegetation, fish communities, and phytoplankton can produce alternative stable states (Scheffer et al., 1993). However, once the turbid state is established, simply reducing nutrient loading may not immediately restore the clear-water state, as internal feedback mechanisms continue to sustain high phytoplankton biomass (Dunalska, 2025). This nonlinearity is central to the management of eutrophication because it shows that prevention is often easier and less costly than restoration (Dunalska, 2025).

A second major consequence of eutrophication is oxygen depletion (Wurtsbaugh et al., 2019). As algal biomass increases, a larger quantity of organic matter eventually settles and decomposes (Carstea et al., 2013). Microbial decomposition of organic matter consumes dissolved oxygen, especially in bottom waters, while low-oxygen conditions can stress or kill fish and benthic organisms (Paraschiv et al., 2013), alter nutrient cycling, and stimulate the release of phosphorus from sediments (Moore et al., 2003). Søndergaard et al. (2003) emphasised the role of sediments and internal phosphorus loading in shallow lakes, showing that sediments are active components of the eutrophic dynamics, so the legacy of past nutrient loading can continue to influence the lake long after external inputs have been reduced.

Proliferation of cyanobacteria is another important effect of eutrophication, and one of its most visible and socially problematic symptoms (Popa et al., 2023). Cyanobacterial blooms can form dense surface scums, reduce recreational value, produce unpleasant odours, and, in some cases, release toxins that threaten humans, domestic animals, livestock, and wildlife (Florescu et al., 2022). Paerl and Otten (2013) described harmful cyanobacterial blooms as a major challenge for freshwater ecosystems, linking their occurrence to nutrient enrichment, hydrological alteration, and warming conditions. Thus, cyanobacteria are not only indicators of degraded conditions but also active drivers of ecological deterioration, affecting the suitability of lake water for recreation and other uses (Ho et al., 2019).

Social and economic impacts accompany the ecological effects of eutrophication as lakes affected by algal blooms may lose attractiveness for bathing, boating, fishing, waterfront tourism, and real estate development (Dodds et al., 2009). Local communities may experience reduced quality of life, economic losses, and increased costs for monitoring, water treatment, public information, and restoration (Tammeorg et al., 2024). The social effects are often seasonal and episodic, but their cumulative importance can be high; thus, a single intense bloom during the summer season may affect the public perception of a lake for years, especially where tourism and recreation are important (Walker et al., 2013). This is particularly relevant for lakes located near urban and coastal tourism areas, where ecological degradation can quickly become a planning and development issue (Bucur et al., 2012).

Recovery from eutrophication is often slow, as Jeppesen et al. (2005), based on long-term data from multiple case studies, showed that lake responses to reduced nutrient loading are variable and can take many years. McCrackin et al. (2017) further demonstrated, through a global meta-analysis, that recovery from eutrophication in lakes and coastal systems is often partial, late, and dependent on ecosystem characteristics and management context. This delayed response has important implications for strategy preparation, which requires long-term monitoring, realistic expectations, and adaptive revision.

Eutrophication of a lake also has a strong spatial dimension given that it is connected to its catchment through surface runoff, groundwater, drainage systems, land use, and human infrastructure (Hernández-Hernández et al., 2026). Nutrient loads are shaped by agriculture, urbanisation, wastewater treatment, shoreline development, and hydrological connectivity (Popa et al., 2020). For this reason, effective eutrophication strategies must consider the lake-catchment system, the distribution of nutrient sources, the institutional responsibilities across administrative boundaries, and the behaviour of users and land managers (Shkaruba et al., 2024). Carpenter et al. (1998) underlined the importance of nonpoint pollution from phosphorus and nitrogen in surface waters, showing that diffuse nutrient sources are especially difficult to regulate because they are distributed across landscapes and activities.

As Dokulil and Teubner (2010) showed, climate change accelerates eutrophication. Warmer temperatures favour cyanobacteria, extend the growing seasons, strengthen thermal stratification, and interact with nutrient enrichment to intensify the risk of blooms (Wang et al., 2025). Extreme precipitation events increase nutrient runoff, while droughts reduce flushing and concentrate nutrients (Li et al., 2018). These interactions make eutrophication management more uncertain and increase the need for adaptive planning. Strategies based only on historical conditions may be insufficient under the changing climatic and hydrological regimes (Wang et al., 2025). Healthy lakes therefore require not only nutrient reduction but also resilience-oriented governance capable of responding to uncertainty (Han et al., 2024).

The importance of eutrophication for a lake can thus be summarised through four main arguments. First, eutrophication directly degrades its ecological structure and function by altering nutrient dynamics, phytoplankton biomass, oxygen conditions, vegetation, and food webs (Popa et al., 2020). Second, it undermines ecosystem services and social values, including recreation, tourism, fisheries, landscape quality, and public health (Ho et al., 2019). Third, it is difficult to reverse the process because of internal loading, nonlinear dynamics, and delayed recovery (Jeppesen et al., 2005; McCrackin et al., 2017). Fourth, it is spatially and institutionally complex because its drivers are distributed across catchments and sectors (Wang et al., 2025). This is why a lake eutrophication mitigation strategy requires a combination of scientific, participatory, and adaptive approaches.

3. PARTICIPATION AND ENVIRONMENTAL MANAGEMENT

3.1. Advantages of participatory approach

The management of eutrophication has traditionally been strongly science-driven (Conley et al., 2009). Without lake monitoring, nutrient budgets, ecological modelling, and water-quality assessment, it is impossible to understand the sources, mechanisms, and trajectories of lake degradation (McCrackin et al., 2017). However, in addition to controlling the direct mechanisms of eutrophication, a complex mitigation strategy requires changes in land management, wastewater treatment, urban planning, shoreline use, agricultural practices, public behaviour, tourism management, and institutional coordination (Shkaruba et al., 2024). These changes involve actors with different interests, responsibilities, resources, and perceptions of the same problem. Thus, participation becomes necessary because eutrophication is not only a biophysical process but also the outcome of social practices and governance arrangements (Schindler, 2006).

Primarily, participatory approaches are important because they improve and fine-tune the definition of the environmental problem, as different actors may perceive eutrophication in different ways. So, scientists may define it through nutrient concentrations, chlorophyll-a, phytoplankton composition, oxygen profiles, or ecological status (Wurtsbaugh et al., 2019). Residents may perceive it through water colour, odour, bathing restrictions, fish mortality, or the loss of landscape quality (Drexler, Boles, 2024). Farmers may relate the issue to fertiliser management, drainage, soil erosion, or regulatory burdens (Feng et al., 2025). Municipal authorities may connect it to infrastructure, wastewater, urban development, and public complaints (Khalili, Moridi, 2025). While tourism operators may focus on destination image, seasonal attractiveness, and economic losses (Guimont, Lapointe, 2016). Overall, it results in a more complex perspective that it is useful for identifying the best management directions (Duan et al., 2026). A participatory process makes all these different problem framings explicit, but this does not mean that all perceptions are equally valid as scientific explanations. However, it does mean that strategies become more realistic when they understand how the problem is experienced and interpreted by different groups with various, often divergent, interests within the same space.

In addition, participation helps to identify sources of knowledge which are not captured by formal monitoring. Such knowledge can complement scientific data and can help formulate more relevant hypotheses and measures. Reed (2008) emphasised that stakeholder participation can improve environmental decision-making by incorporating broader information inputs and by increasing trust and learning. In eutrophication planning, local knowledge may be especially valuable where monitoring networks are limited, historical data are incomplete, or diffuse sources are difficult to trace (Schindler, 2006).

Participatory approaches can also increase decision legitimacy as the measures to reduce eutrophication may impose costs or constraints on certain actors. Agricultural nutrient reduction, restrictions on shoreline development, improved wastewater management, buffer strips, wetland restoration, stormwater redesign, or changes in recreational practices may all generate community resistance if they are perceived as imposed, unfair, or poorly explained (Reed, 2008). Participation can reduce this risk by allowing the affected actors to understand the evidence, to express their concerns in addressing the issue, to negotiate intervention priorities, and to contribute to the design of measures (Voicu-Dorobanțu, 2016).

The lake-catchment system rarely corresponds neatly to administrative boundaries. That is why it is often managed and impacted under the decision-making of multiple public institutions and communities. Water authorities, municipalities, environmental agencies, agricultural institutions, tourism bodies, protected area administrations, landowners, and private operators may all influence the lake, but each operates under a different mandate (Guimont, Lapointe, 2016). Management fragmentation can lead to inconsistent actions, duplicated efforts, or gaps in responsibility. In the era of fragmented responsibilities, participatory environmental planning supports the improvement of coordinated management by bringing actors into a shared process (Duan et al., 2026). Nonetheless, while it may contribute to environmental effectiveness, the outcome eventually depends on the institutional context, scale of action, communication structure, and the degree of actor involvement (Newig, Fritsch, 2009).

The temporal dimension of an environmental strategy implementation is often underestimated. Many eutrophication strategies fail not because the proposed measures are scientifically wrong, but because they are not maintained long enough. A plan may recommend nutrient reduction, but the implementation may weaken after a political cycle, a funding period, or a change in institutional priorities. Thus, participation can overcome this flaw by creating broader ownership and social memory around the strategy (Antaki et al., 2026).

3.2. Challenges of participatory approach

At the same time, participatory approaches must be treated critically as the environmental outcomes of collaborative management are often difficult to demonstrate, and the enthusiasm for participation in the process may exceed the evidence of effectiveness for the proposed measures (Koontz, Thomas, 2006). In the case of lake eutrophication, a participatory process may produce stakeholder meetings, reports, and consensus statements without reducing nutrient inputs or improving its ecological status. Conversely, a scientifically rigorous strategy may fail politically if community participation is weak. The challenge is therefore not to choose between expertise and participation, but to design processes where both are integrated.

Participatory governance acknowledges that power relations are a major issue, as stakeholders do not enter participatory processes with equal resources, but they are strongly backed by their technical expertise, institutional authority, financial capacity, political access, or communication skills (Antaki et al., 2026). Some relevant stakeholders may lack time, confidence, or formal recognition and they are, therefore, marginalised in the decision-making process. If these asymmetries are ignored, participation may only reproduce the existing power relations rather than to democratize decision-making (Visser, Kreemers, 2020). In eutrophication planning, powerful actors may seek to avoid responsibility for nutrient inputs, while less powerful communities may experience the consequences of lake degradation without influencing its causes. So, careful facilitation, transparent rules, and deliberate inclusion are therefore essential in a participatory governance process (Fernández-Pacheco Sáez et al., 2026).

Identifying and engaging the relevant actors in a participatory process is a challenge of representation (Visser, Kreemers, 2020). In the case of lake eutrophication, they may include water authorities, municipal administrations, wastewater operators, agricultural producers, tourism businesses, fishers, residents, environmental NGOs, schools, researchers, health authorities, protected area managers, and recreational users. In some specific contexts, seasonal users and tourists may also be relevant, although they are harder to get systematically involved (Li et al., 2025). So, the participation design must distinguish between the different involvement roles of the stakeholders: those who should be involved in decision-making; those who should be consulted; those who should receive information; and those who should contribute to monitoring or to implementation (Drexler, Boles, 2024).

Participation also requires translation between various knowledge systems (Visser, Kreemers, 2020). For the governance of lake eutrophication, scientific indicators such as total phosphorus, total nitrogen, and chlorophyll-a, may not be easily understood by the non-specialists who have decision-making responsibilities or who participate in the design of planning. Conversely, the experiential observations of different population groups may be difficult to integrate into technical assessments (Dobre et al., 2019). A participatory approach must therefore be based on boundary objects: maps, diagrams, scenarios, indicators, narratives, and monitoring dashboards, so the different actors can discuss the same problem without reducing it to purely technical language. This is a significant reason for the relevance of the Living Lab approach, as it provides a framework not only for consultation, but also for co-creation, interdisciplinary experimentation, and reciprocal learning (Fernández-Pacheco Sáez et al., 2026).

4. LIVING LABS AND EUTROPHICATION MITIGATION

The Living Lab concept has been defined in different ways, but several features recur across the literature: real-life setting; active user involvement; multi-actor collaboration; co-creation; openness to all voices; experimentation; and iterative learning, based on problem diagnosis, measure design, implementation, and evaluation to inform each other continuously (Bergvall-Kåreborn, Ståhlbröst, 2009; Leminen et al., 2012; Hossain et al., 2019). So, a Living Lab is not simply a laboratory in the conventional scientific sense; it is a structured environment in which actors jointly explore a problem, develop solutions, test them in real-life conditions, evaluate the outcomes, and adapt their actions (Müller, 2026). In sustainability contexts, Living Labs are often used to connect knowledge production with practical territorial transformation (Voytenko et al., 2016; McCrory et al., 2020).

For lake eutrophication, a Living Lab can be understood as a participatory lake-catchment platform designed to support the preparation, implementation, monitoring, and revision of strategies and plans to reduce nutrient enrichment and algal blooms. Its main function is to serve as a ground for interaction among the actors who influence or who are affected by the lake’s health.

4.1. Framework characteristics

Given the spatial specificity of lake ecosystems, a eutrophication Living Lab should begin with establishing clear territorial and institutional boundaries. The territorial boundary must include the entire lake catchment area, while the institutional boundary should identify which authorities and organisations are responsible for water quality, land use, environmental protection, public health, tourism, agriculture, infrastructure, and local development – so, the Living Lab should be lake-centred but catchment-sensitive (Dunalska, 2025).

The most important structural component of a Living Lab is the convening core, referring to the actor group responsible for initiating and maintaining the Living Lab (Bulkeley et al., 2016). It may include a municipality, a water authority, a university or research institute, an environmental agency, or a partnership among them. The convening core should ensure continuity, logistics, communication, documentation, and connection to formal planning mechanisms.

Another component is the multi-actor platform, representing the participatory body that brings together the relevant stakeholders (Chroneer et al., 2019). Following the actor-role perspective developed in the Living Lab research, the stakeholders may play four different roles in relation to lake management: users, providers, utilizers, and enablers (Leminen et al., 2012; Nyström et al., 2014). In a lake eutrophication Living Lab, the users may include residents, recreational users, farmers, fishers, tourists, and local businesses. Providers may include scientists, technical experts, monitoring agencies, and infrastructure operators. Utilizers may include municipalities, water managers, planning authorities, and organisations that will apply the results. Enablers may include funding bodies, regulatory institutions, NGOs, and educational organisations. Clarifying these roles makes responsibilities more transparent for strategy implementation.

A shared evidence base is also important for a eutrophication Living Lab, as it creates a common factual reference for discussion (Chroneer et al., 2019). It should include available water-quality data, nutrient concentrations, chlorophyll-a records, phytoplankton information, cyanobacteria observations, oxygen profiles, sediment data, land-use maps, wastewater information, hydrological data, and historical documentation of blooms. Where data is insufficient, the Living Lab can identify monitoring gaps and it can propose a further realistic monitoring plan.

The specificity of a Living Lab as a participatory governance tool is represented by the multistakeholder problem framing (Papadaki et al., 2026). So, before management measures are proposed, the involved actors should jointly discuss the main problem in relation to lake eutrophication: how it is experienced; which drivers are the most important; which uncertainties remain; and which objectives and evaluation criteria should guide the following strategy.

The stage of co-design of measures should combine catchment, shoreline, in-lake, communication, and governance actions: reducing nutrient and diffuse pollution, improving wastewater and stormwater management, restoring riparian buffers, regulating shoreline development; while carefully assessing in-lake interventions, informing the public, supporting citizen reporting, coordinating institutions, securing funding, assigning responsibilities, and defining implementation timelines (Barati, Bankaru-Swamy, 2026).

Through the experimentation phase, Living Labs are particularly useful because they support testing first the proposed measures under real-life conditions (Dobre et al., 2019). In eutrophication planning, experimentation may involve pilot buffer zones, demonstration wetlands, citizen monitoring protocols, participatory mapping of pollution sources, or educational campaigns.

Monitoring and evaluation of small-scale experimentation results allow the actors to learn what works, what is socially acceptable, what is technically feasible, and what institutional barriers exist, in order to further ensure the success of the desired strategy (Müller, 2026). Because lake recovery is slow, evaluation should combine ecological, implementation, governance, and social indicators: nutrients, chlorophyll-a, cyanobacteria, oxygen, transparency, macrophytes, completed measures, stakeholder participation, coordination, transparency, learning, public awareness, perceived quality, recreation, and user satisfaction (Khalili, Moridi, 2025). But the Living Lab decision-making should not rely solely on process indicators, as active participation does not automatically imply ecological improvement; and it should also not rely only on short-term ecological indicators, because lake recovery may lag management action (Duan et al., 2026).

As a Living Lab should operate through well-defined cycles (diagnosis, co-design, and experimentation), the monitoring and evaluation phase needs to be followed by the adapted revision of proposed measures, depending on the internal and external factors continuously impacting the lake dynamics (Armitage et al., 2008). For example, eutrophication is influenced by ecological feedback, climate variability, land-use change, and political priorities (Pavelescu et al., 2014).

A brief reference to Siutghiol Lake, a Natura 2000 site, illustrates why such a framework may be relevant in Romania. Siutghiol Lake is located on the Romanian Black Sea coastal area, partially within Constanța Municipality, and it is associated with urban, recreational, tourism, and ecological interests (Skolka, 2024). Studies on Romanian coastal lakes, including Siutghiol, have discussed eutrophication in this regional context and in terms of water-quality assessment, and it is among the lakes affected by nutrient and phytoplankton dynamics (Godeanu, Galatchi, 2007; Ghiță et al., 2023). Without entering into a detailed territorial diagnosis, Siutghiol can be considered a useful example of a lake where ecological processes are inseparable from shoreline development, urban pressures, recreation, tourism, and institutional responsibilities (Bucur et al., 2011; Bucur et al., 2012; Anton et al., 2021; Skolka, 2024).

This is why the eutrophication of Siutghiol Lake became a major focus of local research and a Living Lab would be appropriate in such a context because it could bring together scientists, local authorities, tourism actors, residents, environmental organizations, and water management institutions to develop a shared strategy to reduce the risk of blooms and to improve the lake health in relation to the sustainable development of both urban, natural and tourist areas (Li et al., 2025).

4.2. Adaptive lake management

The Living Lab approach is valuable for eutrophication mitigation because it reframes its management as an adaptive planning process. When lake strategies are prepared exclusively as static documents, they often struggle to respond to the changing ecological conditions, stakeholder conflicts, or unexpected outcomes. The Living Lab creates a structured framework in which the strategy can be interpreted, tested, evaluated, and periodically revised, in relation to the new territorial challenges and eutrophication dynamics (Azadi, 2026).

Such a management instrument is especially important for large lakes, as they are affected by multiple pressures, competing uses (urban development, tourism, agricultural runoff), and fragmented governance (Anton et al., 2021). In their case, a Living Lab may provide added value, especially by addressing the main difficulty of not only knowing what should be done, but also by bringing all the different interested parties to the same table with the unique goal of mitigating eutrophication under a sustainable development framework (Lakatos et al., 2024).

The Living Lab approach is also compatible with adaptive management, which recognises that environmental policies are implemented under uncertainty and dependence on ecosystem dynamics, and that management should be treated as a learning process based on a participation framework (Bulkeley et al., 2016). In eutrophication control, adaptive management is essential because ecological responses may be delayed or nonlinear, being under the influence of different factors, so they may not correspond to the initial planning of implementation terms to achieve the mitigation objectives.

Another important contribution of the Living Lab for sustainable lake management is the integration of both ecological and social indicators. Classic eutrophication strategies often focus on technical indicators, such as phosphorus, nitrogen, or dissolved oxygen, but a sustainable strategy should also include the quality of participation, public trust, behavioural change, institutional coordination, and the perceived value of the lake (Palmer et al., 2022). Conversely, participatory projects sometimes focus on social engagement without measuring ecological improvement, so a successful eutrophication Living Lab should combine both.

Nevertheless, the Living Lab approach should be applied carefully, in order to maintain a rigorous planning framework and to avoid the risk to only use the concept as a fashionable terminology for any simple public consultation (Voicu-Dorobanțu 2016). To avoid this, a eutrophication Living Lab aiming at sustainable lake management should satisfy the minimum conditions of having: a clear lake-catchment focus; a stable convening structure; meaningful stakeholder participation; a scientifically credible evidence base; real-life testing of measures; transparent monitoring of both ecological and social indicators; adaptive revision of planning and interventions; and strong connection to formal governance (Lakatos et al., 2024).

5. LIVING LAB CHALLENGES

5.1. Theoretical challenges

Although the Living Lab approach is promising, it raises several theoretical challenges when applied to eutrophication. The primary one concerns conceptual clarity, as the Living Lab concept has been used across many fields, including digital innovation, urban planning, sustainability transitions, health, agriculture, and education (Hossain et al., 2019). This flexibility can be useful, but it can also create conceptual ambiguity. For eutrophication, conceptual clarity requires distinguishing a Living Lab from other participatory formats. Thus, a public consultation invites stakeholders to comment on the proposed plans; a stakeholder focus group facilitates discussion among the interested actors; and a research project produces scientific knowledge. A Living Lab should integrate all these participatory forms, but it should also go beyond them by emphasising co-creation, iterative learning, and connection to implementation (Fernández-Pacheco Sáez et al., 2026).

The relation between participation and expertise is another theoretical challenge of using the Living Lab as the core of eutrophication mitigation. Eutrophication, as a scientifically complex process, involves knowledge on hydrology, nutrient cycling, phytoplankton ecology, sediment chemistry, food-web interactions, climate effects, and restoration techniques (Matsuzaki et al., 2021). A purely deliberative process cannot replace expert assessment, but it complements strategy development. At the same time, a purely expert-driven process may fail to address social practices, stakeholder responsibilities, and implementation barriers. The challenge is to create a co-production model in which scientific expertise remains rigorous while local knowledge and stakeholder perspectives are meaningfully integrated (Armitage et al., 2008).

Another challenge is the risk of depoliticising conflict. Although Living Labs focus on a positive and constructive approach to territorial problems, eutrophication may involve conflicts among the stakeholders (farmers, municipalities, tourism businesses, developers) over responsibility, costs, land use, regulation, limitations, and development priorities. A theoretically robust Living Lab must recognise that participation occurs within power relations and that consensus may not always be possible (Ersoy, Van Bueren, 2020).

Given that eutrophication processes are multi-scalar – nutrient inputs may originate upstream, while ecological impacts appear in the lake; decisions about land use may be local, while water-quality regulations may be national or European – the literature on urban and sustainability Living Labs warns on the importance of the analysis scale in order to avoid local experimentation to remain isolated while it is required to be connected to a wider governance framework and to related scaling processes (Voytenko et al., 2016; McCrory et al., 2020).

The temporal specificity of Living Labs, which are often project-based, represents an additional challenge, especially as eutrophication recovery is a long-term process (McCrackin et al., 2017). A project may last two or three years, a political cycle lasts 4 years, but ecological improvement may require decades. The mismatch between the different life cycles of management contexts can generate unrealistic expectations on the results. For a successful eutrophication mitigation strategy, the Living Lab must therefore be theorised not as a temporary participation project but as a governance infrastructure capable of persisting beyond the initial funding cycles.

The final concern is related to innovation, as a specific requirement for Living Labs (Anton et al., 2022). But eutrophication management does not always require novelty, given that many effective measures are already known: nutrient reduction, wastewater treatment, buffer zones, erosion control, wetland restoration, monitoring, and land-use regulation, to name the most important ones (Morelato et al., 2026). In the territorial context of Siutghiol Lake, for example, the problem with eutrophication mitigation is rather related to implementation than to the lack of innovative technologies. Therefore, a eutrophication Living Lab should be better organised around institutional, social, procedural, or communicative innovations (Anton et al., 2022), which does not exclude, however, using novel technologies as a tool to facilitate or to accelerate de-eutrophication processes.

5.2. Methodological challenges

The methodological design of a eutrophication Living Lab is as important as its theoretical justification, given that it brings additional challenges to address. First, the identification of relevant stakeholders needs to be as exhaustive as possible to avoid including only obvious institutional actors, while excluding groups that influence nutrient flows or that directly experience lake degradation. So, stakeholder mapping should consider influence, interest, responsibility, vulnerability, knowledge, and capacity to act within and beyond the Living Lab framework (Ersoy, Van Bueren, 2020). In the context of eutrophication management, it should also distinguish between permanent residents, seasonal users, land managers, economic actors, and public institutions.

Second, considering that participation in Living Labs must be deliberately configured, i.e. deciding on who participates, at what stage, by which methods, and to what extent, it should be done based on explicit rules. Otherwise, participant involvement may become confusing, inefficient, or dominated by those with more time and resources (Akasaka et al., 2022).

Third, scientific and participatory methods are difficult to integrate in a eutrophication Living Lab due to the combination of various research methods, such as water sampling, remote sensing, GIS mapping, nutrient-source assessment, interviews, workshops, participatory mapping, scenario planning, citizen science, and policy analysis (Ersoy, Van Bueren, 2020). Because each method has different validity standards – scientific monitoring requires precision and quality control, while participatory approaches require inclusiveness and facilitation – the methodological challenge is to connect all of them without weakening none (Ersoy, Van Bueren, 2020).

In the specific case of lake eutrophication, its dynamics is mostly unpredictable because the process depends on many highly variable factors, such as weather conditions, hydrological variability, land-use change, sediment processes, biological interactions, and climate variability (Morelato et al., 2026). So, an important level of uncertainty dominates the results of a eutrophication Living Lab. The solution would be scenario planning, as it allows the stakeholders to explore possible futures of territorial evolution and mitigation in relation to the impact of various drivers – such as increased tourism pressure, improved wastewater treatment, agricultural changes, extreme rainfall, or warmer summers – while the lake health depends mainly on their interaction rather than on isolated management measures (Anton et al., 2021).

Within a eutrophication Living Lab, the evaluation of results should be multi-layered, given that ecological recovery may be slow, and the challenge is to address it in a complex way, across all its pillars (Koontz, Thomas, 2006). Thus, the process evaluation should assess the quality of participation, representation, transparency, trust, and learning; the output evaluation should assess whether the Living Lab produced a strategy, an action plan, a monitoring protocol, pilot measures, or institutional agreements; the outcome evaluation should assess whether implementation occurred and whether the nutrient inputs declined; and, finally, the impact evaluation should assess long-term ecological improvement (Müller, 2026).

Data accessibility and communication are another challenge for successful Living Labs, as they are based on both scientific data, which are often difficult to interpret by non-specialists, and stakeholders' co-involvement (Papadaki et al., 2026). So, for an efficient participatory approach to eutrophication mitigation, a Living Lab should translate technical indicators into understandable formats without oversimplifying them, while communication must avoid creating false certainty about the lake dynamics. For example, a low bloom risk at one moment does not mean that the lake is now healthy, while the absence of visible algal scum does not necessarily indicate low nutrient pressure (Wei, 2026).

The institutionalisation of the Living Lab results is also important as the participatory framework can produce valuable knowledge and social learning, but if it is not connected to formal planning instruments, its influence may remain limited (Palmer et al., 2022). That is why eutrophication strategies must be linked to water management plans, spatial planning, municipal development strategies, wastewater investments, and agricultural policies, and the Living Lab should therefore include mechanisms for transferring co-created recommendations into official decisions.

The final methodological challenge is related to the comparability and transferability of the Living Lab results to other territorial contexts confronting the same issue of eutrophication. Although each lake is unique, every eutrophication Living Lab should produce lessons that can be compared across different spatial contexts, which requires documenting in detail the methods used, the involved actors, the chosen evaluation indicators, the decisions of mitigation made, and the expected outcomes (Müller, 2026). While the Living Lab for the mitigation of eutrophication in the case of one lake should not be copied mechanically to another, its design principles need to be transferable, especially when the territorial context is similar. Also, the general stages of work within a Living Lab – shared diagnosis, co-design, pilot testing, monitoring, and adaptive revision – are broadly applicable and they need to be respected regardless (Barati, Bankaru-Swamy, 2026), although the specific measures which result in the end differ depending on the case study characteristics.

5. CONCLUSIONS

Eutrophication is one of the most significant threats to healthy lakes because it affects the ecological structure, the biogeochemical functioning, fishing resources, biodiversity, water quality, public health, recreation, and local development (Feng et al., 2025). Its impacts are visible through algal and cyanobacterial blooms, reduced water transparency, oxygen depletion, habitat degradation, and loss of ecosystem services (Khalili, Moridi, 2025). The management of eutrophication is difficult because nutrient sources are numerous, ecological responses are nonlinear, internal loading can delay recovery, and climate change may increase the intensity and amplitude of related drivers (Morelato et al., 2026). For these reasons, this anthropogenic process should be treated as a complex socio-ecological problem rather than a narrow water-quality issue, especially due to its territorial effects in relation to all dimensions of sustainable development.

Participatory approaches are important because eutrophication management requires cooperation among all actors who influence or who are affected by the nutrient dynamics. Participation can improve problem framing, integrate local knowledge, increase legitimacy, support coordination, and strengthen long-term implementation; however, participation must be carefully designed within a functional structure (Voicu-Dorobanțu 2016).

In this sense, the Living Lab approach offers a promising participatory framework for preparing strategies and plans to reduce eutrophication and algal blooming within lakes. Its main contribution lies in organising co-creation, experimentation, monitoring, and adaptive learning – significant participatory processes – in real-life settings, at the scale of the lake-catchment system and based on a convening core, a multi-actor platform, a shared evidence base, and a participatory problem framing (Barati, Bankaru-Swamy, 2026).

Nonetheless, the theoretical and methodological challenges of Living Labs require attention and adaptation specific to each territorial context. Usually, conceptual ambiguity, power relations, the balance between expertise and participation, temporal mismatch, stakeholder representation, uncertainty, evaluation, and institutionalisation must all be addressed. Nonetheless, the value of a Living Lab lies in creating a structured participatory environment in which scientific knowledge can be translated into legitimate, feasible, and adaptive strategies.

For lakes such as Siutghiol in Romania, where ecological objectives of biodiversity conservation and of eutrophication mitigation intersect with pressures such as urbanisation, recreation, tourism, and institutional complexity, the Living Lab approach could support more integrated and participatory planning to achieve sustainable development and, thus, to harmonise all competing needs and interests (Li et al., 2025).

The objective would be to build a continuing participatory governance process, through which the lake health becomes a shared responsibility.

6. ACKNOWLEDGEMENTS

This work was supported by the grant from the Ministry of Research, Innovation and Digitization project "Competence Center for Climate Change Digital Twin for Earth forecasts and societal redressement: DTEClimate. SP2: Act4D-Eutrophication" within PNRR-III-C9-2022 - I5.

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CINQ CONTINENTS
REVUE ROUMAINE DE GEOGRAPHIE

Volume 16 / Numéro 33
Été 2026
ISSN : 2247 - 2290
p. 30-59

Geomorphological aspects of Putna Valley (Lepșa – Tulnici sector), Romania

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Citer ce document :

NEDELCU, M.-A. 2026. Geomorphological aspects of Putna Valley (Lepșa – Tulnici sector), Romania. Cinq Continents 16 (33): 30-59.

Geomorphological aspects of Putna Valley (Lepșa – Tulnici sector), Romania

Marius-Andrei NEDELCU

Aspecte geomorfologice ale Văii Putnei (Sectorul Lepșa – Tulnici), România. Prin complexitatea fizico-geografică, dar și a factorului antropic, prezent aici încă din timpuri istorice îndelungate, valea Putnei vrâncene reprezintă principala arteră hidrografică de pe teritoriul județului Vrancea. Sectorul analizat este situat în partea de nord-vest a bazinului Putnei, și reprezintă cursul montan inferior al văii, începând din aval de satul Lepșa și până la intrarea în Subcarpații Vrancei, în dreptul localității Tulnici, la confluența cu pârâul Coza. Evoluția îndelungată a rețelei hidrografice este exprimată prin dezvoltarea unor umeri de vale dispuși în lungul văii. Cadrul geologic general al văii Putnei este reprezentat de contactul dintre unitatea de Orogen carpatic și unitatea Platformei valahe din Vorland, iar unitatea de orogen fiind formată din fliș cu depozite cretacice, paleogene și miocene. În funcție de tectonică, dar și de elementele de detaliu, valea Putnei a suferit diferite schimbări de direcție. Din punct de vedere al regimului scurgerii, râul Putna se încadrează din punct de vedere hidrologic în categoria râurilor cu o mare variabilitate a parametrilor scurgerii (lichide și solide). Toate aceste elemente, precum și alcătuirea litologică au determinat o dinamică actuală a râului, cu schimbări aduse peisajului general al văii.

Cuvinte cheie: Putna, umăr de vale, neotectonică, dinamica văii.

Geomorphological aspects of Putna Valley (Lepșa – Tulnici sector), Romania. Defined by its physical-geographical complexity and a long-standing anthropogenic presence, the Vrancean Putna Valley serves as the primary hydrographic artery of Vrancea County. The analysed sector is situated in the northwestern part of the Putna basin, encompassing the valley's lower mountain course. This reach extends from downstream of Lepșa village to the gateway of the Vrancea Subcarpathians, near Tulnici, at its confluence with the Coza stream. The prolonged evolution of the hydrographic network is evidenced by the development of valley shoulders situated along its course. The general geological framework of the Putna Valley is defined by the contact between the Carpathian Orogenic unit and the Wallachian Platform in the foreland; the orogen itself consists of flysch featuring Cretaceous, Paleogene, and Miocene deposits. Influenced by both tectonic activity and localized structural details, the Putna Valley has undergone several changes in orientation. In terms of its discharge regime, the Putna River is hydrologically classified among rivers characterized by high variability in runoff parameters (both liquid and solid). These factors, compounded by the lithological composition, drive the river's contemporary dynamics, resulting in significant alterations to the overall landscape of the valley.

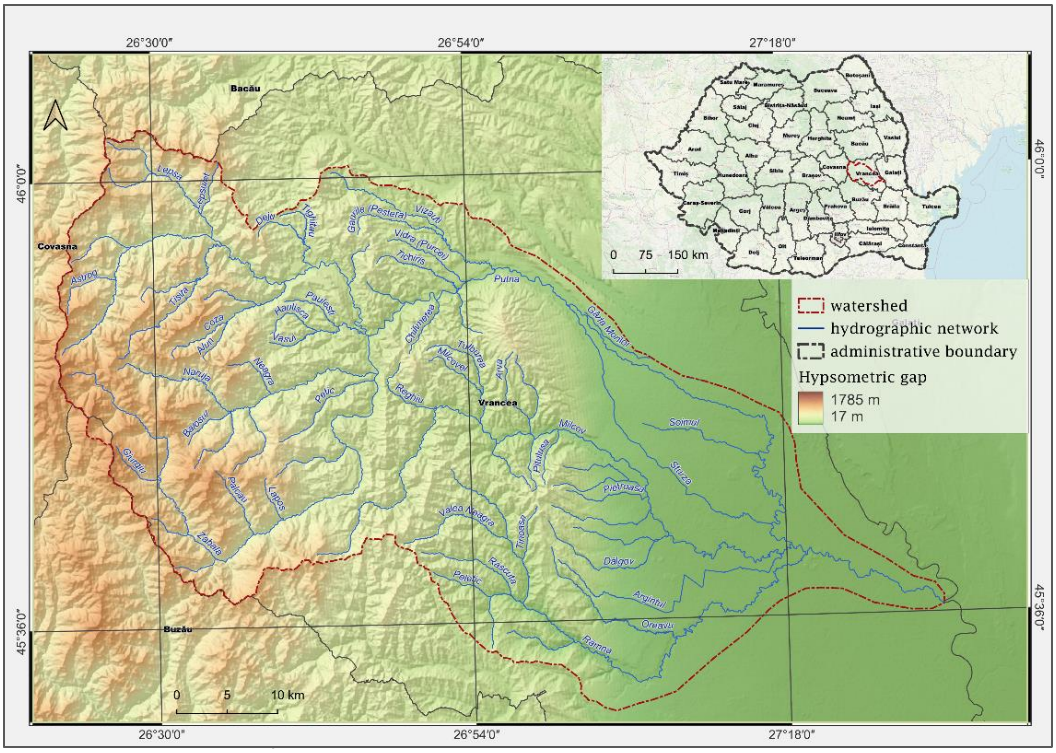
Keywords: Putna, valley shoulder, neotectonics, valley dynamics.

1. INTRODUCTION

1.1. Geographical setting

From the point of view of the geographical belonging of the valley sector, it is located within the Putna hydrographic basin, being part of the river system of the Siret River (Figure 1). The name Putna has numerous origins, one of them is the Slavic one (Puhna or Pucna), meaning "endowed with a road" or "with a path", being a proof of the inhabitation of the valley by the people of Vrancea, since ancient times (Mihăilescu et al., 1970).

The Putna River is located in the south-eastern part of the country, on the outer side of the Curvature Carpathians, sectioning all the relief steps, from west to east: the Vrancea Mountains, the Vrancea Subcarpathians, the north-east of the Romanian Plain. Some general data on its development: L = 160 km, basin area of 2,488 km^2, with a percentage of 5.37% of the total area of the Siret basin and only 1.04% of the country's.



Source: ANAR, https://data.gov.ro/dataset/hidrografie; ANCPI, https://data.gov.ro/dataset/unitati-administrativ-teritoriale-07-03-2024

The Putna basin is delimited by the drainage divide to the other neighbouring basins: to the north, the Șușita basin, to the north-west, the Trotus basin, to the west, the boundary is made with the Olt basin, to the south, the Râmnic-Sărat basin, to the south-west, the Buzău basin, and to the east, the delimitation is made on the lower course of the Siret River (Zaharia, 1999). Altitudinally, there are important variations of the hypsometric steps, from west to east there being a difference in level of about 1763 m.

The measured length of the analysed sector is 11.6 km and represents 7.2% of the total length of the river, and the area holds 30.4 km², which means only 1.22% of the total basin. The maximum altitude is recorded in the Tisaru Massif, reaching 1,267 m at the Tisaru Mare peak, while the minimum value of approximately 430 m is found at the floodplain level, where the river enters the Subcarpathians and meets the Coza tributary.

1.2. General geomorphological characteristics

The morphological delimitation of the Putna Valley is addressed in Cristea's work (2011), which employs specific evolutionary and morphometric criteria to identify traces of old leveling surfaces shaped by denudational processes, as well as slope surfaces that represent distinct stages in the valley's deepening.

In the area of the Vrancea Mountains, several levelling surfaces have been identified, which correspond to the stages of evolution of the relief. The first delimitation of these is due to Rădulescu (1937) through his study entitled "Vrancea. Physical and Human Geography" and includes five levels of erosion, three of which are relevant to the present study: the "platform of the medium lands", between 1400-1480 m, medium altitudes, but it is also found lower, at 1100-1180 m (under the Zboina Neagră peak), the "lowland platform" between 1200-1300 m, is also identified north of the Putna River, but between 960-1060 m and the "lower platform", between 1000-1100 m, with a lower development. Their age has been attributed to the Pliocene and Miocene, a period characterized by intense tectonic uplifts.

The morphological features of this valley sector are characteristic of the peripheral mountain units. The mountain unit is located in the west of the basin, highlighted by the Vrancea Mountains, which extends from the western water ridge, to the right of a line, with a general north-south direction, which could be represented by the alignment of the marginal fault of the Carpathian flysch, with altitudes between 800-900 m and passes to the west by the localities of Tulnici, Coza, Păulești, Vetrești – Herăstrău, Păvălari.

According to Roman (1989), the Vrancea Mountains are structured on three main alignments, almost parallel, arranged V – E: the Western Ridge, the Middle Ridge and the mountain border. The western ridge has the highest altitudes, and on this alignment, there are also the maximum altitudes, Lăcăuți (1777 m), Goru (1785 m) and Giurgiu (1722 m).

As a result of the action of the hydrographic network, which led to the fragmentation of the relief, but also under the influence of local factors (lithological and/or structural), 5 depression basins resulted, which occupies 1/2 of the length of the sector: the Ciuta, Porcu, Putna Waterfall basins, one located upstream of the Mociarului confluence and another downstream of it, all of which make up the "Putna Vrancea Gorge" according to Roman (1989).

If we talk about the orientation of the valley, in the mountainous sector and implicitly, in the analysis sector, 3 changes of direction are observed, due to geological causes. Thus, from the springs to the confluence with the Mărului stream, the Putna valley has an SSV-NNE direction, from the Mărului stream and up to the exit of the Greșu – Lepșa Depression, the Putna river has a west-east orientation, and after leaving the depression, it changes its direction to the south-east, until close to Tulnici.

2. METHODOLOGY

2.1. Data and methods

From a methodological point of view, I used both classical methods, such as the analysis and interpretation of previous geographical studies, field observations, and geomorphological profiling using GPS, and modern methods, such as data processing through Geographic Information Systems (GIS). These were based on a Digital Elevation Model (DEM) to generate maps for hypsometry, morphography, slope inclination, aspect (slope exposure), and the depth and density of relief fragmentation. Additionally, using GIS applications, morphometric parameters of the riverbed and key indices for the valley's dynamics were automatically calculated. As for the DEM used to obtain the mentioned maps, it was made on the basis of the interpolation of contour lines, with an equidistance of 10 m altitude, resulting in a raster with a pixel size of 1 meter.

The morphometric and morphographic analysis of the study area was carried out in relation to the main morphometric parameters, calculated with the help of the measuring instruments of the QGIS 3.34 program, based on the topographic maps at a scale of 1:25,000, developed by the Military Topographic Directorate. The mapping process renders the following aspects: the hypsometric features of the sector (altitude steps), the degree of horizontal fragmentation (fragmentation density), where the cartogram method was used, the degree of vertical fragmentation (depth of fragmentation), the main morphographic characteristics, through a map that renders the landforms on 10 categories depending on the geometry of the surfaces identified based on a DEM, slope by slope categories, slope exposure by slope categories (rendered for 8 cardinal and intercardinal points).

Regarding the evolution and genesis of the valley, lithology, geological structure, and tectonics are crucial factors; furthermore, the diversity of rocks and their distribution across various facies provide this sector with a distinct character. Geological data concerning the distribution and composition of the main lithological formations were derived from the 1:100,000 scale Geological Map of Romania – Bârsești sheet

(Dumitrescu, 1958). Subsequently, using GIS tools (QGIS, version 3.34), the geological data were processed, simplified, and categorized to determine the percentage distribution of the various rock types.

To characterize the climatic features of the analysed sector, data from the Lăcăuți meteorological station (1,777 m) were used for the mountain area (1961–2013), alongside data from Tulnici (571 m) for the Subcarpathian sector (1961–2003); these datasets were used to generate monthly and seasonal average precipitation graphs. The thermal regime varies between the western and eastern parts of the valley: the average annual temperature ranges from approximately 1°C (e.g., Lăcăuți Peak at –1.2°C) to over 10°C in the plain area (e.g., Focșani at 10.6°C). The studied valley sector falls within the 5°C to 7°C range, typical of low-mountain environments.

From the point of view of the runoff regime of the Putna River, it fits into the courses with a great variability of liquid and solid flows, due to its basin located in the Curvature region of the Carpathians, a region considered to have the intense sedimentary dynamics in the temperate zone of Europe (Ichim et al., 1998).

The characteristics of vegetation and land use influence riverbed and slope processes, with direct implications for valley dynamics. In the analysed area, the primary influencing factor is the altitudinal zonation of vegetation. Consequently, the study sector is situated within the forest zone, comprising two main belts: boreal (coniferous) and deciduous forests, each containing several mixed sub-zones. Data regarding land use and the proportions of each category were extracted from the Corine Land Cover (CLC 2018) database and processed using QGIS.

An additional argument that can strengthen a geomorphological study or analysis is the field practice, which brings new and topical elements and contributes to the formation of an overview of the researched element. Thus, the creation of geomorphological profiles, necessary to understand some aspects of the peaks and slopes, required several field trips to establish the points necessary to mark the profile and its subsequent processing. Three trips were made in September, respectively on 5.09.2024, 7.09.2024 and 21.09.2024, which resulted in the completion of five slope geomorphological profiles, including secondary ridges (with special regard to the valley shoulders).

Furthermore, riverbed and slope dynamics, along with channel geometry, were observed in detail during fieldwork, resulting in an extensive photographic record. Key insights into the factors favouring specific geomorphological processes can also be derived from the analysis of anthropogenic microforms; these are highly prevalent in inhabited areas, manifesting through both residential development and road infrastructure.

For the analysis of the chosen sector, the approach is an interdisciplinary one, using geographical and geological knowledge from the nineteenth – twentieth centuries, useful for knowing the paleogeographical evolution of the valley. The multitude of data and information found in more recent studies offers numerous concepts related to neotectonic evolution, and the consequences of tectonic uplifts in the current dynamics of the riverbed.

2.2. Research history

The numerous scientific contributions made to the Putna Valley have had the effect of better understanding its evolution. The existence of theories regarding the initiation and evolution of the hydrographic network at the Carpathian Curvature provides an overview of the complexity of the study area. In particular, starting with the twentieth century, several geologists and geographers, among whom stand out: Martonne (1907), Mateescu (1927), Rădulescu (1937), Paucă (1942), Sîrcu (1966), and Grumăzescu (1973).

According to De Martonne (1907), who synthesized the geological data that appeared at the beginning of the twentieth century, the sub-Carpathian depression of Vrancea would have a tectonic origin, as a result of the collapse of the dissolved salt formation. He also assumes that in the Lower Quaternary there would have been a longitudinal river, which was later disturbed by several transverse courses, which advanced regressively from the plain.

Mateescu (1927) adopted and further developed these ideas, demonstrating the existence of two primary evolutionary phases: the first occurred during the Early Quaternary, when the rivers were longitudinal in character, followed by a second phase (Middle Quaternary), during which the drainage network reorganized into a transverse pattern due to neotectonic movements.

Rădulescu (1937) demonstrated the existence of two longitudinal courses: one presenting a south-north direction, also called "the southern course of Vrancea", and one with a north-south direction, "the northern course of Vrancea". Later, Paucă (1942) proposed a contrary hypothesis, arguing that the valley sectors—from their headwaters in the mountains through the Subcarpathian area—exhibit a predominant west-east orientation alternating with north-south sections; this view is based on the general eastward tilt of the relief. Subsequently, Orghidan (1969) reinforced this hypothesis, providing additional evidence based on the significant thickness of Pleistocene-Quaternary gravel deposits along the line of the outer Subcarpathian peaks.

Sîrcu (1966) and Grumăzescu (1973) substantiate the theory of initial transverse courses and correlate specific terraces to highlight the developmental stages of the drainage network.

Utilizing data from more recent studies supports ongoing efforts to resolve tectonic issues and, by extension, the evolution of the hydrographic system. The study conducted by Fielitz, Seghedi (2005) determines that the development of the current drainage system (Figures 2 and 3) began during the Early to Middle Miocene (20–11 million years ago).

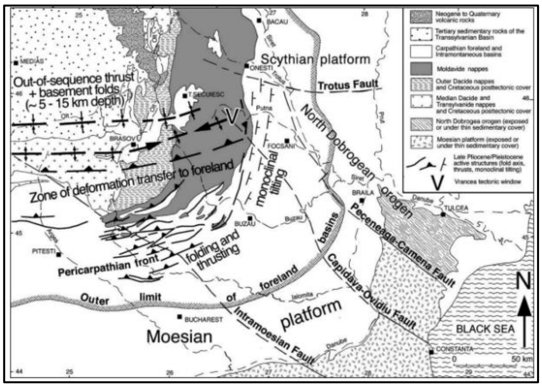


Figure 2. Geotectonic sketch of the Curvature Carpathians, highlighting active neotectonic structures from the late Pliocene and Pleistocene (after Fielitz, Seghedi, 2005).

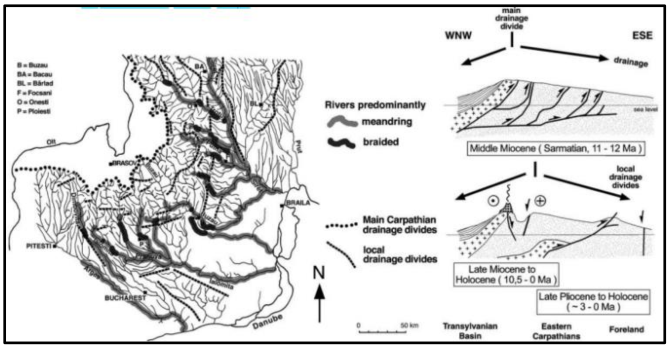


Figure 3. Characteristics of riverbed planform typology in the SE Carpathians and its relationship with transverse structural uplifts (left); correlations between the emergence and development of drainage divides and the recent neotectonic evolution of the Eastern Carpathians (after Fielitz, Seghedi, 2005).

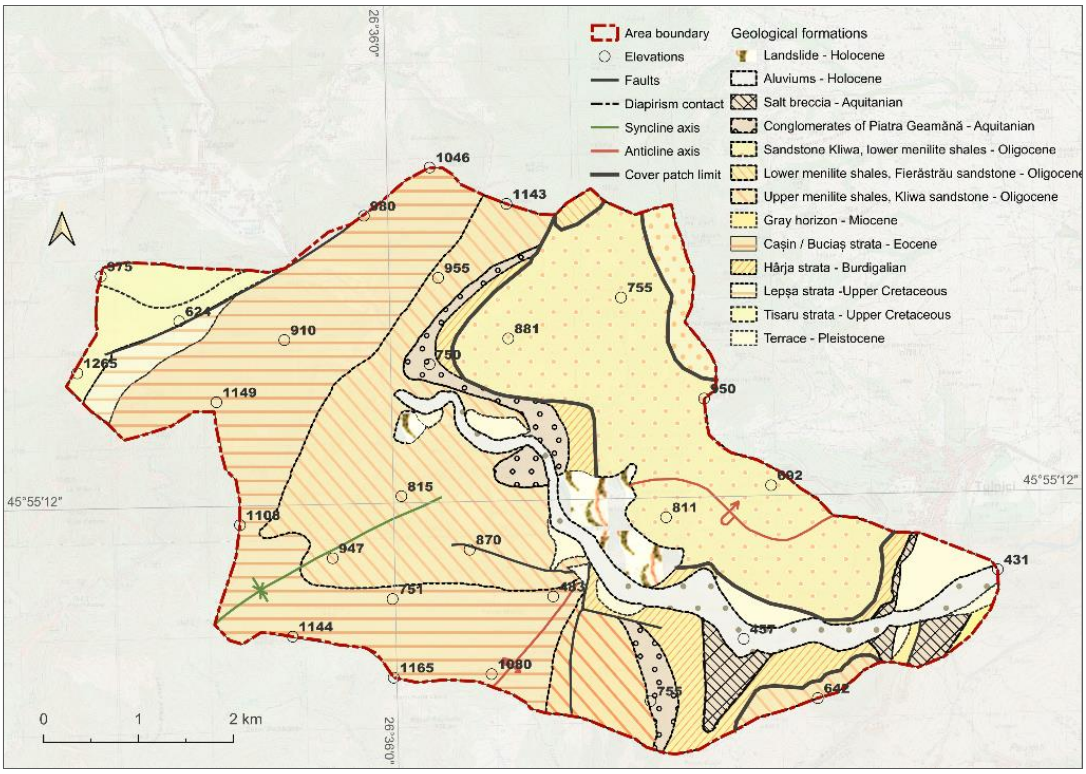
3. RESULTS

3.1. Morphogenetic factors

The formation and, specifically, the paleogeographical evolution of the Putna Valley were conditioned by numerous morphogenetic factors: internal forces (lithology, structure, tectonics, and neotectonics) and external forces (climate, vegetation, hydrography, and soils). The general geological framework of the Putna Valley consists of the Outer Moldavides (Outer Nappes) of the Eastern Carpathians and the Carpathian Foredeep. The external flysch deposits belong to two tectonic units: the Tarcău Nappe and the Vrancea Nappe (Dumitrescu, 1952). The primary geological and structural elements were synthesized and simplified into a map (Figure 4), where the represented formations are delineated either by clear tectonic contacts (faults, thrust planes, etc.) or by discontinuities resulting from sedimentation cycles.

Regarding the distribution of lithological facies (Figure 5), the most representative category in this sector comprises the Cașin Strata, Buciaș, and conglomerates (Figures 6 and 7), which account for 25% of the total area. The following two categories have similar weights: Lower Menilite and Kliwa Sandstone (23%), and Upper Menilite and Kliwa Sandstone (18%). Consequently, more than half of the sector's surface is developed on high-resistance (hard) rocks, significantly influencing the morphogenesis and evolution of the valley.

Among the aforementioned sedimentary formations of the Carpathian flysch, those belonging to the Vrancea Nappe are clearly predominant within the analysed sector; these are found in the Vrancea Half-window (which also constitutes the autochthon of the Tarcău Nappe). This unit consists of Cretaceous, Paleogene, and Miocene deposits that succeed one another from west to east. Tectonically, it is divided into two subunits—the Greșu and Coza digitations—the latter being the most extensive and including the aforementioned deposits.



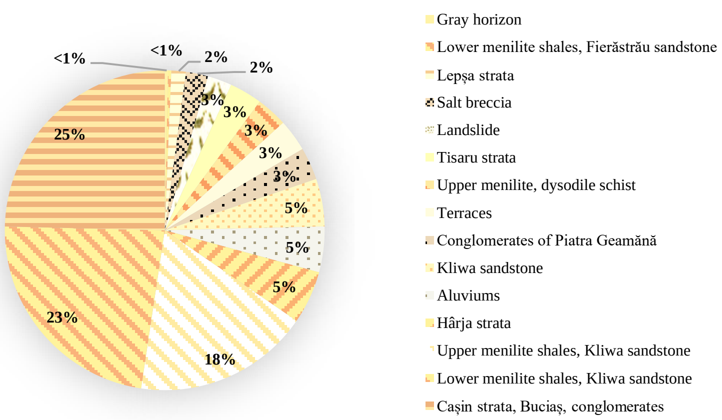


Figure 4. (upper) The main lithological subdivisions in the Lepsa – Tulnici area; source: QGIS 3.34 and processing of the Bârsești geological sheet – 1:100.000
Figure 5. (lower) Percentage distribution of geological formations in the studied area

Figure 6. (left) Opening at the level of the Buciaș strata,
arranged in successive horizons, on the left slope of the Putna valley
Figure 7. (right) The development of the Twin Stone Conglomerates imposed
the appearance of towers and other landforms

From a structural perspective, the western part of the basin consists of folded formations with a general NNE–SSW orientation. The Putna Valley has undergone several changes in direction, influenced by both regional tectonics and detailed structural elements. For instance, in the upper sector, the course of the Putna Valley is aligned with fault systems (Cristea, 2011).

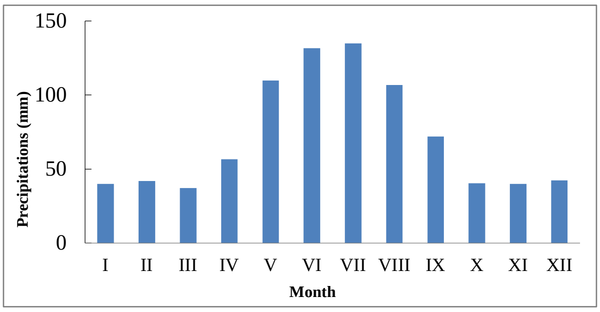
Thermochronological data indicate that the highest rate of tectonic uplift occurs within the Vrancea Nappe, with values of approximately 3.2 ± 0.3 mm/year (Necea, 2010). This uplift has contributed to the restructuring of the drainage network, leading to a predominantly transverse orientation. The development of a tectonic axis of elevation (horst-type) along a SW–NE direction forced changes in the hydrographic network; this resulted in the current configuration of the Putna Valley, characterized by a longitudinal character in its upper course and a predominantly transverse character throughout the rest of its mountain sector.

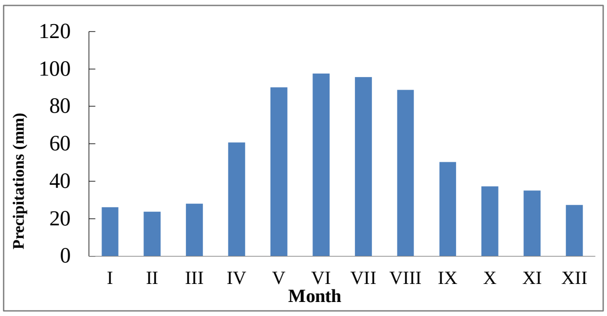
From a climatic perspective, the Putna basin is characterized by a temperate-continental transitional climate. However, factors such as the degree of topographic fragmentation (more pronounced in the west), the predominantly north–south orientation of the ridges, and varying slope aspects have fostered local atmospheric circulations and climatic differentiations between the mountainous area and the extra-Carpathian space.

The dynamics and frequency of air masses influence climatic elements, causing variations in temperature and precipitation regimes that are directly reflected in geomorphological processes.

In addition to the thermal regime, precipitation characteristics are relevant for analysing valley dynamics. The rainfall regime is influenced by humid air masses and the general orientation of the main ridges exposed to advection. Consequently, the directly exposed western slopes and higher peaks receive greater amounts of precipitation, exceeding 800 mm (e.g., Lăcăuți – 827 mm); these amounts are significantly reduced to the east, where the foehn effect occurs (e.g., Tulnici station – 645 mm).

The nature of precipitation is crucial for current geomorphological processes, with a key indicator being exceptionally rainy years, such as the intervals 1966–1967, 1969–1972, 1978–1982, and 2000–2005. At the monthly level, the highest precipitation occurs in May, June, and July in the mountain area, with values at the Lăcăuți station exceeding 100 mm.





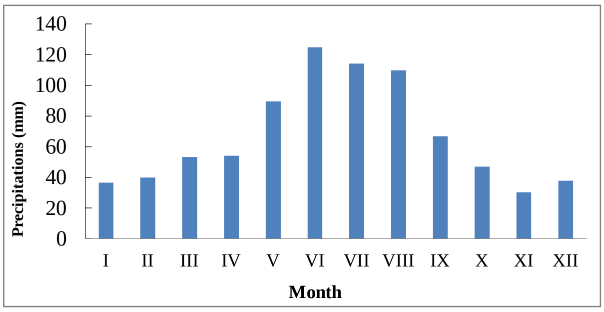
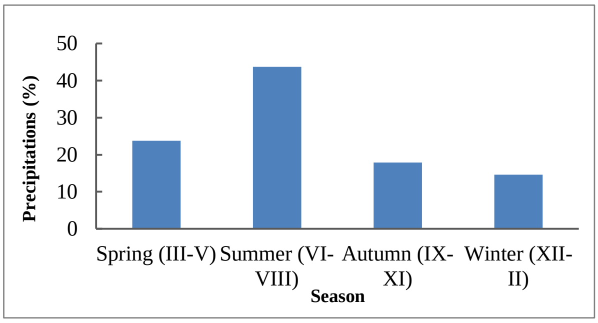


Figure 8. (upper left) The monthly rainfall regime at the Lăcăuți meteorological station Figure 9. (upper right) the monthly rainfall regime at the Tulnici meteorological station; modified after Zaharia, 1999; Figure 10. (lower) Monthly rainfall at the Lăcăuți meteorological station (1991 – 2013); processed according to meteorological data of the National Meteorological Administration

In the upland area of the Putna Valley (Lăcăuți station), precipitation distribution for the 1961–1990 period (Figure 8) varied from 37.1 mm in March to 134.9 mm in July. During the winter season, precipitation occurs in solid form, generating a significant snowpack; this constitutes a major component of the river runoff regime during the spring months and can lead to increased discharge and even flooding. At the contact with the Subcarpathians (Tulnici station), precipitation levels range from 23.7 mm in February to 97.5 mm in June, reflecting a reduction in total annual precipitation and a distinct eastward decline (Figure 9). Between 1991 and 2013 (Figure 10), the precipitation distribution underwent shifts, particularly at the monthly level, with values ranging from 30.3 mm (November) to 124.8 mm (June). Compared to the 1961–

1990 interval, the maximum monthly precipitation decreased slightly, and a discernible gap emerged during the summer months.

The seasonal distribution of precipitation (Figures 11 and 12) reflects these monthly characteristics. Summer accounts for 34% to 44% of the annual total, while spring contributes 23.8% at Lăcăuți and 27% at Tulnici. In winter and autumn, the values range from 17.9% to 14.6% at Lăcăuți, and from 19.5% to 11.7% at Tulnici (Zaharia, 1999).



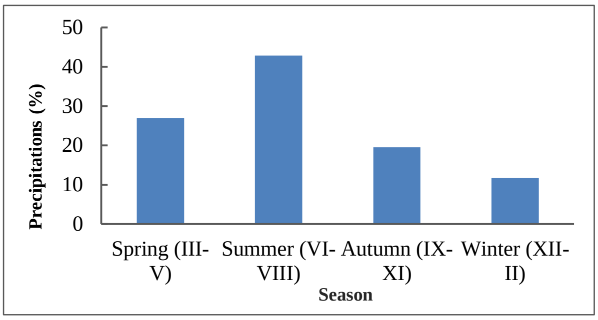


Figure 11. (left) The seasonal rainfall regime at the Lăcăuți meteorological station
Figure 12. (right) the seasonal rainfall regime at the Tulnici meteorological station; modified after Zaharia, 1999

The water resources within the analysed sector belong entirely to the Putna drainage basin. Their spatial distribution (Figure 13) highlights the most significant permanent and seasonal watercourses; these were extracted using the military topographic map as a primary base map. The discharge from tributaries occurs perpendicular to the main channel, locally influencing the lateral migration of the floodplain and contributing to the maintenance of a dynamic equilibrium.

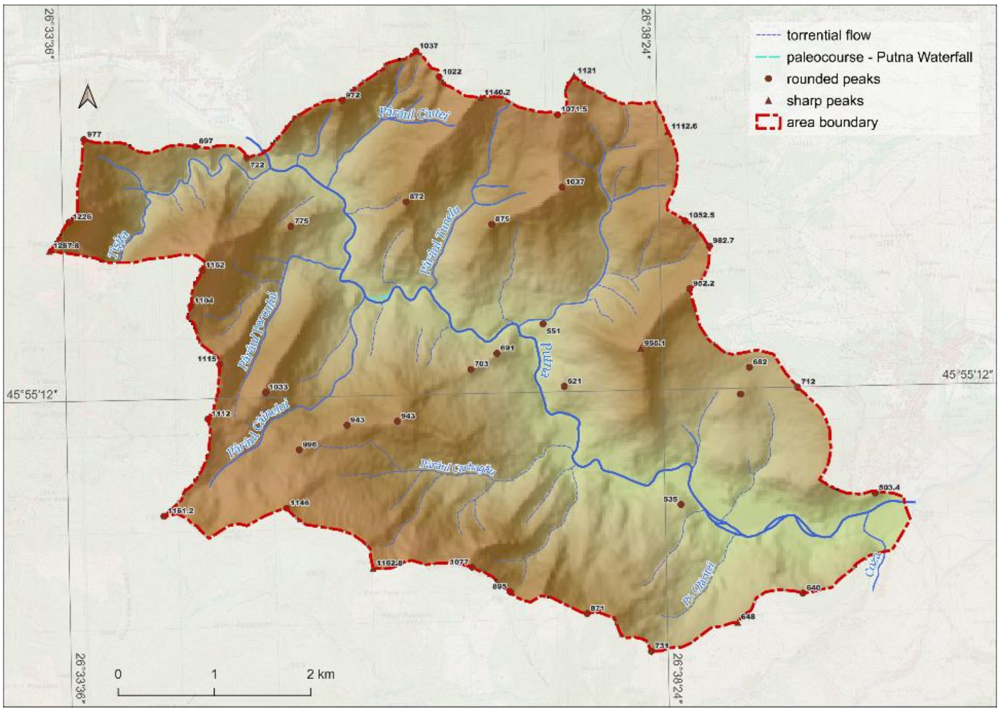
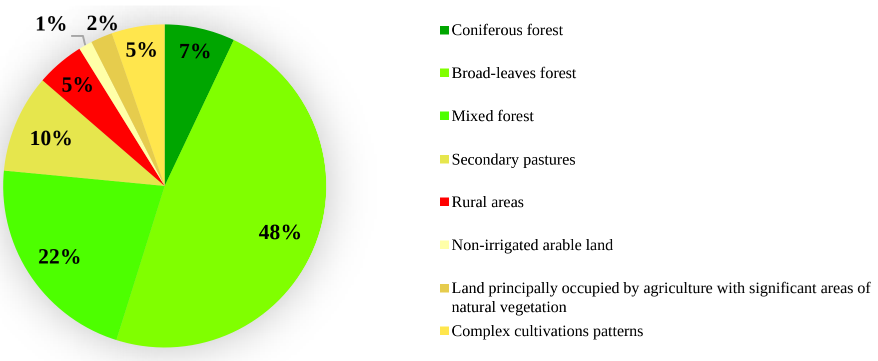


Figure 13. Distribution of water resources in the Lepsa – Tulnici sector

The most significant liquid discharge is contributed by the Tișița River, which, after carving an impressive system of gorges, flows into the Putna downstream of Lepșa on the right bank; at the confluence, it forms a small alluvial fan composed of gravels. Other significant tributaries influencing fluvial dynamics include the Porcului and Câinelui streams (with confluences near the Putna Waterfall), the Coza (noted for its high sediment input), and the Mociaru and Ciuta streams on the left bank.

The analysis of land-use categories (Figure 14), based on 2018 processed data, identified eight distinct types of land cover. The current vegetation composition has also been slightly influenced by human activity, specifically through the development of settlements and land-use patterns (Figure 15).



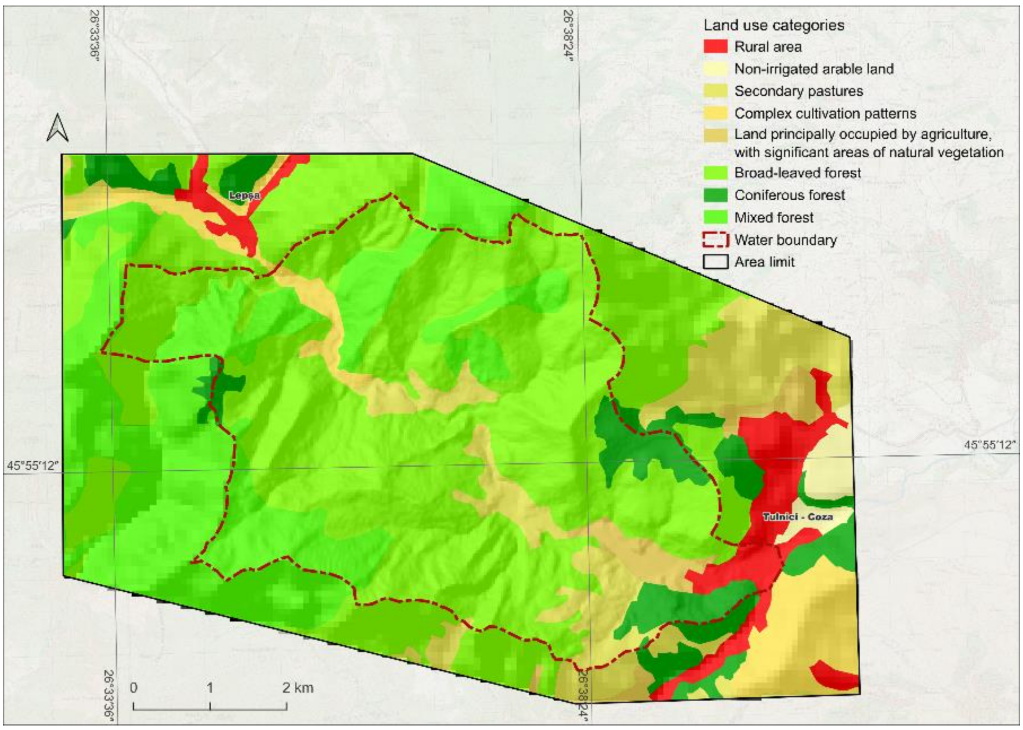


Figure 14. (upper) Percentage distribution of land use categories, according to CLC data – 2018
Figure 15. (lower) Degree of vegetation cover and land use, processing according to CLC data – 2018 (from the Corine Land Cover database);

Deciduous forests occupy the largest area, accounting for 48% of the total, with a relatively uniform distribution. These are followed by mixed forests (transitional between coniferous and deciduous) at 22%, and coniferous forests at 7% (represented by isolated patches of artificial pine plantations).

Secondary grasslands account for 10% of the area; these are confined to the lower valley levels, having replaced former forested areas. Rural built-up areas (comprising the villages of Tulnici, Coza, and Lepșa, located on the periphery of the study sector) and complex cultivation patterns each occupy 5%. The smallest shares are recorded by land principally occupied by agriculture with significant areas of natural vegetation (2%) and non-irrigated arable land (1%). The latter are identified on the terraces located east of the Tulnici perimeter.

3.2. Morphometry and morphography

In order to summarize the main morphometric parameters of the study sector (Table 1), the results of the calculations and measurements were briefly presented, using analysis tools from the QGIS program.

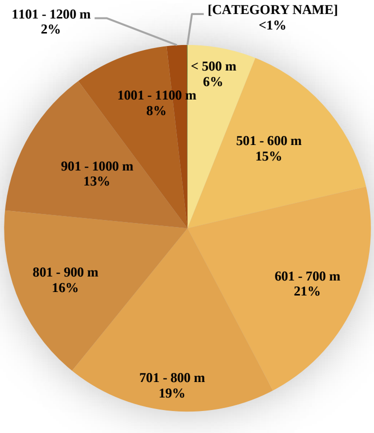
Table 1. Main morphometric parameters of Lepsa – Tulnici sector

Morphometric parameters	Unit of measurement
Area of the sector analysed	30.49 km^2
Perimeter of the secondary water divide	28.62 km^2
Length	11.6 km
General relief energy	834.8 m
Shape of the area	If = 0.33 (Form factor)

From a hypsometric perspective, the dominant altitudes characterize a typical mid-altitude mountain relief (reaching a maximum of 1,267.8 m at Tisaru Mare Peak). Lower altitudes occur along the valley sectors; towards the contact with the Vrancea Subcarpathians, the floodplains broaden significantly in the eastern part, where elevations drop below 500 m (with a minimum of 433 m) within the Putna riverbed.

The graphical representation of the hypsometric belts (Figure 16) reveals that the highest percentages, 21% and 19%, correspond to the 601–700 m and 701–800 m altitudinal intervals, respectively. The lowest weights are found below 500 m (6%), located within the floodplains and terraces along the valley, while the 1,100–1,200 m range (2%) covers several peaks (e.g., Fântâna lui Bucur, Porcului Peak). Additionally, peaks exceeding 1,200 m (within the Tisaru Ridge) are noteworthy, though they occupy less than 1% of the total area.

The hypsometric map (Figure 17) shows that elevation values generally decrease from west to east, following the general tilt and the regional relief steps, which also dictated the NW–SE orientation of this valley sector.



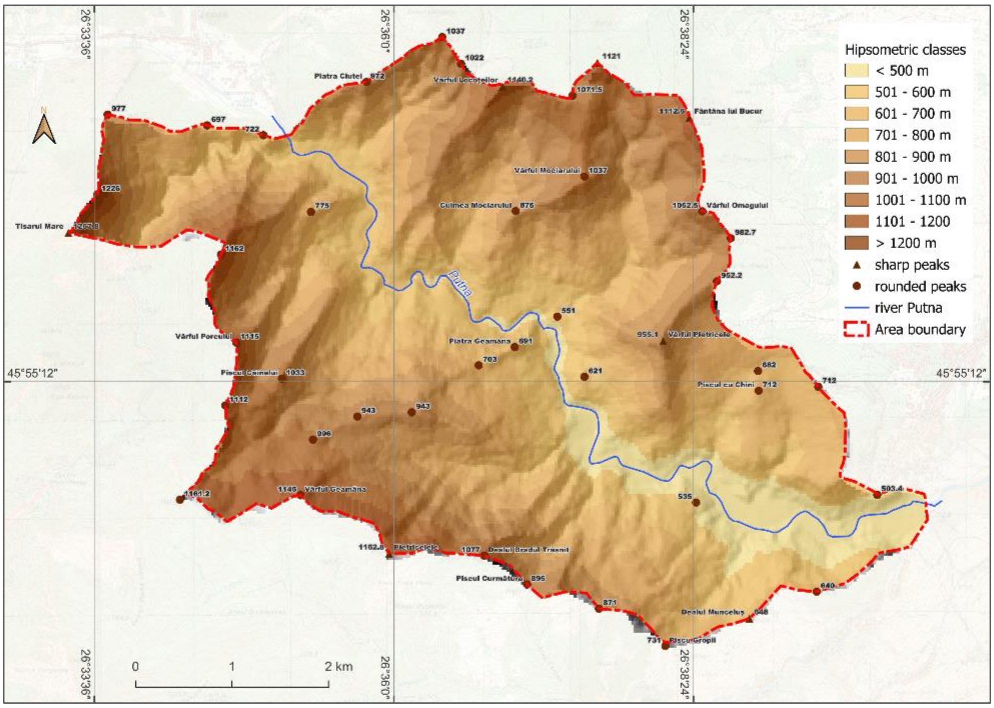
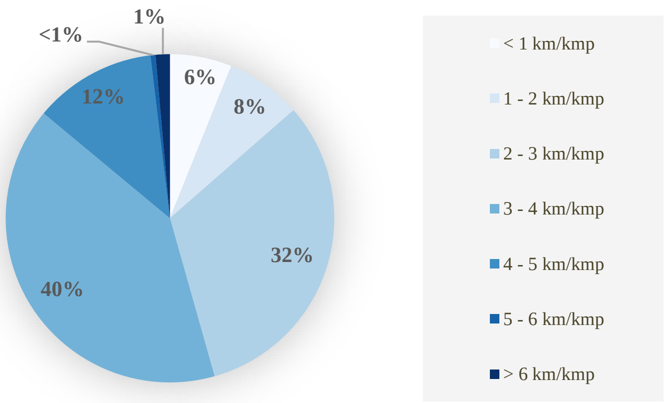


Figure 16. (upper) Percentage distribution of hypsometric steps
Figure 17. (lower) Distribution of altitudes in the area of the Putna valley

The degree of horizontal fragmentation (drainage density) is crucial for understanding the evolution of the river basin network (Marcu, 2013). The maximum calculated value for fragmentation density is 6–6.45 km/km², appearing only as isolated points at the eastern extremity of the study area, where the Putna River enters the Subcarpathian sector (Vrancea Depression). There is a distinct ratio between the weights of the 2–3 km/km² (32%) and 3–4 km/km² (40%) intervals, which represent the average densities for the entire area, covering 72% of the total surface. The lowest percentages are assigned to density values > 6 km/km² accounting for only 2% and occurring sporadically towards the eastern limit of the valley (Figure 18). Low values are also recorded in the 5–6 km/km² interval (less than 1%), corresponding to the Tisaru Mare peak and the gorge sectors formed by the Tișița River in the western extremity (Figure 19).



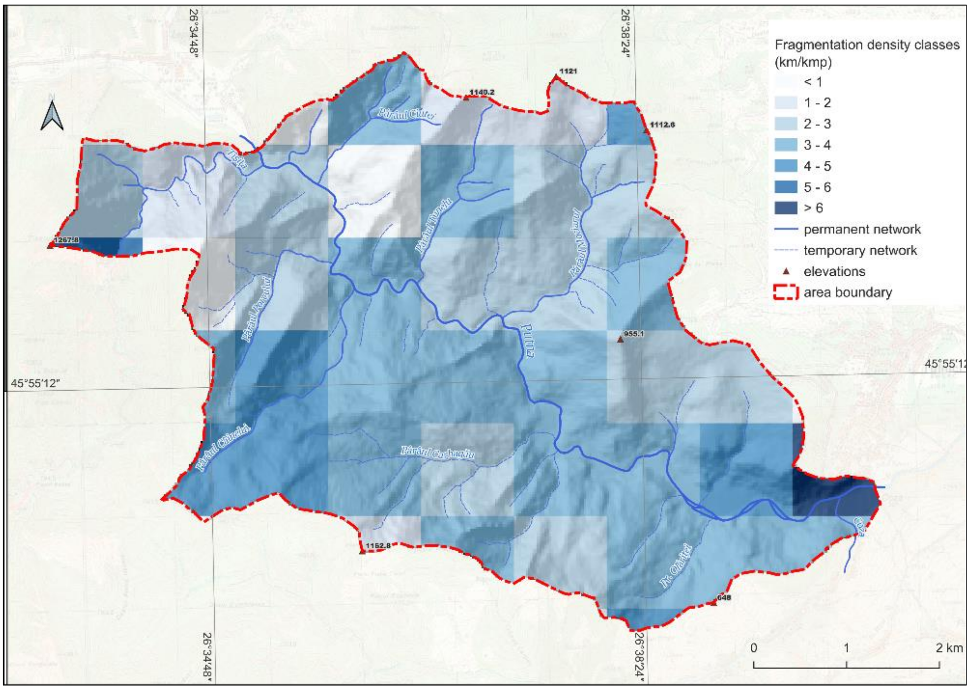
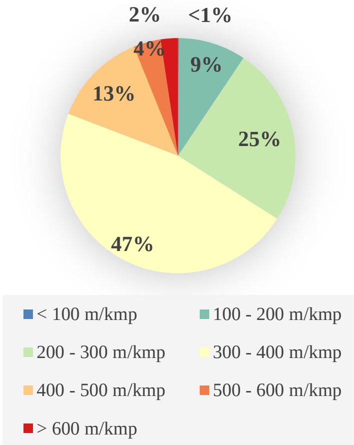


Figure 18. (upper) Percentage distribution of horizontal fragmentation of the relief
Figure 19. (lower) Distribution of horizontal fragmentation of the relief

The degree of vertical fragmentation (relief energy or fragmentation depth) results from erosional processes acting upon the lithological substrate (Marcu, 2013). Following the generation of the fragmentation depth map, seven intervals were identified, with values ranging from 15 to 620 m/km². Notably, nearly half of the entire sector's surface (47%) exhibits fragmentation depth values between 300 and 400 m/km², which represent the average vertical fragmentation for the area (Figure 20). The least represented classes are those below 100 m/km² (<1%) and those exceeding 600 m/km²; the latter are restricted to the western part (2%) and are conditioned by the higher altitudes of the Tisaru Massif. The 200–300 m/km² range (25%), covering one-quarter of the sector with an uneven distribution, also holds significant weight. The 100–200 m/km² (9%) and 400–500 m/km² (13%) classes are influenced, in terms of their spatial distribution, by their proximity to areas of high (over 500 m/km²) and low (less than 100 m/km²) relief energy, which have limited spatial coverage (Figure 21).



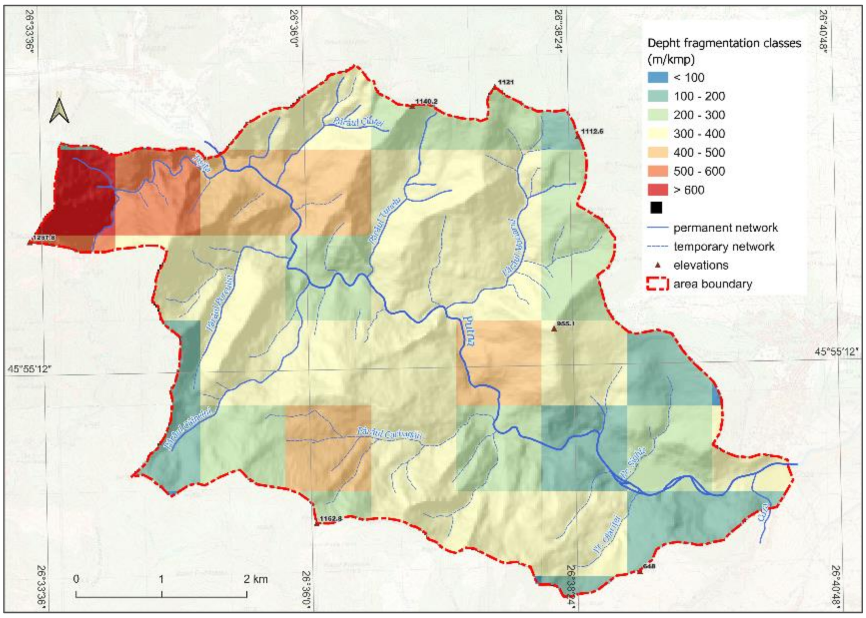
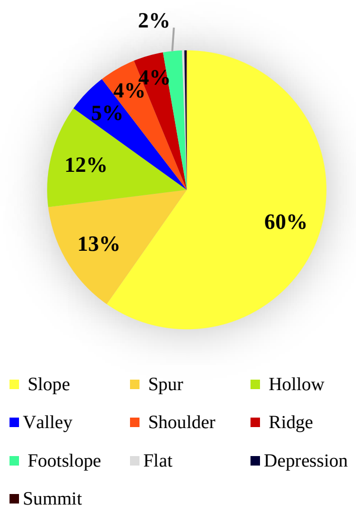


Figure 20. (upper) Percentage distribution of vertical relief fragmentation
Figure 21. (lower) Distribution of vertical relief fragmentation

The general morphographic characteristics of the Putna Valley and the detailed features of the study area highlight the dominance of slopes (Figure 22), which account for 60% of the total surface (Figure 23). Ridge areas, in all their forms (main ridges or valley shoulders), occupy 13% of the valley area. These are followed by valley-floor landforms (12%), while the channels themselves—characterized by permanent or seasonal runoff and significant incision depth—occupy only 5%. The smallest shares are recorded by flat surfaces (< 1%), which occur locally on terrace treads, and isolated peaks (< 1%).



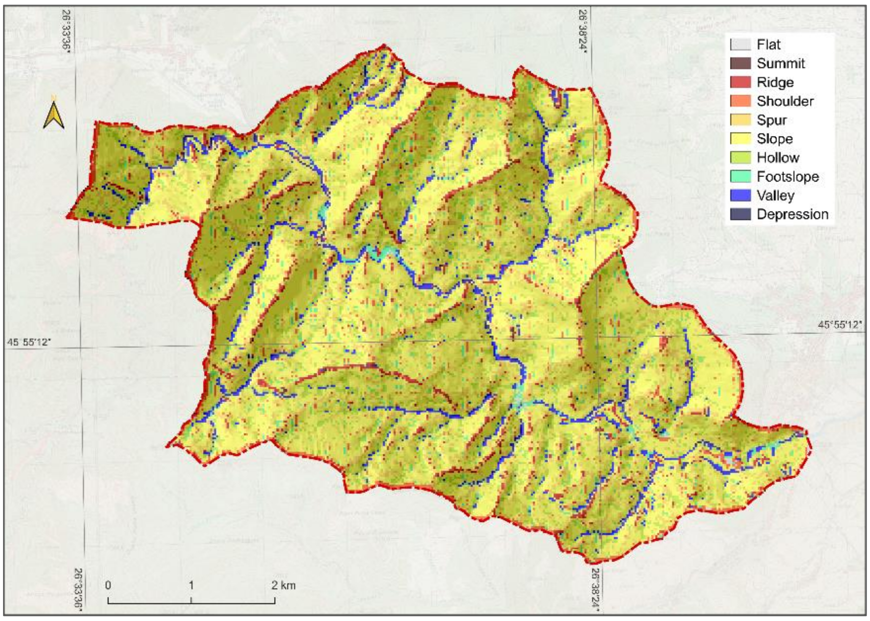
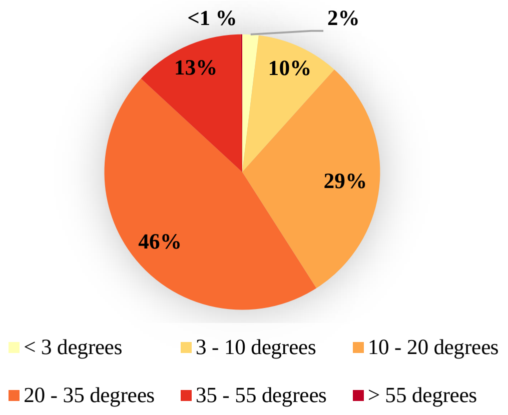


Figure 22. (upper) Percentage distribution of landforms
Figure 23. (lower) The main categories of landforms

Slope, as a fundamental property of surfaces, is a decisive factor in the development of geomorphological processes and the density of vegetation cover (Marcu, 2013). Six slope categories were defined, ranging from a minimum interval (0–3^0) to values exceeding 55^0. According to the percentage distribution of these categories (Figure 24), a significant share is held by the 20–35^0 range (46%), which characterizes most of the valley's slopes (Figure 25). The extremes—slopes above 55^0 and below 3^0—account for less than 1% and 2%, respectively.



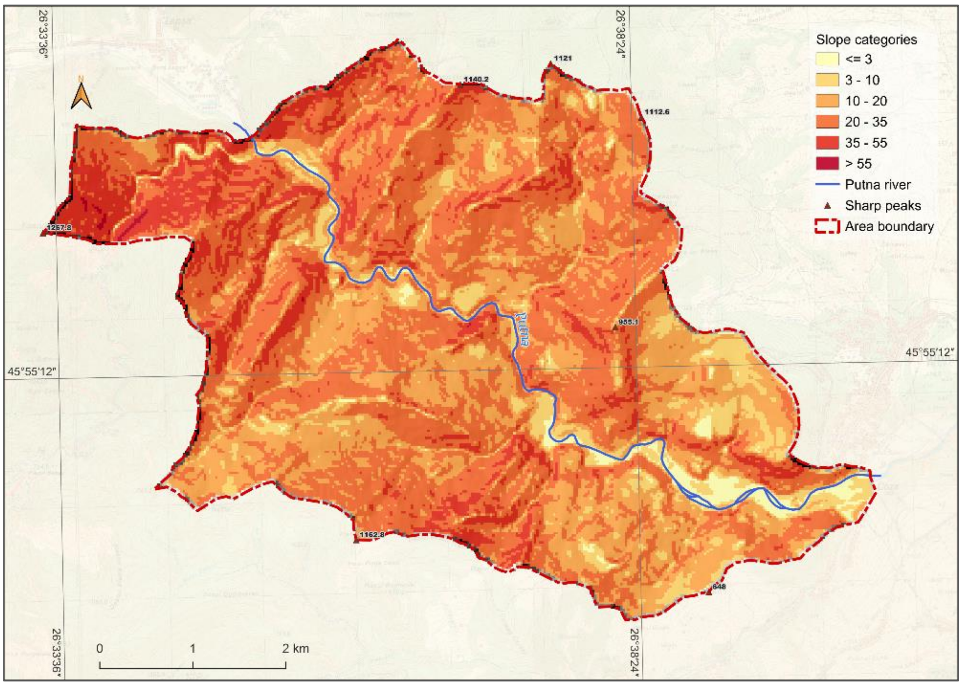
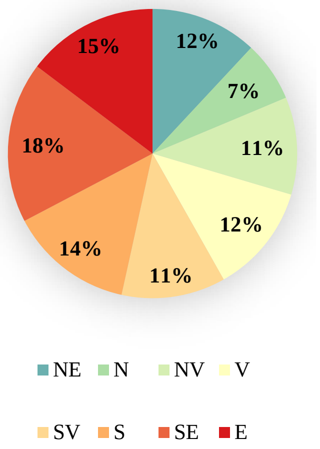


Figure 24. (upper) Percentage distribution of slope categories
Figure 25. (lower) Slopes in the area of the Putna valley

Slope orientation, or aspect, is determined by its position relative to the cardinal and intercardinal points, directly influencing exposure to solar radiation (Marcu, 2013). The distribution of slope aspects is diverse and relatively balanced (Figure 26): southeastern exposure accounts for 18%, followed by eastern (15%), southern (14%), western (12%), and northeastern and northwestern (11% each). Northern exposure represents the smallest share at 7%, while southwestern exposure accounts for 11% (Figure 27).

The geomorphological and morphographic characteristics of the ridges and slopes result from the formation and evolution of the Putna Basin relief. Field-based geomorphological profiles exemplify specific aspects of the valley's dynamics. In the profile (Figure 28a), the rounded appearance of the ridge is evident, prominently marked by Mociaru Peak; this landform is developed on a resistant lithological substrate, primarily sandstone, which asserts itself within the topography. Mociaru Peak represents a well-defined valley shoulder, with an altitude of approximately 900 m and a length of about 500 m, extending in a NE–SW direction, perpendicular to the axis of the Putna River.



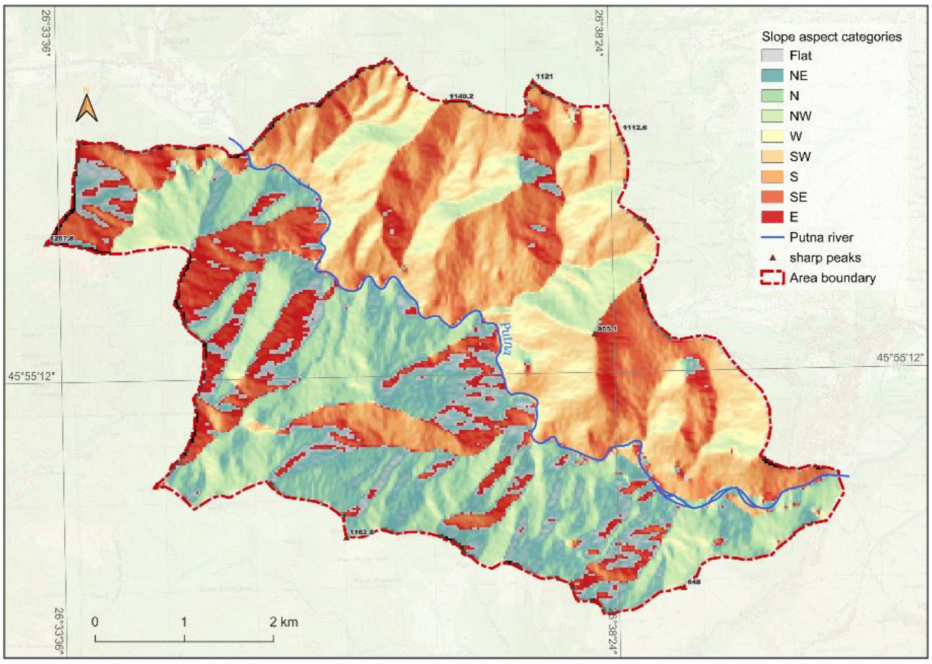


Figure 26. (upper) Percentage distribution of slope orientation
Figure 27. (lower) Slope orientation in the Putna valley area

The additional profiles (Figure 28b and 28c) reveal the presence of three distinct terraces on the lower slopes, resulting from the valley's evolution during the Pleistocene; additionally, fragments of older, higher-level terraces dating back to the Neogene are also preserved.

The profiles (Figure 28d and 28e) also illustrate the slope characteristics below the valley shoulder marked by Pietricele Peak (955 m). In terms of position and orientation, this landform develops nearly parallel to Mociaru Peak (1,052 m), situated to its east, and asserts itself topographically due to the presence of resistant Kliwa Sandstone. Regarding the evolution of the drainage network, several secondary levels can be identified along the slopes (secondary valley shoulders at +800 m), resulting from successive phases of incision by the Putna River and its tributaries.

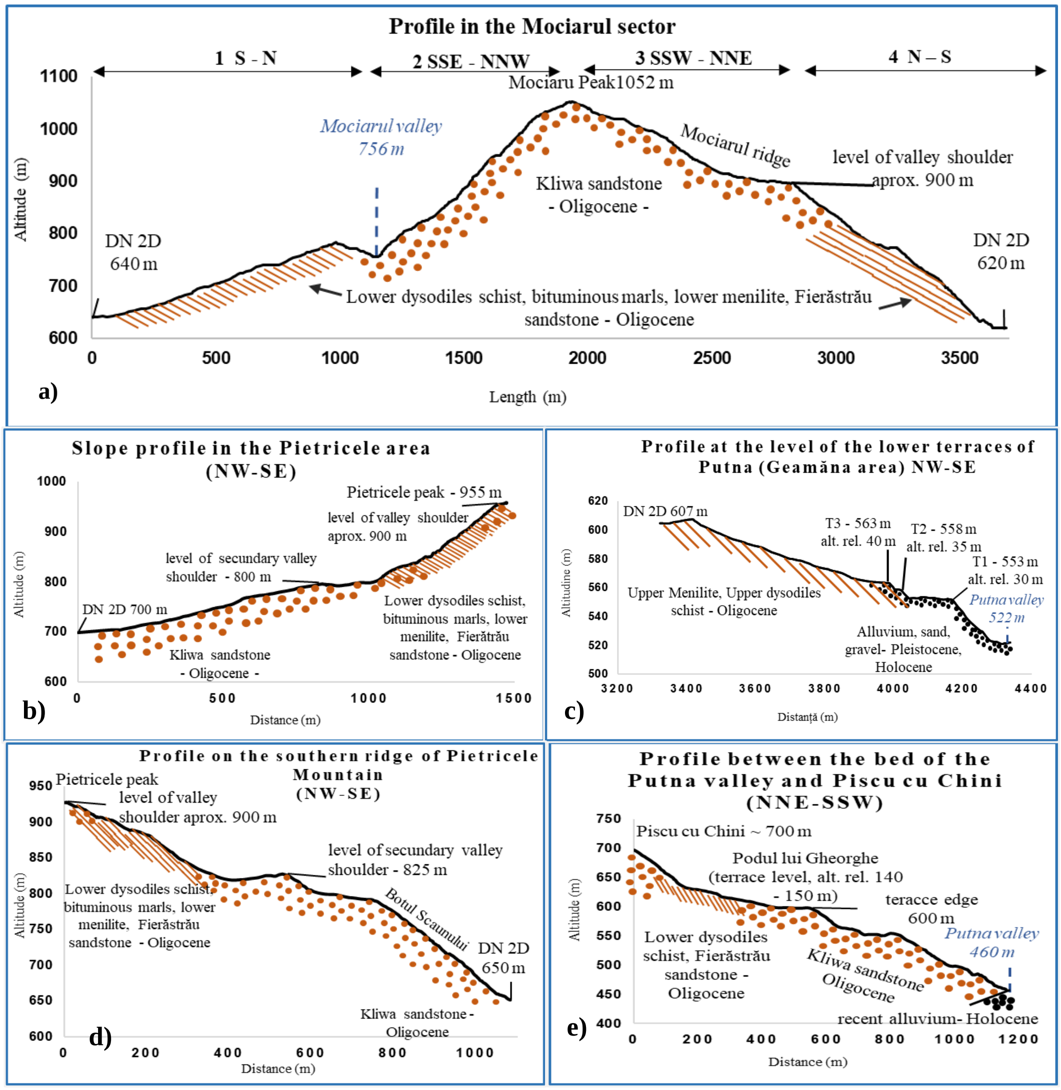


Figure 28. a). Mociaru; b). Pietricele1; c). terraces; d). Pietricele2; e). Piscu cu Chini

Acquiring primary data on the detailed morphology of the ridges and valley shoulders within the study area required the selection of routes relevant to these geomorphological features. The generation of geomorphological profiles was facilitated by the good road accessibility, particularly on the left bank of the Putna Valley (Figure 29).

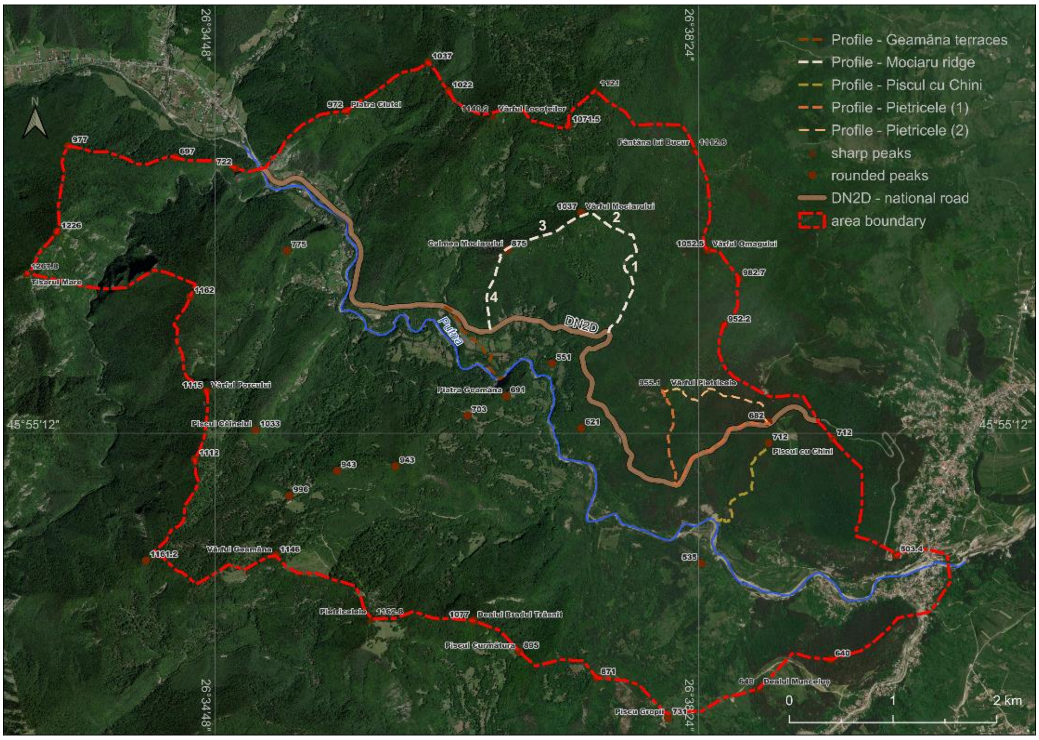


Figure 29 Satellite image of the Putna valley in the studied sector with the highlighting of the profiles made

The survey routes were recorded via GPS in .gpx format, then processed and converted for visualization in QGIS, maintaining the projection of the corresponding base layer. In the case of the Mociaru Peak profile, specific points were marked (1 to 4) to clearly identify changes in direction, unlike the other profiles, which follow a single primary orientation based on ridge alignment or slope aspect.

3.3. Current dynamics of the riverbed and slopes

Regarding the Putna Basin, current slope processes include various forms of surface erosion (such as rilling) and mass movements, including rockfalls on lithological and structural scarps, landslides on deforested slopes, and mudflows (Cristea, 2011). Within the study sector, we observe slopes affected by active mass wasting, particularly near the contact with the Subcarpathians. In this area, the deposits are younger and more friable (Lower Neogene), and the presence of salt breccia further contributes to instability (Figure 30).

The development of gullies leads to surface degradation on slopes covered by secondary grasslands. Figure 31 illustrates a ravine system modelled by intense rainfall; these features reach depths of one meter or more and act as traps for debris (such as foliage and branches) transported by runoff. Furthermore, large-scale landforms associated with torrential systems (Figure 32) have developed, fed by heavy rainfall and seasonal snowmelt.

Figure 30. Badland Relief

Figure 31. (left) Gully channel developed following the action of intense rainfalls
Figure 32. (right) torrential valley, with temporary runoff, with transport of alluvial material

Figure 33. Forms of deposition in the minor bed of the Putna

The development of braided channels results from the interplay of factors related to the runoff regime—specifically sediment load (bedload)—as well as channel slope, grain size, and bank stability (with easily erodible deposits facilitating accumulation processes). From downstream of Pietricele Peak to the Subcarpathian border near Coza, specific fluvial landforms occur, such as small bars and eyots (river islands), which undergo morphological changes during flood events (Cristea, 2011).

Figure 33 illustrates the characteristics of a braided channel, a configuration particularly prominent towards the contact with the Subcarpathians, where the riverbed widens significantly. Deposition processes along the median axis created an alluvial bar that subsequently evolved into a stable river island following the establishment of riparian vegetation (alders and shrubs).

In analyzing fluvial processes, the morphology of the floodplain is essential, as it borders the active channel belt and, in certain mountainous reaches, completely overlaps with it where resistant rock formations limit lateral valley expansion. Within the studied sector of the Putna Valley, several floodplain terraces can be identified; the most recent of these, with heights of 1–2 m and 2–4 m, are composed of gravels, sands, and boulders deposited by the river. Between Lepșa and Tulnici, the Putna's floodplain is intermittently narrowed or absent due to lithological and structural constraints. This causes the floodplain width to decrease to less than 20 m near knickpoints, such as the Putna Waterfall (Figure 34), while expanding to 200 m towards the Subcarpathian contact. The 1-meter terrace is situated immediately above the bankfull level, indicating its relatively recent formation.

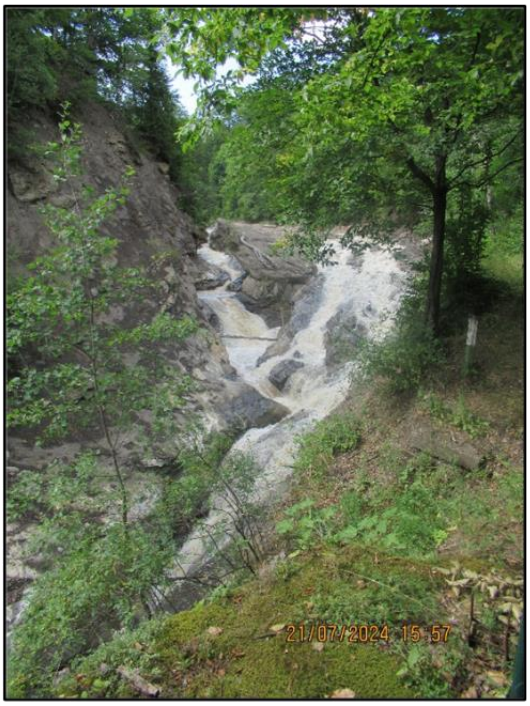


Figure 34. Putna Waterfall

Figure 35. Rockfall in the Lepsa area, on the national road DN 2D.
Source: https://shorturl.at/4nBOm

Mass wasting processes affect slopes and surfaces with inclinations exceeding 3^0, causing rock fragments or debris to move under the influence of gravity. In the mountainous sector of the Putna Valley, the extensive forest cover limits the occurrence of rockfalls, collapses, and rock rolls, except on slope sectors anthropogenically modified by road construction and adjacent infrastructure (Figure 35). Additionally, rockfalls occur in areas dominated by conglomerates and massive sandstones, which form prominent scarps due to their resistance. The most representative examples include the scarp below Piatra Streiului (formed on the eponymous conglomerates), where the Putna receives the Tișița stream on its right bank; the scarp at the confluence with Tunelul Stream on the left bank (opposite the tunnel on the DN2D road, km 70); and the scarp on the Piatra Geamănă conglomerates, which is also tectonically controlled by a fault axis.

On slopes or slope segments exposed by vegetation removal, the impact of external factors (such as precipitation and runoff), combined with the absence of effective protection measures, leads to rockfalls that can disrupt traffic on critical road segments.

Figure 36 summarizes the primary geomorphological characteristics of the study area, employing standardized symbols for each landform category in accordance with the general geomorphological legend used for the cartographic outputs. Consequently, landforms were classified based on several criteria—primarily genetic—to highlight both their spatial distribution and the relationships between their various components.

4. DISCUSSION

The presence of tectonic outliers (*covering patches*) at the outer edge of the Vrancea Nappe contributes to its structural complexity; these consist of Oligocene rocks (Kliwa Sandstone) that were originally part of the Tarcău Nappe to the west.

Topographically, these features are marked by Munceluș Hill (648 m) on the right bank of the Putna, and on the left bank by the Mociaru ridge (1,037 m) – Piatra Șoimului (682 m), followed by the Țiua Neagră – Țiua Spână ridge (1,069 m) and Omagu Peak (1,053 m) (according to the Bârsești geological map, 1:100,000 scale, Dumitrescu, 1952).

Associated with the folding of the strata, several tectonic disturbances (*faults*) occurred, as documented on the Bârsești Geological Sheet. A significant fault for the detailed morphology of the Putna Valley is the one intersecting the valley at the exit of the Greșu–Lepșa Depression (to the west); it creates two prominent scarps where the Piatra Streiului Conglomerates outrop—specifically, the scarp at the base of Tisaru Mare and the one highlighting Piatra Streiului on the left bank (Dumitrescu, 1952).

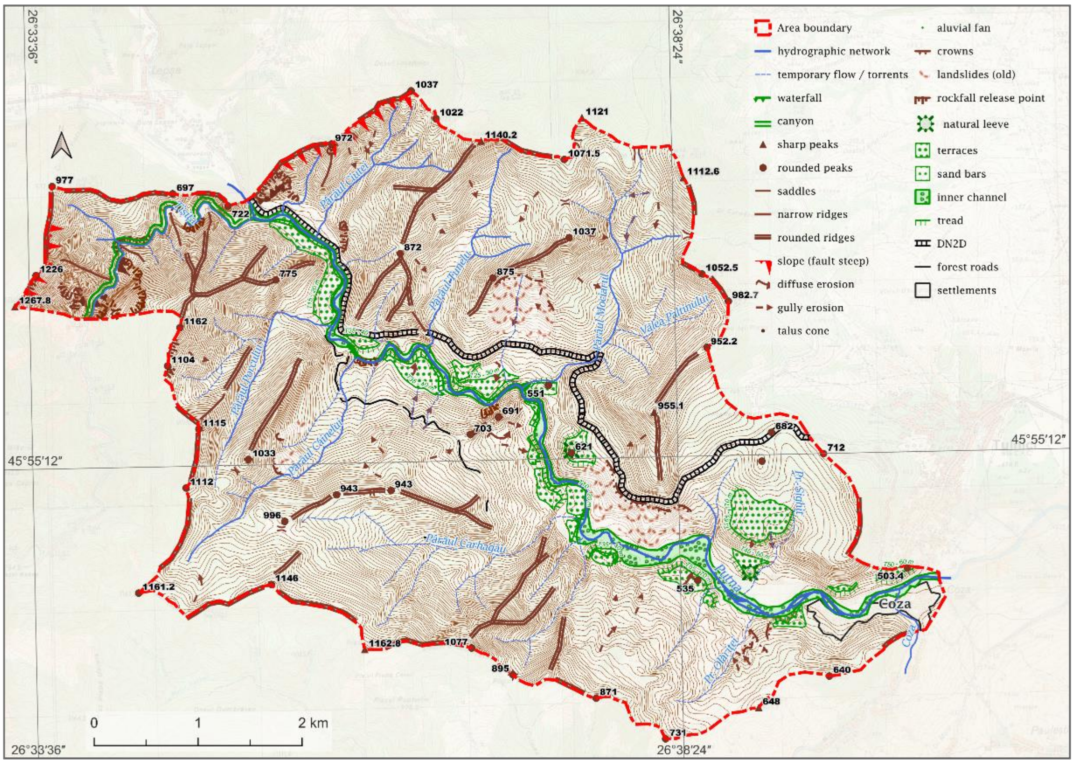


Figure 36. The main landforms and microforms resulting from the action of external and internal factors

The general west-east orientation of the river's flow is a result of large-scale tectonic uplift during the Pliocene–Quaternary period; consequently, the Putna River has incised through the geological formations within this segment. The valley's south-eastward deviation is attributed to the presence of Oligocene formations composed of Kliwa Sandstone, which is harder and more resistant to erosion (Cristea, 2011).

In fluvial networks, two types of tectonic movements can be identified, uplifts and subsidence, and relations between them leaded to two types of terraces formed, *strath* (where incision is dominantly) and *fill* (where sedimentation is preponderant) terraces (Necea et al., 2013). The distribution of fluvial terraces reveals that in SE Carpathian, especially in Putna basin, eleven terraces' levels was formed, from T1 to T11 (Necea et al., 2013). Within the analysed valley sector, there are both *strath terraces* and *fill terraces*. The study led by Necea et al., 2013, focused on identifying and determining the ages of river terraces in the SE Carpathians, but also on understanding the mechanisms of control of their development. Thus, relevant for the sector between Lepșa – Tulnici are the terraces T5 – T7 (*Upper Pleistocene*), between Porcului and Mociarului stream, T8 – T9 (*Holocene*), between Tișița and Porcului stream and T2 (*Holocene*), between Carhagău stream and Coza (Necea et al., 2013).

The runoff regime is governed by precipitation input and the geomorphological setting of the drainage basin. At the Tulnici gauging station on the Putna River, the average multi-annual runoff depth is 390.7 mm; this value is higher in mountain basins, driven by more intense rainfall and increasing average altitudes. Regarding the distribution of average annual discharge, the year 2005 brought significant changes to peak runoff parameters, particularly within the Putna Basin (Chendeș, 2011). The highest discharge ever recorded for the Putna River was triggered by the July 2005 flood, which caused substantial material and human damage. At the Tulnici gauging station (located at the Carpathian-Subcarpathian contact), the maximum instantaneous discharge reached 342 m^3/s, while the peak specific runoff was 938.9 $l/s/km^2$—a record for July 2005. Consequently, the massive volume of sediment transported during the 2005 flood led to significant accumulation within the channel, forming new fluvial deposits (river islands, sand and gravel bars, etc.), particularly toward the Subcarpathian entrance, upstream of the confluence with the Coza stream.

The influence of lithological and structural factors is evident in the distribution of hypsometric belts, particularly through the maintenance of higher altitudes along the interfluves (water divides) that delineate the study area. The lithological characteristics described above reflect a diverse composition and varying rock resistance, which are directly manifested in the morphology and orientation of the ridges. These substrate elements dictate the succession of sharp or rounded peaks grafted onto resistant rocks (such as Kliwa Sandstone), as well as a series of secondary ridges characterized by prominent valley shoulders at altitudes of 800–900 m. These features are situated below the general peak level of 1,000–1,100 m, where fragments of a levelling surface are preserved; this surface was termed the *'lower platform'* by Rădulescu (1937) and likely corresponds to the Carpathian marginal surface identified along the borders of mountain ranges at their contact with major depressions (e.g., the Brașov Depression). Furthermore, the valley shoulders below the level of the secondary ridges align with Carpathian erosion levels, locally referred to as either the *'Dacian erosion surface'* or the *'Lower Quaternary erosion surface'* (Ielenicz, 2011).

In the slopes systems, which slopes are the most common features of the landscape, it could be identifying several processes that lead to sediment mobilisation on hillslopes. Thus, hillslopes represent the main source of sediment for river systems (Harvey, 2022). There had been identified four groups of hillslope processes, depending on the nature of the material entrained and the type of process, erosion – deposition: *scree processes*, *overland flow*, *creep*, *mass movements* and *landsliding* (Harvey, 2022).

On the other hand, fluvial systems provide, trough flowing water, an incisional development on the landscape and represents the main pathway for sediment transfer in the drainage basins. Therefore, fluvial processes include three main processes, which lead to sediment transport and deposition trough river channels: erosion, transport and deposition (Harvey, 2022). Depending on the processes mentioned above, it could be separated two main types of channel morphology: *bedrock channels*, which resulted by a high stream power (erosion is dominant) and *alluvial channels*, which evolved under the influence between erosion and deposition (Harvey, 2022).

5. CONCLUSIONS

In the analysed sector, the Putna Valley exhibits numerous characteristics shaped by its overall morphogenesis and evolution. Specifically, the presence of valley shoulders—resulting from modelling processes—testifies to successive evolutionary phases within the Carpathian valley system. Various hypotheses proposed over the last century, particularly concerning the Curvature Carpathians, have emphasized the initial existence of longitudinal courses (N–S direction). Following the structural completion of the Subcarpathian sector during the Miocene–Pliocene, local drainage axes developed, leading to a reorganization of the pre-existing hydrographic network. According to theories dating back to Paucă (1942), this earlier network followed a predominantly west-east orientation.

Lithological and structural components have played, and continue to play, a decisive role in the current configuration of the valley. The fact that this sector developed exclusively within outer flysch formations provided a significant sediment source, fuelling the vigorous fluvial dynamics of the mountainous Putna basin. The coupled dynamics of the riverbed and slopes are integral to the contemporary processes governing the hydrographic system. Furthermore, the interplay between controlling factors and variables—such as fluctuations in liquid and solid discharge, as well as channel geometry—necessitates continuous morphological adjustments within the riverbed.

Unlike similar hydrographic systems, the Putna River maintains a high sediment load, driven by a dynamic hydrological regime and the specific geological and geographical context of its basin.

6. ACKNOWLEDGEMENT

I would like to express my gratitude to Prof. Răzvan Săcrieru, PhD, for his invaluable support during field campaigns, his assistance in generating geomorphological profiles, and his insightful observations. I am also grateful for the cartographic materials he provided, which were essential to this study. Special thanks go to Prof. Alexandru Nedelea, PhD, Dean of the Faculty of Geography at the University of Bucharest, for his guidance in selecting the research topic. Additionally, I have greatly benefited from the expertise and references provided by Mr. Florin Roman, a distinguished researcher of the Vrancea region.

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CINQ CONTINENTS
REVUE ROUMAINE DE GEOGRAPHIE

Volume 16 / Numéro 33
Été 2026
ISSN : 2247 - 2290
p. 60-72

Assessment of land suitability for high-speed road infrastructure development: case study of the Brașov – Covasna sector

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Citer ce document :

NEGULESCU, C.-C, MIREA, I.-A., DOBRE, D.-C. 2026. Assessment of land suitability for high-speed road infrastructure development: case study of the Brașov – Covasna sector. Cinq Continents 16 (33): 60-72.

Assessment of land suitability for high-speed road infrastructure development: case study of the Brașov – Covasna sector

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Evaluarea pretabilității terenurilor pentru dezvoltarea infrastructurii rutiere de mare viteză. Studiu de caz: sectorul Brașov – Covasna. Drumul propus în sectorul cuprins între orașele Brașov și Covasna este fundamentat pe o analiză multicriterială de favorabilitate, care integrează factori naturali și antropici esențiali pentru proiectarea și dezvoltarea infrastructurii rutiere de mare viteză. Printre aceștia se numără pantele, litologia, stagnogleizarea solurilor, precum și utilizarea terenurilor. Analiza de referință evidențiază existența unor restrictivități în zonele montane, unde potențialul morfodinamic accentuat favorizează producerea unor procese geomorfologice active, în timp ce zonele depresionare, cu relief neted, oferă condiții favorabile, dar pot fi limitate de densitatea mai mare a așezărilor umane. Harta finală de favorabilitate a rezultat din agregarea celor patru factori de studiu menționați. Totodată, în proiectarea celor două alternative de drum de mare viteză s-a ținut cont și de infrastructura rutieră existentă. Pe baza acestei hărți de favorabilitate au fost identificate două variante de traseu, dintre care prima s-a dovedit optimă, traversând mai multe areale favorabile într-un procent de 52,34%. Implementarea acestui sector de drum de mare viteză ar contribui la descongestionarea traficului, îmbunătățirea conectivității și stimularea dezvoltării economice regionale.

Cuvinte cheie: infrastructură de transport, geomorfologie environmentală, analiză multicriterială, factori naturali și antropici, pretabilitate.

Assessment of land suitability for high-speed road infrastructure development: case study of the Brașov – Covasna sector. The proposed road sector between the cities of Brașov and Covasna is based on a multicriteria suitability analysis that integrates essential natural and anthropogenic factors relevant to the design and development of high-speed road infrastructure. These include slopes, lithology, soil stagnogleization, and land use. The reference analysis highlights the presence of constraints in mountainous areas, where increased morphodynamic potential favors the occurrence of active geomorphological processes, while depression areas characterized by smoother relief provide more favorable conditions, although they may be limited by the higher density of human settlements. The final suitability map was obtained through the aggregation of the four aforementioned study factors. At the same time, the design of the two high-speed road alternatives also considered the existing road infrastructure. Based on this suitability map, two route alternatives were identified, of which the first proved to be optimal, crossing favorable areas in a proportion of 52.34%. The implementation of this high - speed road would contribute to traffic decongestion, improved connectivity and the stimulation of local and regional economic development.

Keywords: transport infrastructure, environmental geomorphology, multicriteria analysis, natural and anthropogenic factors, land suitability assessment.

1. INTRODUCTION

High-speed transport infrastructure represents one of the fundamental factors shaping the development dynamics of any geographical region (Păunescu et al., 2021). In the current global economic context, regional competitiveness can be supported through direct investment in this sector, highlighting the importance of a geographical approach within the analytical process (Dobre, 2016).

A development model requires an environmental geomorphology study, as it has the capacity to identify solutions aimed at maintaining a balance between the natural and anthropogenic environments (Panizza, 2011).

The assessment of environmental components represents the basis of such analyses, aiming to prevent potential issues that may arise during the design of road infrastructure (Păunescu et al., 2019).

Multicriteria suitability analysis uses up-to-date GIS methods and techniques. From this perspective, the planning of transport infrastructure involves the identification of natural and anthropogenic factors that control territorial functionality (Negulescu, 2024). Therefore, digital modeling and the evaluation of terrain characteristics were applied in accordance with the factors that define suitability for the development of the road network.

In this context, the present study is based on a multicriteria suitability analysis of the sector between the cities of Brașov and Covasna, considering the main factors influencing the development of road infrastructure (Purcăreață et al., 2015). The aim of this type of analysis is to identify favorable areas for the design of an optimal transport corridor, namely a road connection between the cities of Brașov and Covasna, intended both to increase transport flow capacity and to improve the connectivity of settlements to the TEN-T road transport network in Romania.

The study is based on several specific objectives. The first objective consists of delineating the study area between the cities of Brașov and Covasna. Another objective involves the preparation and processing of the database (vector and raster data) for each of the four analysis factors. The third objective is the development of the suitability map for road infrastructure planning, representing the final product of the multicriteria analysis. The final objective consists of identifying two alternative road alignments, taking into account the spatial distribution of favorable areas.

A road sector within the Brașov–Covasna area may be of interest both to local residents and to public authorities due to its potential to stimulate socio-economic development at both the local and regional levels. At the same time, such an analysis provides a systematic and well-founded approach that may support local and regional authorities in making informed and justified decisions regarding the development and construction of high-speed road infrastructure.

The present study is both timely and relevant, and its selection reflects the interest in improving infrastructure development and quality of life in the area, as well as the capacity to apply scientific methods and techniques to support the sustainable and efficient development of high-speed road infrastructure. Moreover, the choice of the case study is motivated by multiple strategic, social, economic, and technical considerations.

2. METHODOLOGY

2.1. Study area

The study area selected for the design and construction of road infrastructure is located in the central-eastern part of Romania and covers between the cities of Brașov and Covasna (Figure 1). This strategic location provides good accessibility as well as geographical relevance, representing a zone of interaction between different physical-geographical, cultural, social, and economic regions. Moreover, the study area is part of the Central Development Region and Macroregion 1. The administrative-territorial units (ATUs) intersected by the study area total 30 units. From a demographic perspective, the study area includes several populated settlements with a total population of 505,064 inhabitants. The most populated settlement within the study area is the Municipality of Brașov, with 291,195 inhabitants in 2025 (National Institute of Statistics, 2025).

From a physical-geographical perspective, the study area overlaps the Brașov Depression (with its subdivisions: the Bârsa Depression, the Prejmer Depression, and the Râul Negru Depression), the Moldavian – Transylvanian Carpathians (with its subdivision the Baraolt Mountains), and the Curvature Carpathians (with its subdivisions: the Piatra Mare Massif, the Postăvaru Massif, and the Întorsura Buzăului Mountains; Ielenicz, 2007; Posea, 2005).

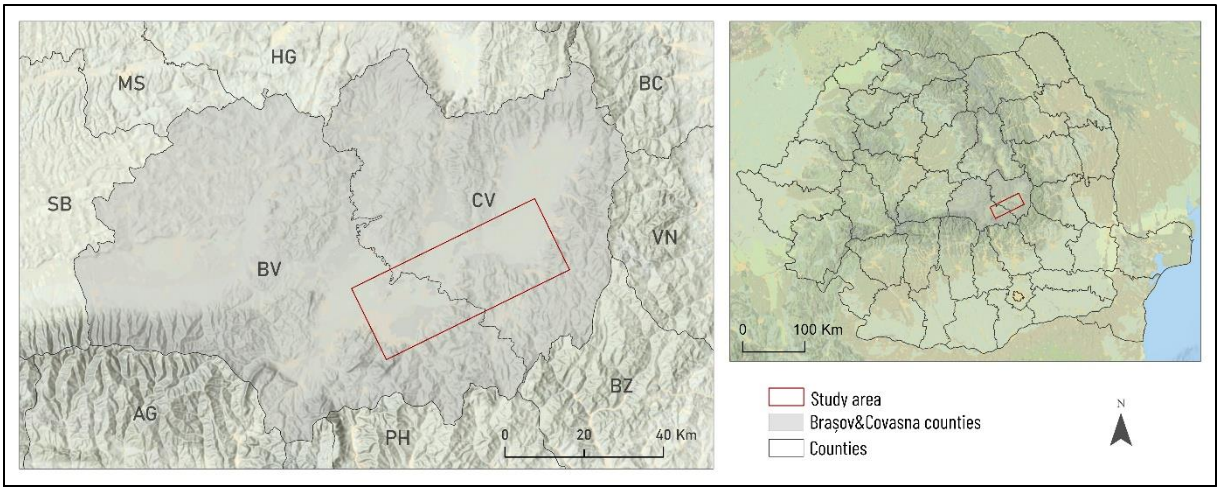

Figure 1. Study area

2.2. Data analysis

For the implementation of the multicriteria suitability analysis, GIS methods and techniques were used. For the preparation of the cartographic materials, a series of vector and raster datasets were employed for each analyzed factor (Table 1).

Table 1. Spatial datasets used in the analysis

Data name	Data type	Source	Use
curbe_25_est	vector, line	Military Topographic Map of Romania, scale 1:25,000, Military Topographic Directorate	for slope gradient analysis
geo200_6_03	vector, polygon	Geological Map of Romania, scale 1:500,000, Geological Institute of Romania	for lithological analysis
clc_18_s70	vector, polygon	European Environment Agency, CORINE Land Cover, 2018	for land use analysis
romania_sol	vector, polygon	Soil Map of Romania, scale 1:200,000, National Research and Development Institute for Soil Science, Agrochemistry and Environmental Protection	for soil stagnogleyization analysis

Data processing was carried out in several stages using ArcGIS Pro software. Various cartographic materials were produced based on the previously mentioned datasets, using the Stereo 70 projection and the Dealul Piscului 1970 datum (Mihai et al., 2008). In the first stage, cartographic representations were generated for each analyzed factor using vector data. Subsequently, the vector data were converted into raster format. The resulting raster datasets were reclassified with values ranging from 0 to 10 (very low suitability to very high suitability) to ensure the homogeneity of the database.

To generate the slope map (Spatial Analyst Tools, Surface) was applied. The resulting raster data were then classified into five slope classes: below 5°, 5.1–10°, 10.1–15°, 15.1–25°, and above 25.1°. The raster information was subsequently reclassified with values ranging from 1 to 10 (from very low suitability to very high suitability) using the Reclassify function (Table 2).

For the preparation of the soil stagnogleization intensity map, polygon-type data were used. The vector data were clipped to the study area using the Clip function and classified into four classes: high, moderate, low and none.

Subsequently, values ranging from 3 to 10 (from very low suitability to very high suitability) were assigned to each category of soil stagnogleization intensity (Table 3). A new field containing the previously established values was added to the attribute table, after which the Feature to Raster function (Conversion Tools, To Raster) was used to generate the reclassified soil stagnogleization intensity map.

Table 2. Values used for slope gradient reclassification

Initial value	Reclassification value	Favorability classes
Below 5^0	10	Very high
5.1 - 10^0	7	High
10.1 - 15^0	5	Moderate
15.1 - 25^0	3	Low
Above 25.1^0	1	Very low

Table 3. Values used in soil stagnogleyization reclassification

Initial value	Reclassification value	Favorability classes
None	10	Very high
Low	7	High
Moderate	5	Moderate
High	3	Low

For the preparation of the geological map, polygon-type vector data were used. These datasets were clipped to the boundaries of the study area using the Clip function (Analysis Tools, Extract), after which the rock types were identified based on their codes from the attribute table (corresponding to the geological ages of rocks in Romania).

Each rock category was assigned a value ranging from 1 to 10 (from very low suitability to very high suitability) (Table 4). A new field containing the assigned values was then added to the attribute table. Subsequently, the Feature to Raster function (Conversion Tools, To Raster) was applied to convert the vector data into raster format.

Table 4. Values used for lithological reclassification

Initial value	Reclassification value	Favorability classes
Sands, gravels, boulders, loess, andesites, schists	10	Very high
Limestones, conglomerates, flysch, volcano-sedimentary formations	7	High
Sandstones, flysch	5	Moderate
Clays and marls alternating with other rocks, loessoid deposits	3	Low
Marls, clays, unconsolidated formations with marly-clayey intercalations	1	Very low

For the preparation of the land use map, polygon-type vector data from the Corine Land Cover dataset (2018) were used. Using the Clip function (Analysis Tools, Extract), the data were clipped to the boundaries of the study area.

Subsequently, the data were classified and symbolized according to land use categories (LABEL3_RO). A new field was added to the attribute table, in which each land use category was assigned a value ranging from 0 to 10 (from very low suitability to very high suitability) (Table 5). In addition, the Feature to Raster function (Conversion Tools, To Raster) was used to convert the vector data into raster format.

Table 5. Values used in land use class reclassification

Initial value	Reclassification value	Favorability classes
Arable land, agricultural land, crops, sparsely vegetated areas, shrub transition areas, secondary grasslands	10	Very high
Forests, subalpine vegetation, marshes	5	Moderate
Natural grasslands, vineyards, orchards, mining extraction areas, rocky areas, water bodies	3	Low
Continuous/discontinuous urban fabric and rural space, industrial/commercial units, recreational areas, communication networks and associated land, urban green areas, airports, landfills, construction sites	0	Very low

The main output of the multicriteria analysis performed in ArcGIS Pro software is the suitability map, which represents a useful tool for identifying favorable and restrictive areas for the design of the proposed express road in the Brașov–Covasna sector (Zăhărăchescu, 2024). The suitability map (SM) for the construction of the proposed road was generated by multiplying the raster datasets obtained for each analyzed factor, using the calculation formula:

SM = Power (S × G × LU × Ss, 0.25), where: S = slope, G = geology, LU = land use, and Ss = soil stagnogleization intensity.

The formula was applied using the Raster Calculator function (Map Algebra). After applying the formula, the map was reclassified into five suitability categories (Negulescu, 2025). Subsequently, based on the suitability map, two alternative road alignments were digitized within the sector delimited between the cities of Brașov and Covasna (Triantaphyllou, Sanchez, 1997). Subsequently, the lengths and their corresponding shares for each suitability class were determined.

3. RESULTS

According to the applied methodology, all analyzed information related to slope, soil stagnogleization intensity, the lithological factor represented by rock types, and land cover were integrated within the suitability map for road infrastructure planning in the Brașov – Covasna sector.

At the same time, the suitability map highlights the most appropriate areas for the development of human activities, particularly for the development of high-speed road infrastructure, based on a complex multicriteria spatial analysis (Dobre et al., 2011).

The use of multicriteria analysis for major road transport projects represents a useful tool for the preparation of road infrastructure development projects (Dobre, 2009). Moreover, this type of map can provide valuable information for subsequent stages of the project, particularly when planning the geometric structures of a road alignment (tunnels, bridges, and cuttings; Păunescu et al., 2019).

The resulting suitability map (Figure 2) indicates that approximately 50% of the reference area is characterized by very high suitability, while 21% of the area presents high suitability. Together, these categories account for 61% of the total study area considered for road infrastructure planning and construction. This percentage corresponds mainly to secondary grasslands, quasi-horizontal surfaces (with slope values below 5°), the absence of highly porous rocks (such as marls and clays), and areas with low or absent soil stagnogleization intensity.

In contrast, areas with low suitability represent 9% of the total surface, while those with very low suitability account for 7%, together totaling 16% of the reference area. These values are mainly determined by the increased morphodynamic potential (associated with the presence of clays and marls and steep slopes), as well as by built-up areas (transport infrastructure networks and their associated land, continuous urban fabric, discontinuous urban fabric, rural settlements, and industrial units).

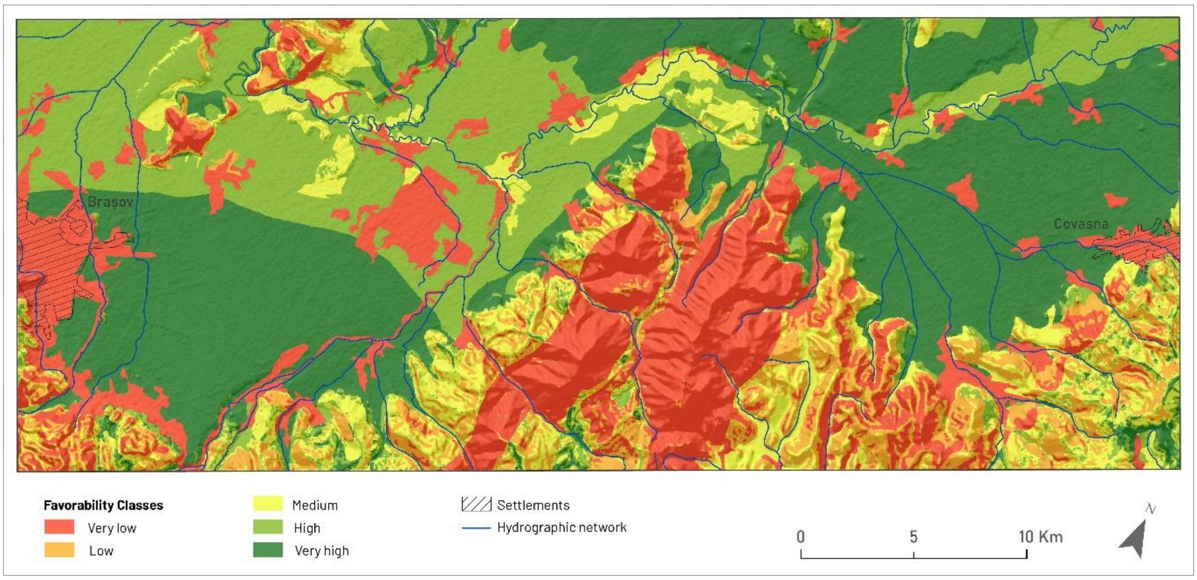

Figure 2. Suitability map

Based on the suitability map, two high-speed road alternatives were designed by making use of the most suitable areas. The first proposed road alternative for the connection between Brașov and Covasna (Figure 3) has a length of 45.1 km and overlaps predominantly with areas of very high suitability (52.34%) and high suitability (41.81%), together accounting for 94.15% of the total route length. In addition, the first route alternative crosses areas with medium suitability in a proportion of 5.85%.

The second road alternative (Figure 4) has a length of 49.2 km and crosses areas with very high suitability (47.31%) and high suitability (51.44%), totaling 98.75% of the route length. Furthermore, the road segment overlaps areas with medium suitability in a proportion of 1.25% (Table 6).

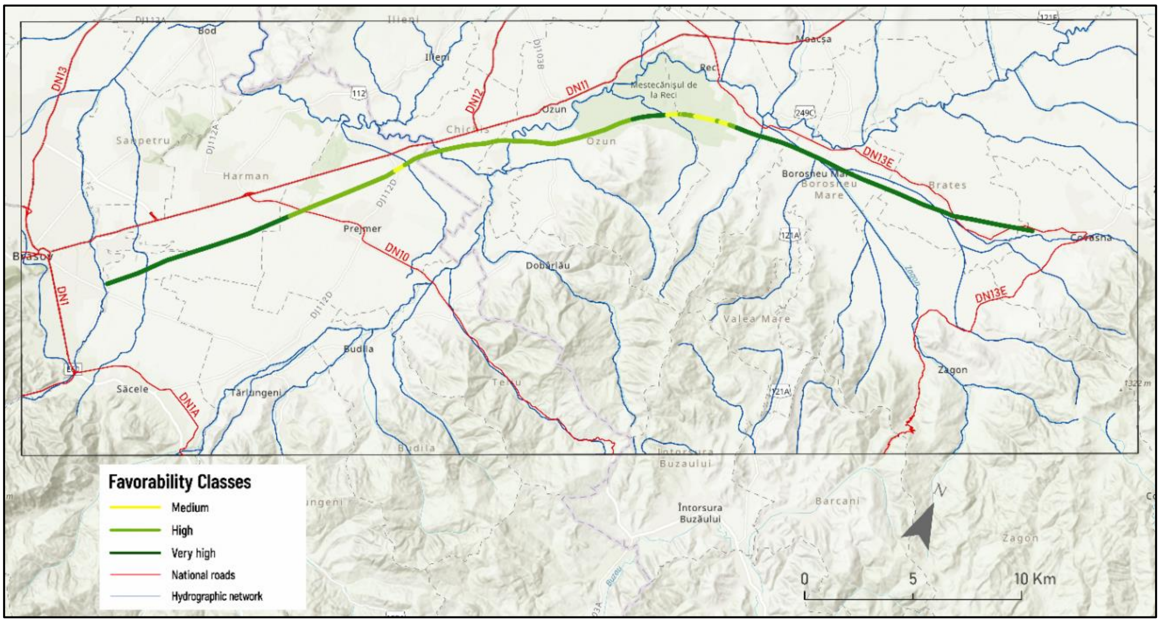

Figure 3. Correlation of the first proposed road alternative with the favorability classes

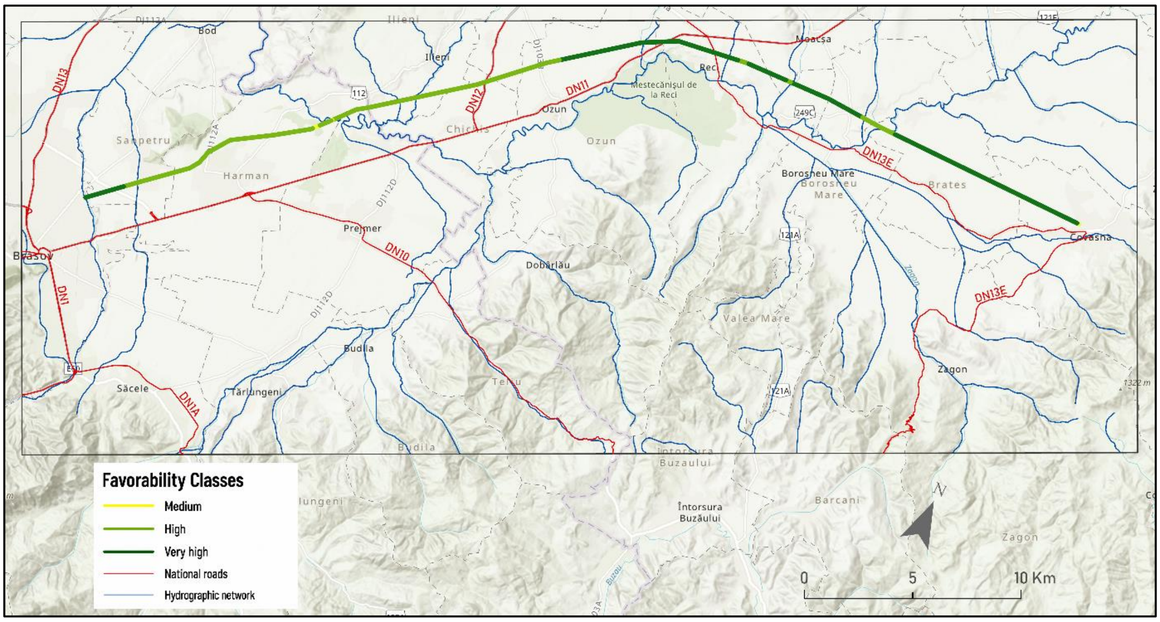

Figure 4. Correlation of the second proposed road alternative with the favorability classes

Table 6. Lengths and corresponding weights for each favorability class

	Alternative 1		Alternative 2	
Favorability classes	**Weight (%)**	**Length (m)**	**Weight (%)**	**Length (m)**
Moderate	5.85	2637.4	1.25	615
High	41.81	18858	51.44	25 308.4
Very high	52.34	23504	47.31	23 276.5
Total	100	45100	100	49200

4. DISCUSSION

Alignment 1 crosses a larger proportion of areas with very high suitability (52.34%) compared to the second alignment. In addition, the total length of Alignment 1 is shorter (45,100 m compared to 49,200 m), which implies a reduced construction time, lower long-term maintenance costs, and a lower impact on the traversed territory. A shorter infrastructure corridor is generally more efficient from both an economic and a functional perspective.

The first proposed road alignment intersects 11 administrative - territorial units: Brașov, Săcele, Hărman, Prejmer, Chichiș, Ozun, Reci, Boroșneu Mare, Brateș, and Covasna (National Agency For Cadastre And Land Registration, 2015). The proposed high-speed road alignment could attract significant economic investments and a larger number of residents to the administrative-territorial units intersected by the route. Thus, it may stimulate local and regional economic development by improving access to markets, while the faster connection between the two urban centers could encourage industrial and commercial development along the corridor.

In this context, the proposed project could lead both to the creation of new jobs to support the labor force and to the stimulation of economic competitiveness for business environment development. The first proposed road alignment creates road connections with the following national roads: DN10 and DN13E. The establishment of these road connections may also contribute to reducing travel times and transport costs, thereby increasing the efficiency of passenger and freight mobility in the area.

The development of a high-speed road between Brașov and Covasna would also contribute to improving regional connectivity and territorial cohesion, facilitating integration with major national and European transport corridors, including the TEN-T network. In addition, given the strategic role of Brașov as an important regional growth pole, improving its connectivity with surrounding areas such as Covasna County may strengthen its function as a transport and economic hub in central Romania.

The development of high-speed road infrastructure may have a significant impact on the environment, influencing various aspects of ecosystems. The construction of a high-speed road would lead to significant deforestation and changes in land use patterns. These actions may result in habitat fragmentation for animal species, creating both physical and behavioral barrier effects.

Consequently, road infrastructure can affect animal communities by restricting their mobility and limiting access to essential resources. In this context, one possible solution to mitigate the negative effects of habitat fragmentation is the construction of ecological corridors (ecoducts, wildlife crossings, tunnels, etc.). An ecological corridor is defined as a natural or designed area that ensures the conditions necessary for movement, reproduction, and refuge for wildlife species. In order for these structures to function effectively as animal crossings, several essential conditions must be ensured. On the one hand, the crossing area should remain in a state as natural as possible, closely resembling local habitats, and on the other hand, the obstruction of animal passages by fences, stored construction materials, or other anthropogenic elements should be avoided (Lazăr et al., 2020).

5. CONCLUSIONS

The proposed road alignment in the Brașov – Covasna sector represents a solution based on multicriteria suitability analysis. In other words, multicriteria suitability analysis can represent an important source of information.

Thus, it relies on established scientific, objective, and independent foundations and aims to evaluate all relevant natural and anthropogenic components (slopes, soil stagnogleization intensity, lithology and land use) that play an important role in the design, construction, and operation of high-speed road infrastructure.

At the macro-scale, the study area presents several constraints in mountainous regions, where morphodynamic potential is particularly high due to the occurrence of numerous exogenous geomorphological processes. In contrast, in depression areas characterized by smoother relief, several favorable zones for road infrastructure development were identified, where special engineering works are less costly. However, the higher density of rural and urban settlements in lowland areas may impose certain limitations on the planning of the express road between Brașov and Covasna.

As a result of the multicriteria analysis, a suitability map was generated, based on which two alternative road alignments were proposed. Subsequently, the first alternative proved to be optimal, as it crosses areas with higher suitability values. Furthermore, such a transport corridor would contribute to reducing traffic congestion on national roads within the analyzed sector, improving connectivity between the intersected settlements, and attracting new economic investments.

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REVUE ROUMAINE DE GEOGRAPHIE

Volume 16 / Numéro 33
Été 2026
ISSN : 2247 - 2290
p. 73-85

GIS analysis for avalanche susceptibility in the upper sector of Bâlea Valley (Făgăraș Mountains, Romania)

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MUNTEANU, D.-I. 2026. GIS analysis for avalanche susceptibility in the upper sector of Bâlea Valley (Făgăraș Mountains, Romania). Cinq Continents 16 (33): 73-85.

GIS analysis for avalanche susceptibility in the upper sector of Bâlea Valley (Făgăraș Mountains, Romania)

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Analiză GIS pentru susceptibilitatea la avalanșe în sectorul superior al Văii Bâlea (Munții Făgăraș, România). Menținerea funcționalității drumurilor montane în sezonul rece reprezintă o provocare majoră în contextul intensificării hazardelor naturale și al creșterii presiunii turistice asupra regiunilor alpine. Sectorul Cabana Bâlea Cascadă – Bâlea Lac (DN7C – Transfăgărășan) este caracterizat printr-o vulnerabilitate ridicată la avalanșe, ceea ce determină închiderea anuală a circulației pentru perioade extinse. Lucrarea are ca obiectiv evaluarea riscului de avalanșă și identificarea unor soluții de amenajare rutieră care să permită extinderea perioadei de acces în condiții de siguranță. Metodologia integrează tehnici GIS și analiză multicriterială, utilizând date open source și modele digitale ale terenului. Au fost analizați principalii factori geomorfologici (panta, orientarea versanților, altitudinea, curbura și utilizarea terenurilor), iar evaluarea riscului a fost realizată diferențiat sezonier, pentru condițiile specifice iernii și primăverii. Rezultatele evidențiază distribuția spațială a zonelor cu susceptibilitate ridicată la avalanșe și rolul determinant al geodeclivității și orientării versanților. Pe baza analizei au fost identificate sectoare critice și formulate propuneri de intervenție, precum galerii de protecție, paravane anti-avalanșă și adaptări locale ale traseului rutier. Studiul demonstrează eficiența utilizării GIS în evaluarea riscurilor naturale și contribuie la fundamentarea unor soluții sustenabile pentru creșterea siguranței și accesibilității infrastructurii montane.

Cuvinte cheie: avalanșă, susceptibilitate, GIS, analiză multicriterială, infrastructură rutieră, Transfăgărășan.

GIS analysis for avalanche susceptibility in the upper sector of Bâlea Valley (Făgăraș Mountains, Romania). Maintaining the functionality of mountain roads during the winter season represents a major challenge in the context of increasing natural hazards and growing tourism pressure in alpine regions. The Bâlea Cascadă – Bâlea Lake sector (DN7C – Transfăgărășan) is highly exposed to avalanche activity, leading to prolonged annual road closures. This study aims to assess avalanche risk and to identify technical solutions for road infrastructure that could extend the accessibility period under safe conditions. The methodology integrates GIS techniques and multicriteria analysis, based on open-source datasets and digital elevation models. Key geomorphological factors (slope, aspect, altitude, curvature, and land use) were analyzed, and risk assessment was performed seasonally, distinguishing between winter and spring avalanche conditions. The results highlight the spatial distribution of high-susceptibility areas and emphasize the influence of slope and aspect on avalanche occurrence. Critical sectors were identified, and mitigation measures such as snow sheds, avalanche barriers, and local route adjustments were proposed. The study demonstrates the effectiveness of GIS-based approaches in natural hazard assessment and supports the development of sustainable strategies for improving safety and accessibility of mountain road infrastructure.

Keywords: avalanche, susceptibility, GIS, multi-criteria analysis, mountainous roads, Transfagarasan.

1. INTRODUCTION

Maintaining the functionality of mountain roads during the winter season represents a major challenge in the context of increasing natural hazards and growing tourism pressure on alpine regions. Snow avalanches constitute one of the primary natural risks affecting mountain road infrastructure, frequently leading to road closures and generating significant economic and social impacts. Alpine roads play a crucial role in ensuring accessibility, supporting tourism, and connecting remote areas, which necessitates the development of effective risk management solutions (O'Gorman, Jones, 2005; Keller, Sherar, 2003).

The Transfăgărășan Road (DN7C), one of the most important mountain roads in Romania, crosses the Făgăraș Mountains and is widely recognized for its touristic and strategic importance. The upper sector of the Bâlea Valley, located between Bâlea Cascadă Chalet and Bâlea Lake, is characterized by a high susceptibility to avalanches, driven by specific geomorphological and climatic conditions, including elevations exceeding 1600 m, steep slopes, and slope orientations that favor snow accumulation and instability. Under these conditions, the road is closed annually for an extended period (October–June), affecting accessibility, economic activities, and tourist flows.

At the international level, avalanche susceptibility analysis has significantly advanced through the use of GIS techniques and multicriteria models that integrate key factors such as slope, aspect, elevation, and land use (Grêt-Regamey, Straub, 2006; Parshad et al., 2017). These approaches enable spatial risk assessment and support the development of effective prevention and protection measures.

In this context, the main objective of this study is to assess avalanche risk in the upper sector of the Bâlea Valley and to identify road engineering solutions aimed at extending the operational period of the road under safe conditions. The analysis is based on the integration of geomorphological factors within a GIS-based multicriteria model, with the purpose of delineating vulnerable areas and supporting decision-making processes related to mountain infrastructure management.

2. METHODOLOGY

2.1. Study area

The analyzed sector is located in the northern part of the Făgăraș Mountains and corresponds to the road segment between Bâlea Cascadă and Bâlea Lake, part of the DN7C-Transfăgărășan highway. The geographical position of the study area is illustrated in Figure 1, which highlights its location within the mountain unit, as well as its relationship with the main landforms and the hydrographic network.

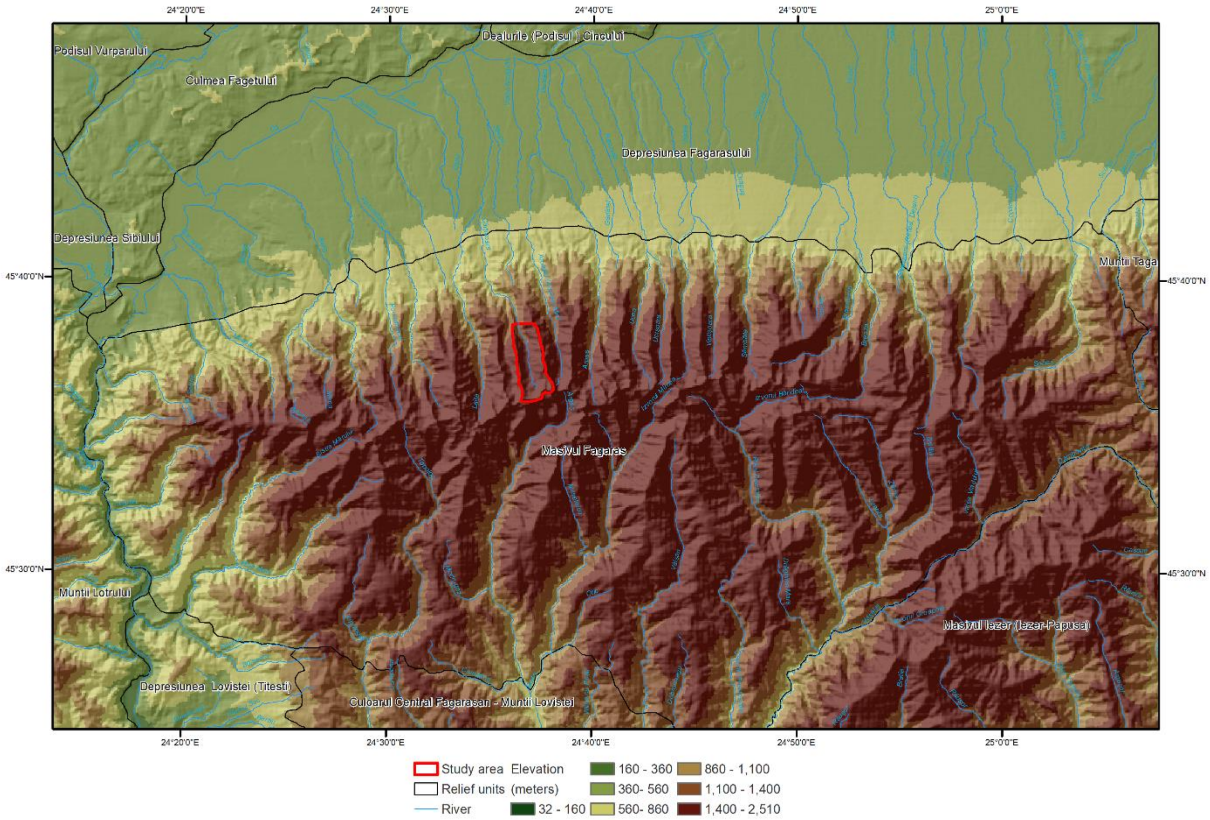

Figure 1. Location of the study area

From a geomorphological perspective, the Bâlea Valley is characterized by highly fragmented apline relief, dominated by glacial landforms such as cirques, U-shaped valleys, steep slopes, and moraines, formed because of Quaternary glacial processes. Elevations range from approximately 1700 m to over 2000 m, while slopes frequently exceed 30–35°, conditions that significantly favor the initiation of snow-related processes.

The climate of the area is alpine, characterized by low mean annual temperatures ranging between −2°C and 2°C, as well as by a prolonged cold season. Snow cover generally persists from November to May, reaching considerable thickness during the winter months. These climatic conditions, together with the influence of dominant winds, lead to uneven snow accumulation and contribute to snowpack instability.

These physical-geographical characteristics result in a high susceptibility to avalanches within the analyzed sector. Documented events, including both historical and recent avalanches, highlight the frequency and intensity of this hazard, as well as its impact on road infrastructure and tourism-related activities.

Currently, the road segment is closed to traffic during the winter season due to avalanche risk and extreme weather conditions. Existing mitigation measures are limited and do not include permanent protective structures, which maintains the high vulnerability of this sector.

Therefore, the geomorphological and climatic particularities of the Bâlea Valley justify the selection of this area as a case study for avalanche susceptibility analysis and for the development of site-specific mitigation measures adapted to local conditions.

2.2. Data and methods

The avalanche susceptibility analysis in the upper sector of the Bâlea Valley was carried out using GIS techniques and a multicriteria approach, based on the integration of geospatial datasets derived from open-source sources and processed in the ArcMap 10.6.1 environment. The methodological framework aimed to identify the key geomorphological factors influencing avalanche occurrence and to evaluate their contribution within a spatial risk model.

In the initial stage, only freely available datasets were used, enabling the physical-geographical characterization of the study area and the implementation of spatial analyses. The database included Digital Elevation Models (DEM), contour lines, hydrographic network data, geomorphological unit boundaries, land use data, and elevation points. These datasets were used to generate thematic raster layers required for morphometric analysis.

The methodological approach integrated several techniques specific to geographical and spatial analysis, including direct observation, cartographic and graphical methods, morphometric and morphological terrain analysis, comparative analysis, and deductive interpretation. These methods enabled the correlation between terrain characteristics and snow-related processes, as well as the assessment of the relationship between natural factors and road infrastructure.

Within the GIS-based analysis, five main factors were considered: slope (geodeclivity), aspect, elevation, plan curvature, and land use. The derivation and processing of these factors were performed using specific GIS tools (Slope, Aspect, Curvature, Reclassify), while a synthesis of the indicators and processing methods is presented in Table 1.

Based on the Digital Elevation Model (DEM) and the thematic datasets, a series of derived maps were generated, representing slope (geodeclivity), aspect, elevation, plan curvature, and land use. These cartographic products provided the foundation for multicriteria analysis.

Data processing involved the reclassification of each factor to standardize values and express their relative influence on avalanche susceptibility. The process was carried out in two stages: an initial reclassification of the original values, followed by the assignment of weighted values according to the relevance of each class.

Table 1. Indicators used and GIS processing methods

Indicator	GIS tool used	Processing method	Analyzed geographical characteristic	Relevance for avalanches
Slope (Gradient)	Spatial Analyst Tools – Surface → Slope	Slope inclination in degrees	Terrain morphology	Areas with steep slopes (>30°) present a higher avalanche triggering risk.
Slope aspect	Spatial Analyst Tools – Surface → Aspect	Cardinal orientation of slopes	Solar exposure / atmospheric circulation	North-facing slopes retain snow longer, while south-facing slopes experience accelerated snowmelt.
Absolute elevation (m)	DEM / Extract by Mask / Zonal Statistics	Terrain elevation above sea level	Terrain elevation above sea level	High-altitude areas retain snow for longer periods and are more prone to avalanches.
Plan curvature	Spatial Analyst Tools – Surface → Curvature	Lateral slope shape (horizontal curvature)	Horizontal landform shape (concave or convex)	Concave areas accumulate more snow, favoring snow deposition.
Land use	Corine Land Cover (2018)	Type of land cover and land use	Vegetation, buildings, pastures, grasslands, etc.	Forested areas retain snow and reduce avalanche risk, while alpine open areas favor snow sliding.

Avalanche susceptibility was assessed by integrating the analyzed factors into an overlay model, based on the combination of reclassified raster layers. The applied relationship is:

Ar= G x A x Pc x E x Le

where Ar represents avalanche risk, G – slope (geodeclivity), A – aspect, Pc – plan curvature, E – elevation and Le – land use.

An important aspect of the methodology is the seasonal differentiation of the analysis. Thus, slope aspect was treated distinctly for the winter and spring seasons, to reflect variations in avalanche triggering mechanisms. During winter, the risk is primarily associated with snow accumulation on north-facing slopes, whereas in spring it is driven by accelerated melting processes on south-facing slopes.

The integration of these factors enabled the identification of areas with high avalanche susceptibility and the assessment of the vulnerability of road infrastructure. The results obtained provide the basis for subsequent analysis and for the formulation of road engineering solutions adapted to the geomorphological and climatic conditions of the study area.

3. RESULTS

The multicriteria analysis enabled the identification and spatial delineation of areas with high avalanche susceptibility within the Cabana Bâlea Cascadă – Bâlea Lake sector. The integration of geomorphological and land use factors highlighted a differentiated spatial distribution of risk, as well as significant seasonal variations, confirming the importance of a seasonal approach in the assessment of snow-related hazards.

3.1. Avalanche risk distribution in the winter season

The results obtained for the winter season highlight a concentration of high-susceptibility areas on north-facing and north-west-facing slopes, where shading conditions and low temperatures favor the accumulation and persistence of an unstable snowpack. These areas are characterized by slope angles ranging between 25° and 45°, elevations exceeding 1600 m, and the absence of forest vegetation, factors that act cumulatively to increase avalanche risk (Figure 2). For the avalanche risk in winter, high susceptibility values are concentrated in the upper sectors of the valley and on the steep slopes overlooking the road corridor. Under these conditions, the risk is primarily driven by the rapid accumulation of fresh snow over an unstable layer, a process typical of dry snow avalanches during the winter season.

3.2. Avalanche risk distribution in the spring season

The model developed for the spring season indicates a significant shift in the spatial distribution of avalanche risk, driven by increasing temperatures and intensified solar radiation. As a result, south-facing, south-east-facing, and south-west-facing slopes become the most vulnerable, due to accelerated snowmelt and the loss of snowpack cohesion.

From a morphometric perspective, the highest susceptibility values are associated with slope angles ranging between 25° and 45°, like those identified in the winter season. However, the key difference lies in the change in slope orientation. During the spring season, these slope intervals become critical particularly on sun-exposed slopes, where melting processes are more intense.

Elevation continues to play an important role, with areas located between approximately 1600 m and 2350 m being the most affected (Figure 3), due to the significant snow accumulation during winter and its persistence into the warming period. Under these conditions, the snowpack becomes saturated with water, leading to a substantial decrease in stability.

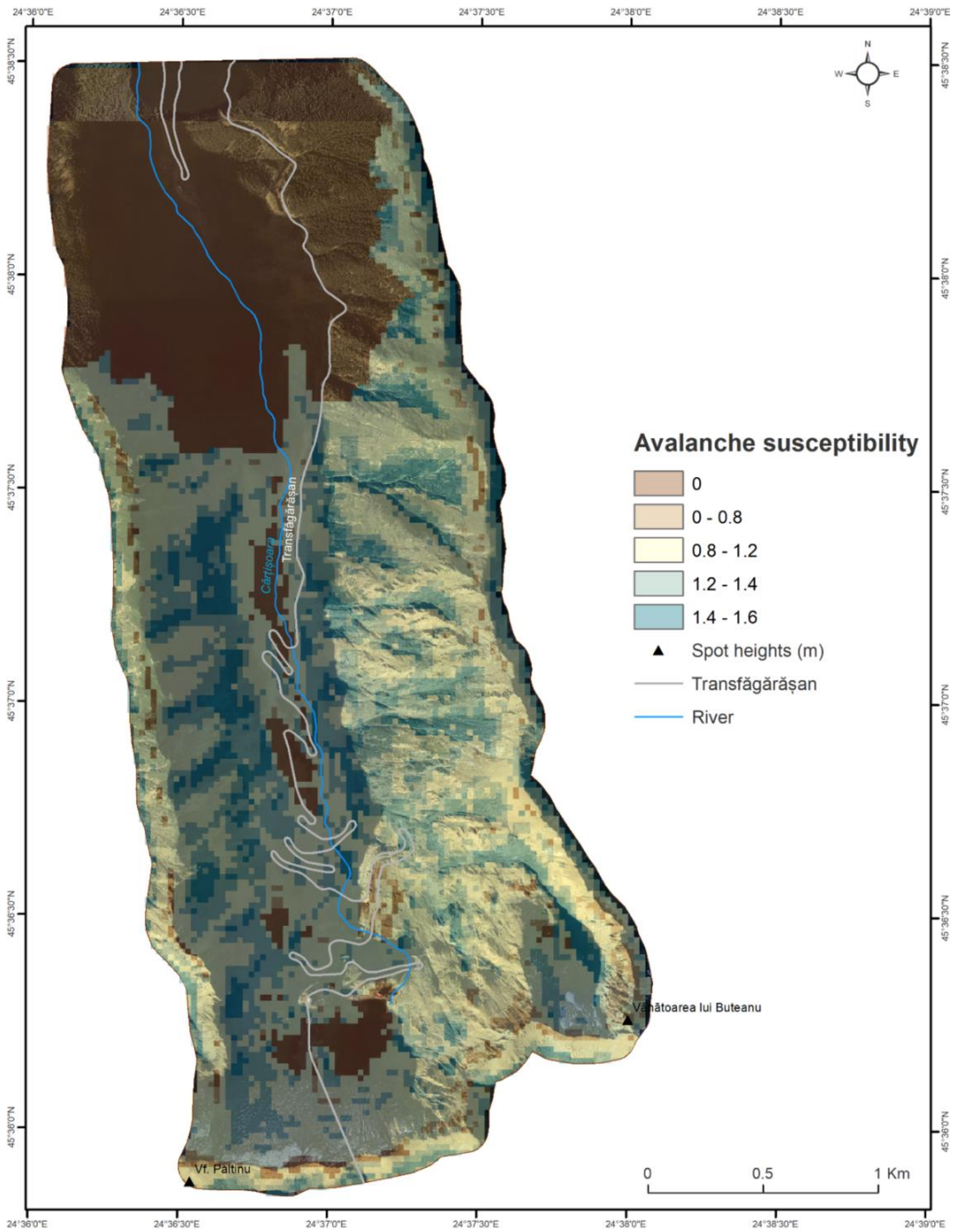

Figure 2. Avalanche risk in winter

Avalanche risk in spring highlights the shift of high-susceptibility zones toward south-facing and south-east-facing slopes. Avalanches characteristic of this season are predominantly wet snow avalanches, generated by water infiltration within the snowpack and the resulting reduction in internal friction.

3.3. Seasonal comparative analysis

The comparison of the two models highlights a clear seasonal dynamic of avalanche risk. While the winter season is characterized by snow accumulation on north-facing and north-west-facing slopes, in spring the risk shifts toward south-facing, south-east-facing, and south-west-facing slopes, where melting processes become dominant (Figure 4).

The overlay of avalanche risk (winter and spring) allows the identification of both seasonally controlled risk areas and zones with persistent susceptibility. Areas where high susceptibility values overlap in both models represent critical sectors, characterized by the convergence of favorable conditions such as steep slopes, high elevations, and the absence of forest vegetation.

The overlay analysis highlights that these sectors are predominantly located in the middle and upper sections of the route, where steep terrain and slope exposure favor both snow accumulation during the winter season and accelerated melting processes in spring.

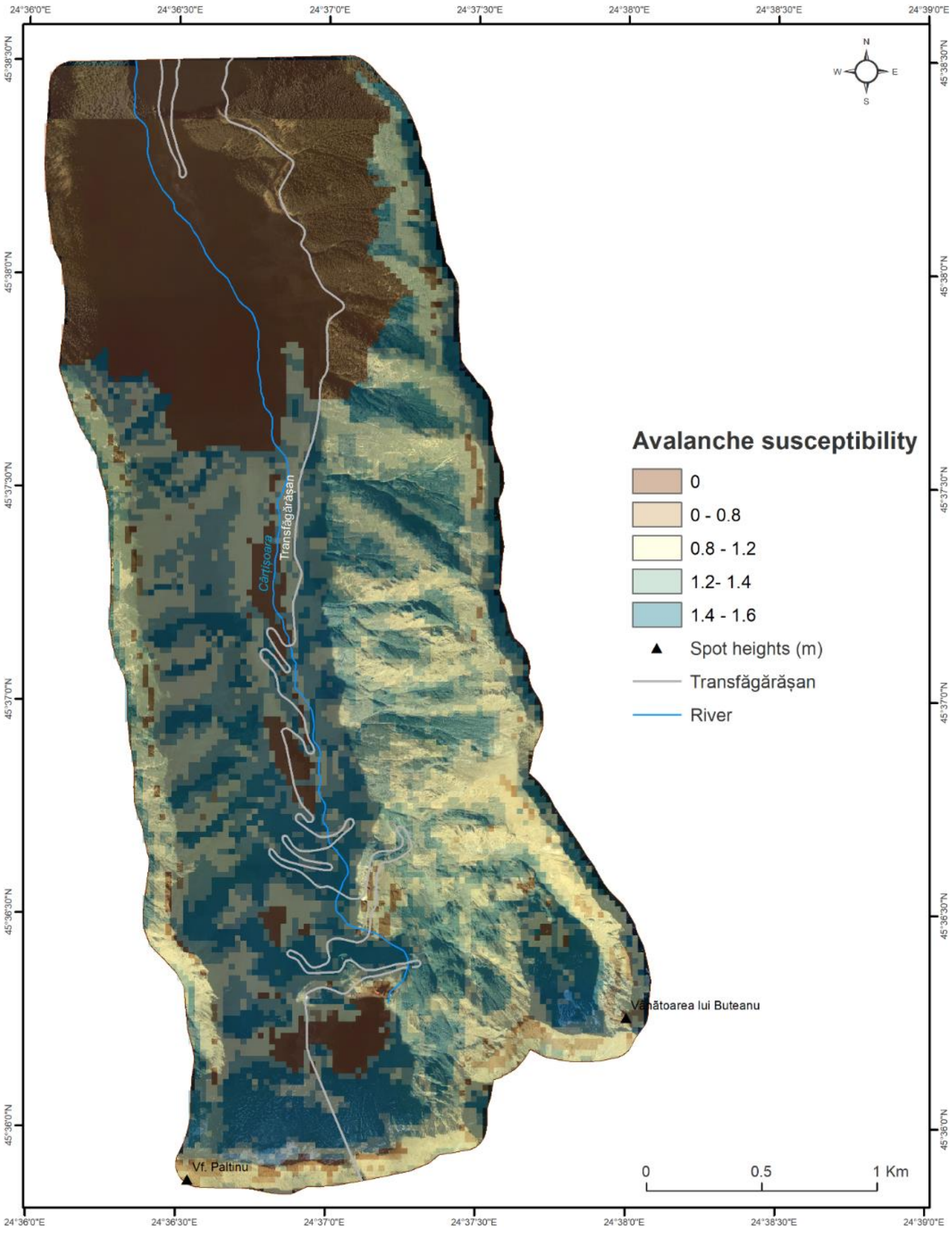

Figure 3. Avalanche risk in spring

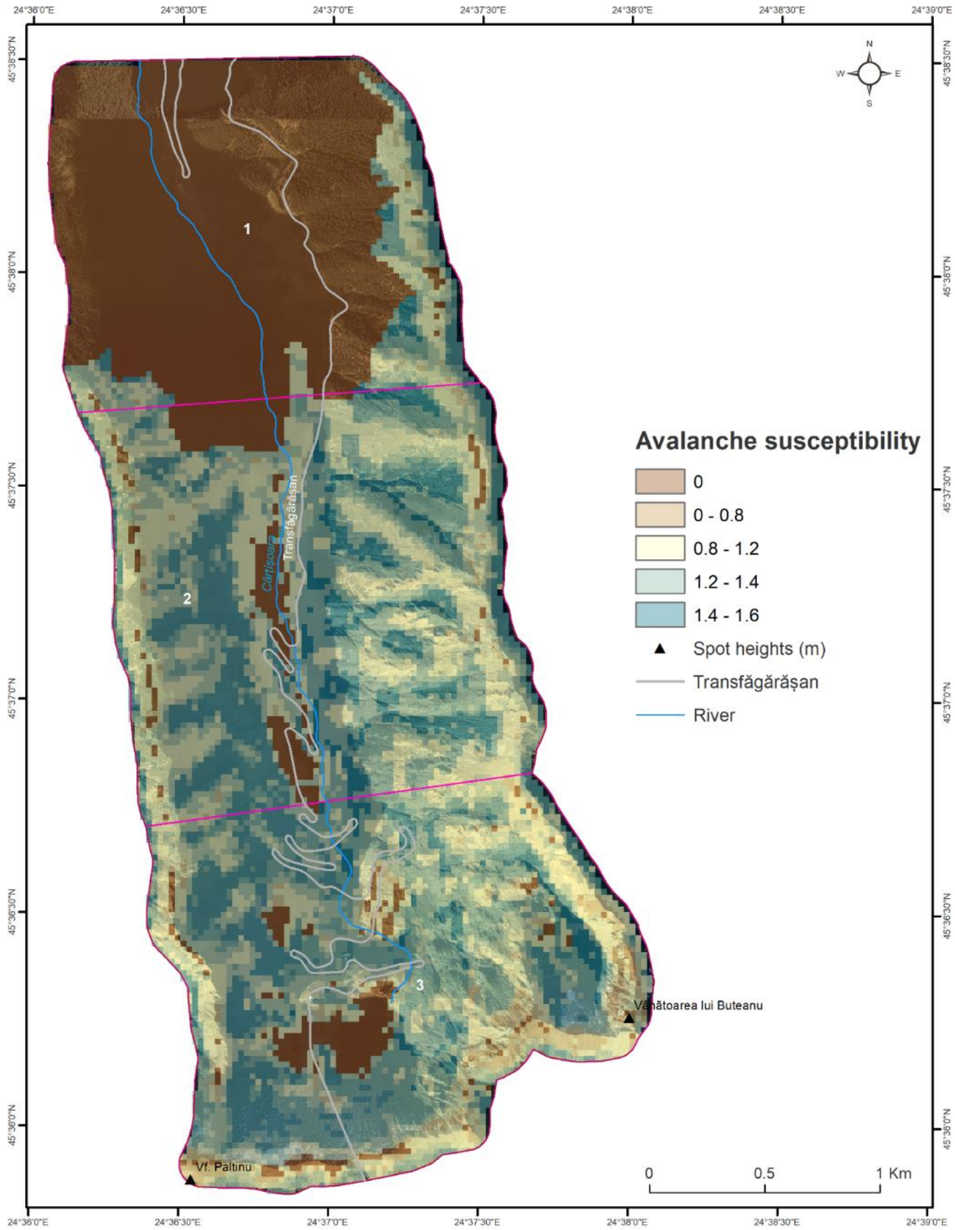

Figure 4. Seasonal evolution of avalanche risk in the upper Bâlea Valley (winter vs. spring)

4. DISCUSSION

4.1. Implications for road accessibility

The results highlight a direct relationship between the spatial distribution of avalanche risk and the vulnerability of the road sector analyzed. Areas with high susceptibility frequently overlap with the Transfăgărășan route or with its adjacent slopes, which explains the frequent blockages and the necessity of road closure during the winter season.

The lower sector, located near Bâlea Cascadă Chalet, presents a lower level of risk due to its lower elevation and the presence of forest vegetation. In contrast, the upper sectors, characterized by steep terrain and direct exposure to snow-related processes, exhibit a high level of risk, particularly in areas where the road intersects potential avalanche paths.

Areas identified as having persistent risk, highlighted through the overlap of the two seasonal models, represent critical points for road infrastructure and require priority interventions. In these sectors, risk is present throughout the entire cold season, being generated by both snow accumulation and snowmelt processes.

Therefore, the GIS-based analysis provides essential support for identifying vulnerable sectors and for substantiating protective measures, contributing to increased traffic safety and to the extension of the road's operational period.

4.2. Road engineering proposals

The results of the multicriteria analysis highlight the presence of sectors with high avalanche susceptibility, both in winter and spring, particularly in areas where steep slopes, high elevations, and the absence of forest vegetation overlap. The areas with persistent risk, identified through the overlap of seasonal models, represent critical sectors for road infrastructure and require priority interventions.

Based on these findings, a set of road engineering solutions has been proposed, tailored to local conditions, with the main objective of reducing risk and extending the operational period of Cabana Bâlea Cascadă – Bâlea Lake road sector.

In sectors with high and persistent risk, particularly where the road is located at the base of steep slopes identified in the GIS analysis, the construction of avalanche protection galleries (snow sheds) is recommended. These structures allow snow masses to pass over the roadway, thereby reducing the direct impact on the infrastructure. Their implementation is especially recommended in the upper sections of the route, where high susceptibility values were identified in both seasonal scenarios.

To reduce snow accumulation in potential release areas, the installation of avalanche control structures such as snow fences is proposed in the upper parts of the slopes. These structures contribute to stabilizing the snowpack and limiting avalanche formation. Their placement should be adapted seasonally, recommended on the north-facing slopes to reduce winter snow accumulation and on south-facing slopes to mitigate wet snow avalanches during spring.

In addition to structural measures, the implementation of non-structural solutions is recommended, including continuous monitoring of snowpack conditions, early warning systems, and controlled avalanche triggering under safe conditions. Furthermore, the establishment of flexible protocols for road closure and reopening, based on seasonal risk levels, can contribute to more efficient infrastructure management.

The implementation of these measures can significantly improve traffic safety and reduce the duration of road closures during the winter season. At the same time, enhanced accessibility may have positive effects on tourism and the local economy. However, all interventions should be carried out in accordance with sustainable development principles, ensuring minimal impact on the mountain environment.

5. CONCLUSIONS

The study conducted on the Cabana Bâlea Cascadă – Bâlea Lake sector highlights the complexity of the factors influencing avalanche occurrence and their impact on mountain road infrastructure. The integration of GIS techniques and multicriteria analysis enabled the identification and delineation of areas with high avalanche susceptibility, as well as the assessment of seasonal variations in risk.

The results indicate that risk distribution is primarily controlled by slope (geodeclivity), aspect, and elevation, factors that operate differently depending on the season. During winter, the most vulnerable areas are located on north-facing and north-west-facing slopes, where snow accumulation is favored by shading conditions. In contrast, during the spring season, the risk shifts toward south-facing, south-east-facing, and south-west-facing slopes, because of accelerated snowmelt processes.

The seasonal comparative analysis highlighted the presence of sectors with persistent risk, where conditions favorable to avalanche release are present throughout the entire cold season. These areas represent critical points for road infrastructure and require priority interventions to reduce vulnerability.

Based on the results obtained, a series of road engineering proposals were formulated, including avalanche protection galleries, snow fences, and risk management measures. Their implementation can contribute to improved traffic safety and to extending the operational period of the Transfăgărășan road within the analyzed sector.

In conclusion, the study demonstrates the effectiveness of GIS-based approaches in natural hazard assessment and emphasizes the importance of an integrated methodology adapted to local conditions and seasonal variability. The results can provide valuable support for decision-making processes related to mountain infrastructure management and the development of sustainable risk mitigation strategies.

6. ACKOWLEDGEMENTS

This research was carried out as part of the author’s dissertation focused on avalanche risk analysis and road infrastructure in the Transfăgărășan area. The author would like to thank the academic supervisor for guidance and support throughout the research process. The study was based on open-source geospatial datasets, including topographic maps, SRTM data, OpenStreetMap (OSM), and Corine Land Cover (2018), which are gratefully acknowledged.

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CINQ CONTINENTS
REVUE ROUMAINE DE GEOGRAPHIE

Volume 16 / Numéro 33
Été 2026
ISSN : 2247 - 2290
p. 86- 108

Le géopatrimoine d'Ait Taguella (Haut Atlas central, Maroc) et valorisation du géotourisme

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Sommaire :

Citer ce document :

HARBOUS, R., EL KHALKI, Y., AIT OMAR, T., ACHKIR, H., OUCHOUIA, I. 2026. Le géopatrimoine d'Ait Taguella (Haut Atlas central, Maroc) et valorisation du géotourisme. Cinq Continents 16 (33): 86-108.

Le géopatrimoine d'Ait Taguella (Haut Atlas central, Maroc) et valorisation du géotourisme

Rajae HARBOUS, Yahia EL KHALKI, Toufik AIT OMAR,
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The geoheritage of Ait Taguella (Central High Atlas, Morocco) and the development of geotourism. This contribution consists of inventorying, evaluating, and promoting the geoheritage sites in the Ait Taguella area, which is part of the M'Goun Geopark, Morocco. This territory is characterized by a rich geomorphological environment. To this end, we have utilized the relatively recent concept of geoheritage, which allows us to identify the most interesting forms of the geomorphological landscape through the use of an appropriate scientific evaluation method. The inventory we conducted in this territory allowed us to select 23 sites. The inventoried geoheritage sites have significant scientific value (0.57) due to their substantial integrity, their remarkable representativeness of the regional geomorphology of the Central High Atlas limestone region, and their moderate rarity. Additional value is also attributed to the fact that the majority of the geoheritage sites possess significant aesthetic and ecological qualities, particularly those located within the Ouzoud Biological Reserve. These geoheritage sites present remarkable geotourism potential that is still largely unrecognized and poorly integrated into national land-use planning. To promote the selected geoheritage sites, we have developed several types of mediation: maps of tourist circuits and trails, promotional materials, leaflets, and tourist brochures.

Key words: Ait Taguella, geoheritage, inventory, assessment, enhancement, geotourism, M'Goun geopark, Maroc.

Le géopatrimoine d'Ait Taguella (Haut Atlas central, Maroc) et valorisation du géotourisme. Cette contribution consiste à inventorier, évaluer et valoriser les géopatrimoines dans la zone d'Ait Taguella qui fait partie du géoparc M'Goun, Maroc. Ce territoire se caractérise par un cadre géomorphologique riche. Nous avons pour cela mis à profit la notion relativement récente de géopatrimoines, qui permet d'identifier les formes les plus intéressantes du paysage géomorphologique à travers l'utilisation d'une méthode d'évaluation scientifique appropriée. L'inventaire que nous avons mené sur ce territoire, nous a permis de sélectionner 23 sites. Les géopatrimoines inventoriés ont une valeur scientifique importante 0.57 liée à leur intégrité importante, leur représentativité remarquable de la géomorphologie régionale du Haut Atlas central calcaire et leur rareté moyennement importante. On adjoint également des valeurs additionnelles où la majorité des géopatrimoines présentent des qualités esthétiques importantes, écologiques intéressantes surtout ceux qui se trouvent dans la réserve biologique d'Ouzoud. Ces géopatrimoines présentent un potentiel géotouristique remarquable encore peu reconnu et peu intégré dans l'aménagement du territoire national. Pour valoriser les géopatrimoines retenus, nous avons élaboré plusieurs types de médiation : des cartes de circuits et sentiers touristiques, des fiches publicitaires, dépliants, brochures touristiques.

Mots clés : Ait Taguella, géopatrimoines, inventaire, évaluation, valorisation, géotourisme, géoparc M'Goun, Maroc.

1. INTRODUCTION

Un grand intérêt est donné aux géopatrimoines depuis la fin du XXe siècle, suite à une prise de conscience grandissante de l'importance de sauvegarder les composantes géologiques pour leur contribution à la science et l'histoire terrestre (Grandgirard, 1997). Le géopatrimoine désigne un ensemble de formations géologiques, des paysages remarquables, des fossiles, des minéraux, des grottes, des volcans ou tout autre élément du sous-sol ayant une importance particulière (Bétard et al., 2017).

Nombreuses initiatives avaient pour objectif de démontrer l'importance des géopatrimoines pour la science et la société. Pour cela, plusieurs chercheurs (Iosif, 2014; Kubalikova, 2013 ; Reynard et al., 2016) ont été engagés dans des démarches pour élaborer des méthodes scientifiques pour la mise en valeur de ces géopatrimoines à travers un processus de vulgarisation précis (Sellier, 2009). Ces géopatrimoines présentent de valeur scientifique, culturelle, écologique, esthétique et touristique où le géotourisme présente une forme de tourisme fondée sur la découverte des géopatrimoines de sites géomorphologiques et géologiques spectaculaires ; ce qui peut être un moteur de développement économique pour les régions concernées (Cayla, 2009). Or, il est essentiel de mettre en place des pratiques responsables pour éviter la surexploitation de ces sites

Au Maroc, la question des géopatrimoines est soulevée notamment lors la reconnaissance de l'UNESCO du géoparc M'Goun en 2014. Cette reconnaissance confirme l'originalité et la rareté de la géodiversité marocaine (Ait Omar et al., 2019).

Cet article présente les géopatrimoines qui caractérisent la zone d'Ait Tuegulla, appartenant au géoparc M'Goun UNESCO, dont l'objectif principal est la réalisation d'inventaire, d'évaluation et la proposition de mesures de valorisation géotouristique. Il s'agit en effet de redéfinir des nouvelles potentialités géotouristiques et diversifier l'offre touristique dans ce géoparc du M'Goun.

2. MÉTHODOLOGIE

2.1. Zone d'étude

La zone d'Aït Taguella est un territoire montagnard (Haut Atlas Central) qui se situe dans la région de Béni Mellal-Khénifra, province d'Azilal, à 170 km au Nord–Est de Marrakech et 100 km de Béni Mellal. Ce territoire montagnard fait partie du « Haut Atlas central » ou « Haut Atlas calcaire » qui est limité par la transversale Marrakech-Ouarzazate à l'Ouest, et la vallée de l'Oued Ziz à l'Est. Ici, la lithologie est caractérisée par l'abondance de roches sédimentaires calcaires, dolomitiques et marneuses du Lias et

Jurassique moyen et d'autres formations continentales du Tertiaire et des dépôts Quaternaires (Couvreur, 1988 ; Figure 1).

La géomorphologie locale est fortement marquée par la dominance des axes anticlinaux formant des crêtes sommitales et des principales vallées au cœur des synclinaux. Des failles et de formes intrusives liées à la dynamique interne de la chaine donnant naissance à des coulées de basaltes, des dykes et des sills (Figure 2).

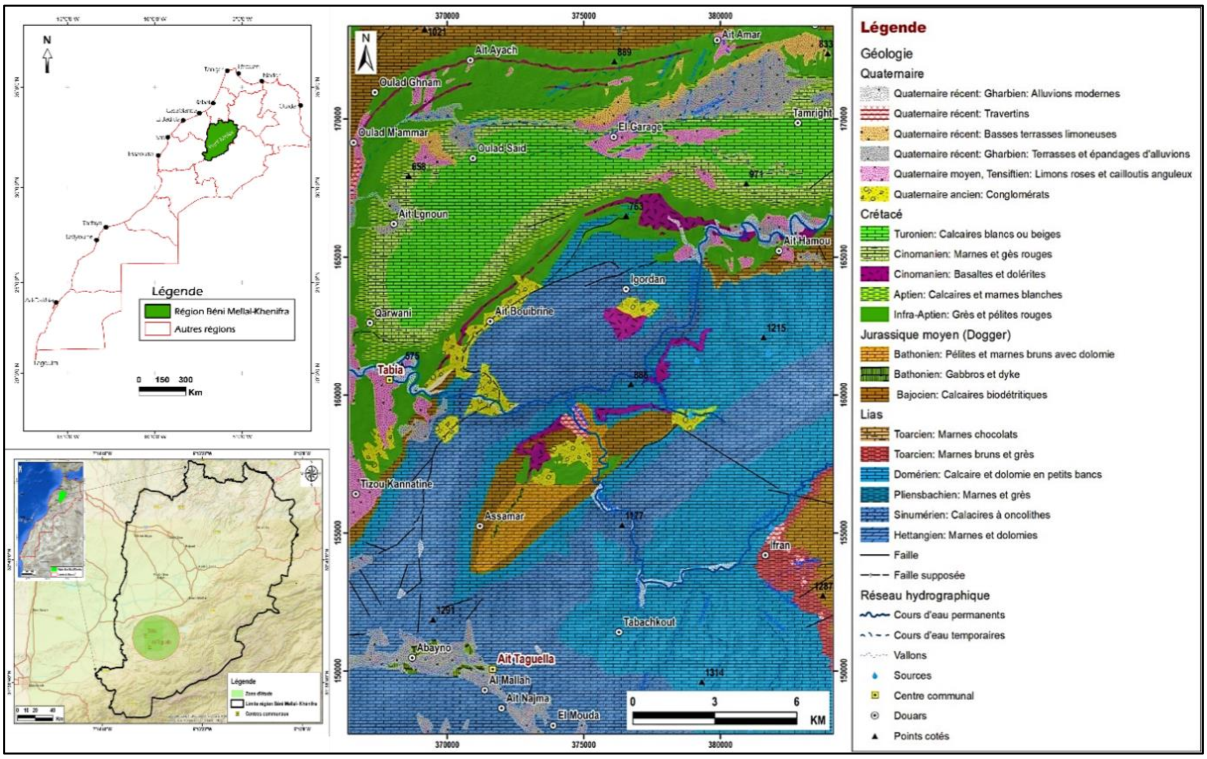

Figure 1. Localisation géographique et géologie de la zone d'Ait Taguella
(Source : Découpage administratif, 2015, carte géologique d'Azilal, 1.10000 et SIG)

Le relief karstique constitue un paysage géomorphologique assez dominant. On trouve sur les plateaux calcaires et les monts dérivés un ensemble des dolines qui suivent les lignes des failles. Des champs de lapiés et des méga lapiés de dissolution et de ruissellement). Ces paysages proviennent généralement de la relation combinée entre la tectonique et la karstification des roches carbonatées (El Khalki, 2001 ; Figure 3).

Des formes karstiques souterraines sont aussi très présentes dans cette zone, issues de l'action dissolvante des eaux souterraines, conduisant à la formation de gouffres, de grottes et des cavités selon les conditions géologiques (failles, pendage, discontinuité, lithologiques). Ces cavités souterraines sont caractérisées par la présence de formations des stalactites et des stalagmites d'importance paléogéographique (El Khalki, 2001 ; Figure 4).

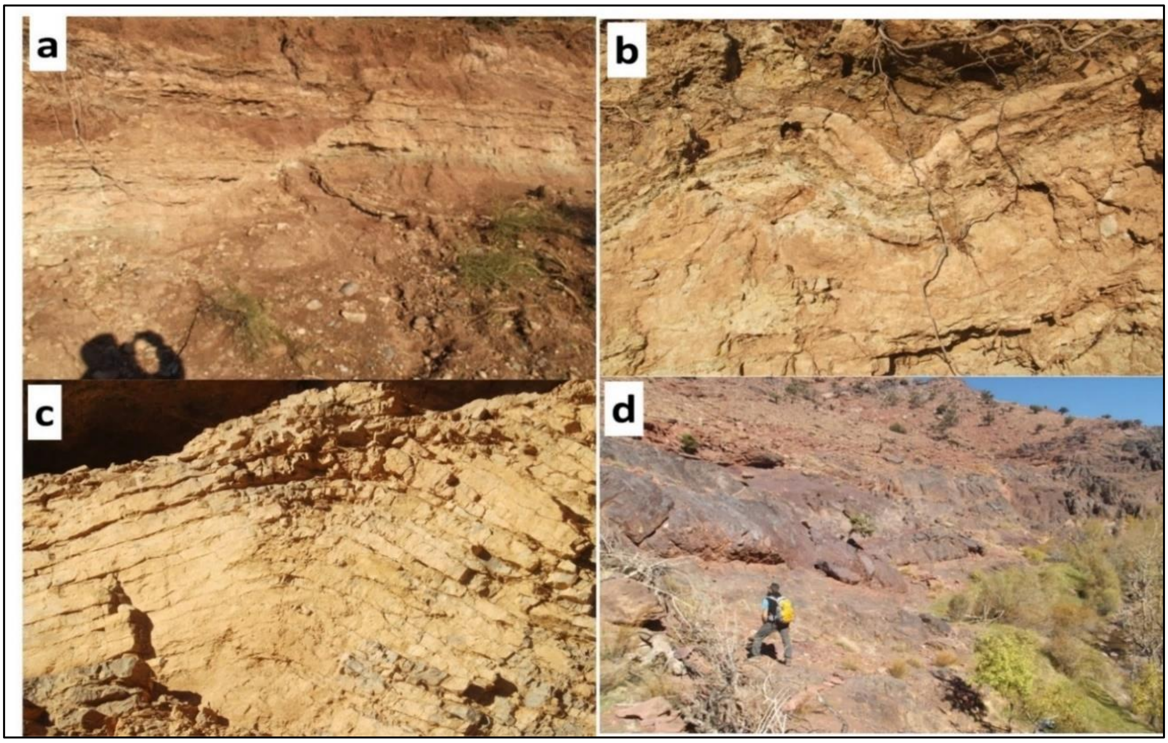

Figure 2. Formes structurales et intrusives dans la zone d'Ait Taguella :
a- Faille inverse, b-c-plis, d- gabbros

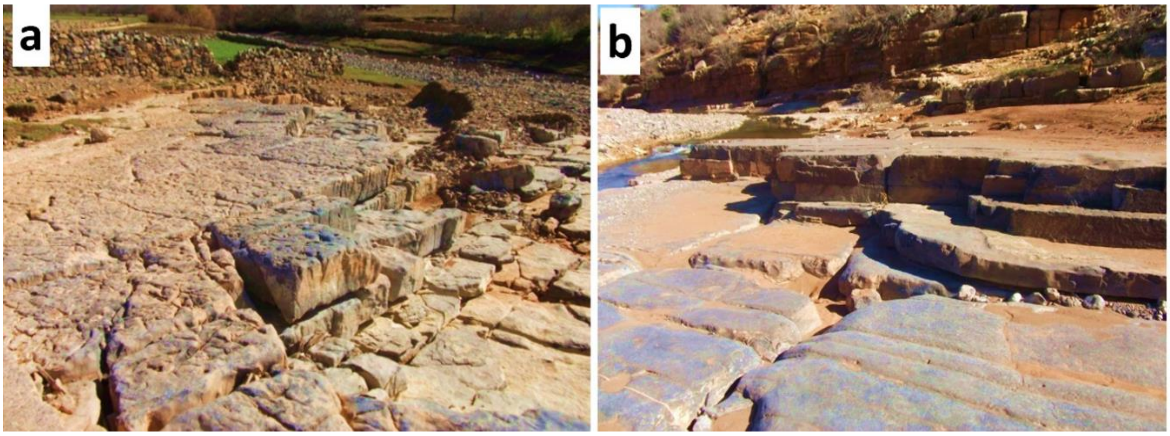

Figure 3. Karst superficiel : a- Lapiés d'Amazir ; b- Lapiés de Tabounot

Le système hydrokarstique donne un aquifère souterrain remarquable drainé par une centaine de sources. Parmi les plus importantes dans ce secteur, on peut citer : les sources de l'oued Ouzoud et de Cheikh et d'autres. Des Formations carbonatées externes liées à la reprécipitation des carbonates après karstification sur des sites des cascades dans le milieux calcaires et/ou à l'embouchure des sources karstiques.

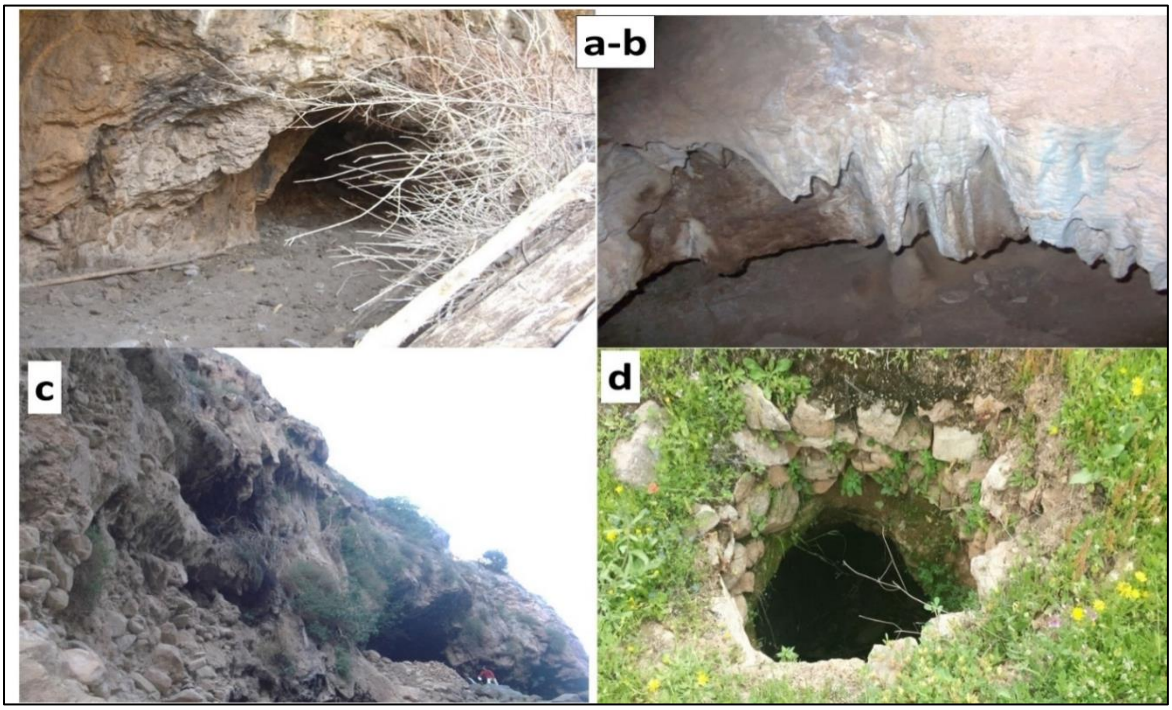

Figure 4. Grottes et cavités karstiques :
a-b- Grotte N Borj N Iroumin, c- Grottes N Tabounot, d- Gouffre Ait Ouabit

Ces formations permettent de réaliser des datations divers (paléomagnétisme, isotopes, radioactifs). Ces dépôts travertineux constituent un traceur de l'évolution et les transformations des environnements passés également via les fossiles, pollens ou charbon piégés dans ces formations (Olivier et al., 2008 ; Figure 5).

Des Formes d'érosion et d'accumulation fluviatile sculptent les massifs karstiques en fort soulèvement tectonique et parfois possèdent des ruptures donnant naissance à des chutes d'eau étagées (Nicod, 1997). Plusieurs canyons et gorges caractérisent le territoire d'étude en citant par exemple : les canyons de l'oued Tissakht, gorges de l'oued El Abid et celles de l'oued Ouzoud. Les méandres sont l'une des formes d'érosion les plus spectaculaires qui caractérisent les cours d'eau à écoulement permanent. Quant à la terrasse fluviale, elle constitue l'élément morphologique le plus important de la vallée de l'oued El Abid (Figure 6).

On trouve également de formes illustratives des relations homme et reliefs. Ces différentes formes géomorphologiques ont, pour certaines, été transformées ou exploitées par les activités humaines. On peut dire alors que « chaque forme du relief terrestre influence la vie des êtres humains dans la mesure où elle facilite ou entrave leurs activités (Figure 7).

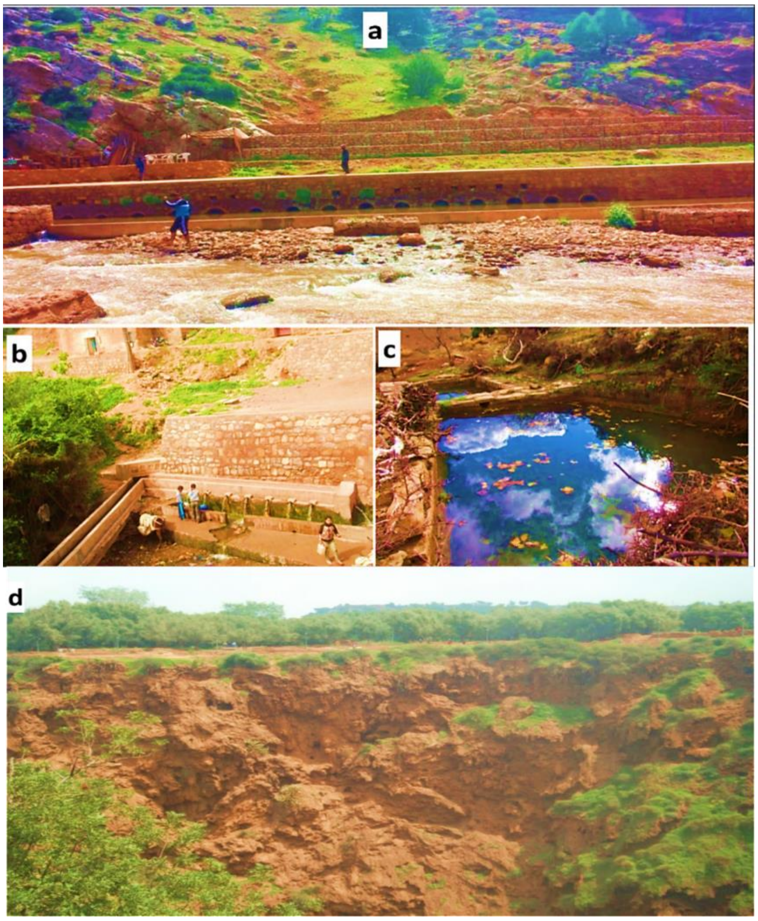

Figure 5. Exemples de sources karstiques dans la zone d'Ait Taguella :
a- sources de Tabounot (amont d'Ouzoud), b- Source Echeikh, c- Source Seddat (El Garage),
d- Travertins de cascades d'Ouzoud

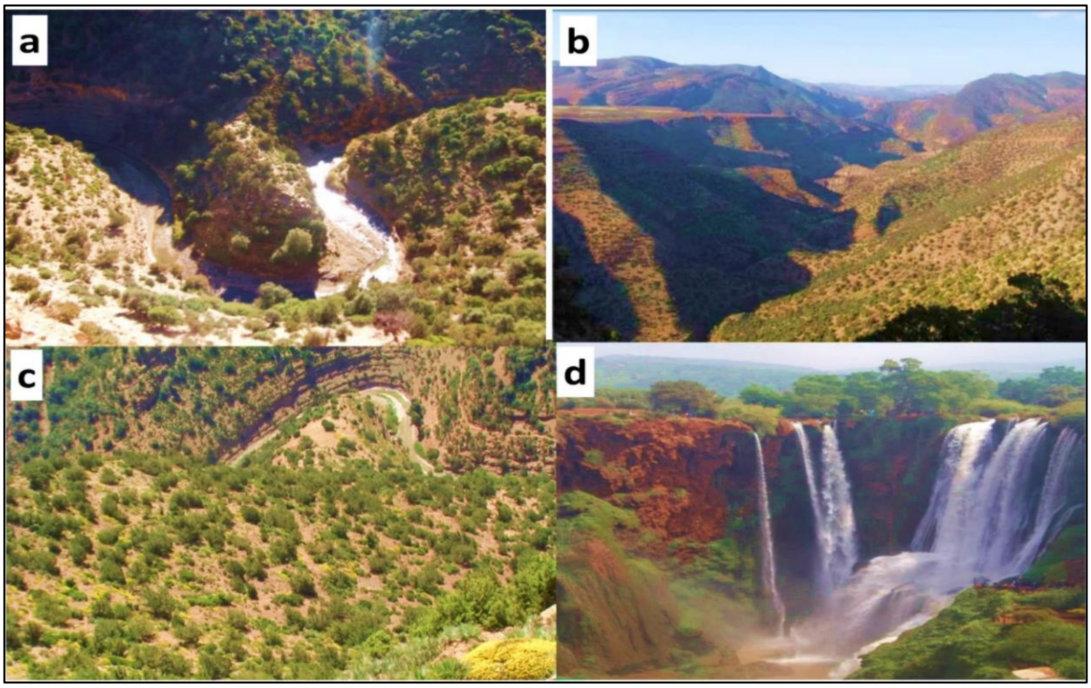

Figure 6. Formes fluviatiles et pluviale dans la zone d'étude : a- canyon Tissakht,
b- gorge oued El Abid, c- méandre oued El Abid, d- cascades d'Ouzoud

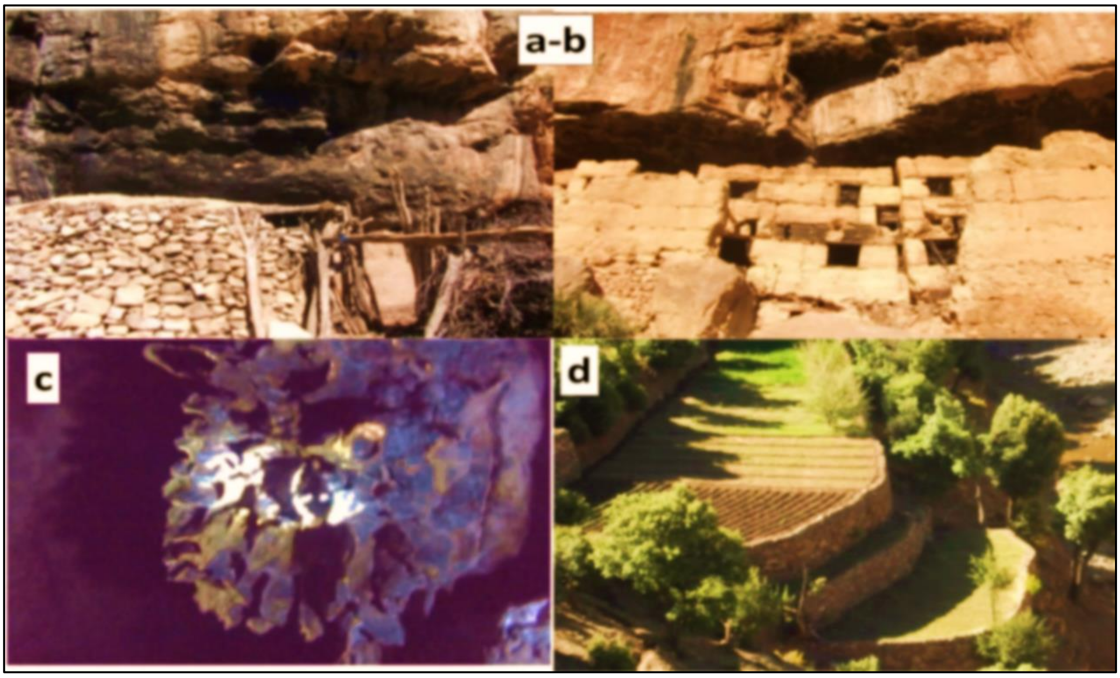

Figure 7. Exploitation de l'homme des éléments du relief : a-b- abri sous roche d'Ouabit, c- Maison troglodyte, d – terrasses agricoles aménagées

En résumé, on peut dire que la zone d'Ait Taguella est marquée fortement par une diversité géomorphologique remarquable qui a été cartographiée en s'inspirant de la légende de l'Université de Lausanne (UNIL) qui se base sur la classification des formes du relief par processus morphogéntiques dominants. Cette légende géomorphologique est intégrée dans un système de SIG ; une symbologie basée sur les trois types d'entités géographiques : des points, des lignes et des polygones (Figure 8).

2.2. Evaluation du géopatrimoine

Un grand nombre de géographes, géomorphologues et géologues ont pris des initiatives pour élaborer des méthodes scientifiques pour la mise en valeur des géopatrimoines à travers un processus de vulgarisation précis (Cayla, 2009). Au début, ces méthodes ont été orientées pour évaluer seulement l'aspect scientifique des géosites dans une perspective de protection de la nature que de promotion territoriale (Grandgirard, 1997). Des méthodes d'évaluation ont été introduites incluant à la fois des valeurs scientifiques et des valeurs additionnelles servant mieux l'évaluation du potentiel touristique des sites (Reynard et al., 2016). Pour l'évaluation quantitative, les scores s'étendent de 0 (valeur nulle) à 1 (valeur maximale), avec des paliers de 0,25 (Tableau 1).

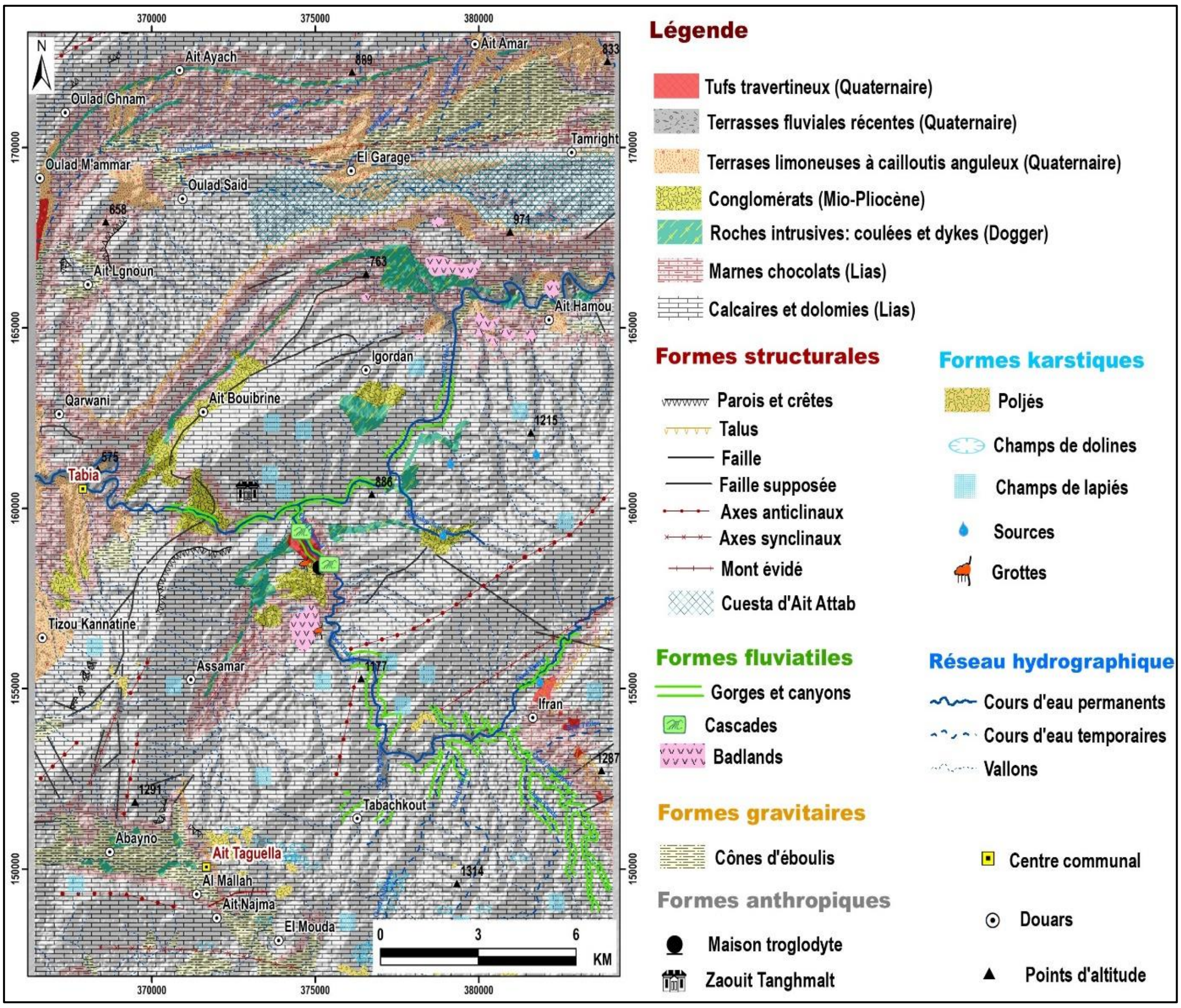

Figure 8. Croquis géomorphologique d'Ait Taguella (Carte géol. Azilal, 1/100000, Google Earth, 2023, cartes topos, Azilal, 1/50000, plus travail du terrain et cartographie)

Tableau 1. Valeurs et critères d'évaluation des géopatrimoines étudiés

La valeur scientifique (VSc)		
In		**L'intégrité :** état de conservation du géomorphosite
Rp		**La représentativité :** exemplaire de la géomorphologie locale
Ra		**La rareté :** site unique ou non à l'espace de référence de l'étude
Ip		**Intérêt paléogéographique** : témoin de l'histoire de la Terre
Les valeurs additionnelles (Vad)		
Eco		**La valeur écologique :** Se réfère aux conditions de biodiversité
Es	**La valeur esthétique**	a) ***Point de vue*** : Se réfèrent à la visibilité du site et b) **structuration de l'espace** : contraste de couleurs
Cul	**La valeur culturelle**	a) ***Religieux :*** le rôle joué par le géomorphosite en termes religieux, spirituel, mythologique ou mystique
b) ***Historique** :* reprend l'histoire au sens large		
c) ***Littérature artistique** :* le rôle joué dans l'inspiration des écrivains et des artistes		
d) ***Géohistorique :*** le rôle qu'il a joué pour le développement des géosciences		
Ec		**La valeur économique** : Evaluation des produits générés par la gestion d'un géomorphosite

Finalement, on détermine la valeur géomorphologique globale du géotope en tenant compte de la valeur scientifique et des valeurs additionnelles (Tableau 2).

Tableau 2. Calculs des moyens des valeurs des géopatrimoines

Valeur	Formule
Valeur géomorphologique globale intrinsèque pour le géotourisme	VGG= VSc + VAd /2 (Max =1)
Valeur scientifique moyenne	V.Sc = (In + Rp + Ra +Ip)/4 avec: (V.Sc Max = 1)
La valeur additionnelle moyenne	V.Ad = (Eco + Es + Cul + Ec)/4, avec: V.Es= (PV + Str)/2 et V.Ec = (Re + Hi + art + Gh)/4, avec: (V.Ad Max = 1)

Source : Reynard et al., 2016

3. RÉSULTATS ET DISCUSSION

3.1. Caractérisation des géopatrimoines inventoriés

Pour protéger et valoriser correctement les géopatrimoines, l'inventaire et l'évaluation constituent l'étape fondamentale dans cette procédure d'évaluation géopatrimoniale. Les chercheurs ont développé une variété de méthodes pour quantifier les différents composants des géopatrimoines sur le plan scientifique, culturel, esthétique et économique (Reynard et al., 2016). Le nombre total des sites inventoriés est de l'ordre de 23 sites qui se répartissent sur l'ensemble du territoire étudié (Figure 9).

Les formes karstiques sont les plus nombreuses présentant 35% vu l'importance des roches carbonatées subissant l'érosion chimique et donnant naissance à une palette de formes superficielles et souterraines. Les processus fluviokarstiques sont aussi importants 35%, ce sont déjà formés en principes sous l'effet de l'action érosive de l'eau mais aussi en faisant la combinaison des roches calcaires et dolomitiques dures comme la càs des canyons karstiques et des sources karstiques sont omniprésentes issues de l'aquifère karstique du Lias. Des processus fluviaux sont aussi inventoriés généralement issus de la dynamique fluviatile des cours d'eau comme des méandres, plaine alluviale et des badlands et d'autres. Les formes structurales et intrusives sont aussi d'intérêt dans cet inventaire 22%, car ce sont des formes uniques comme celle des failles Ait Abdellah, des plis typiques et des anticlinaux et synclinaux avec l'existence d'une Cuesta d'Ait Attab rare dans la zone étudiée. Seulement 4% sont des formes gravitaires. Ils ne sont pas importants en matière du tourisme. Les sites géoculturels présentent 4% présentant des formes du relief actuellement ou historiquement exploitées en plusieurs usages : comme des abris ; c'est le cas de la maison troglodytes et des bâtisses suspendues sur les falaises et des cavités habitées. Des terrasses agricoles étagées qui sont esthétiquement aménagées et exploitées au bord des cours d'eau permanents (Figure 10).

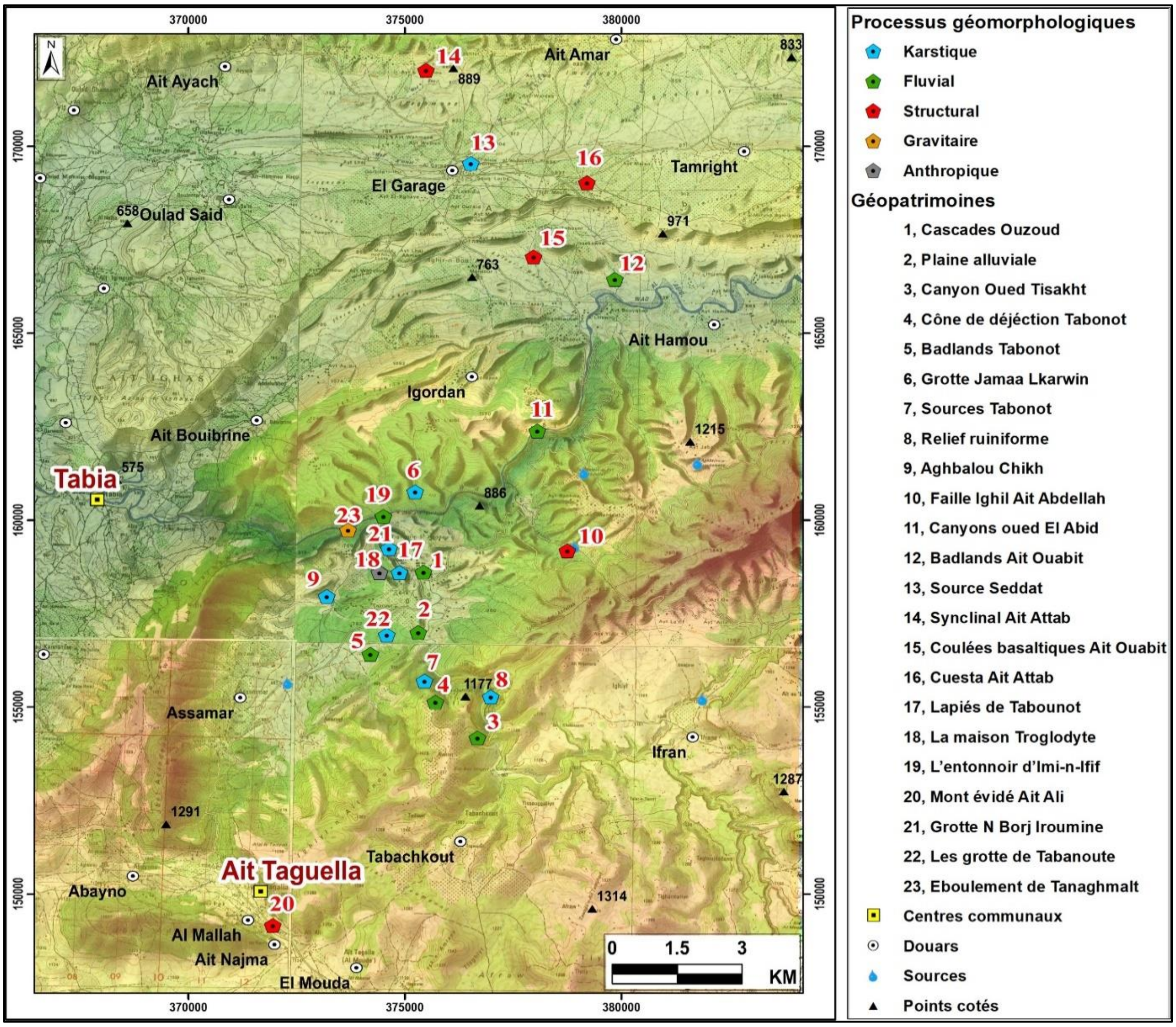

Figure 9. Répartition spatiale des géopatrimoines étudiés par processus
(Carte Topo. Ait Taguella, 1/50000 ; MNT 30 m et SIG)

3.2. Evaluation des géopatrimoines inventoriés

3.2.1. Evaluation scientifique

Nous étudions dans un premier temps, la valeur centrale des géopatrimoines en analysant tout d'abord les résultats de façon globale. La valeur scientifique moyenne de l'ensemble des géopatrimoines est de 0,58. L'analyse des critères scientifiques permet de voir le poids de chaque critère. On déduit que la majorité des géopatrimoines sélectionnées se trouvent dans un environnement globalement intact dont la moyenne arithmétique est d'ordre de 0.86. Or, des géopatrimoines sont anthropisés comme les sources d'Ouzoud et la cuesta d'Ait Attab où le score atteint 0.5. La représentativité des géopatrimoines inventoriés est importante (0.66). Une grande partie de la zone d'étude et ses géopatrimoines sont très représentatifs de la géomorphologie du Haut Atlas central calcaire. Une dominance des roches carbonatées a contribué à une richesse karstique.

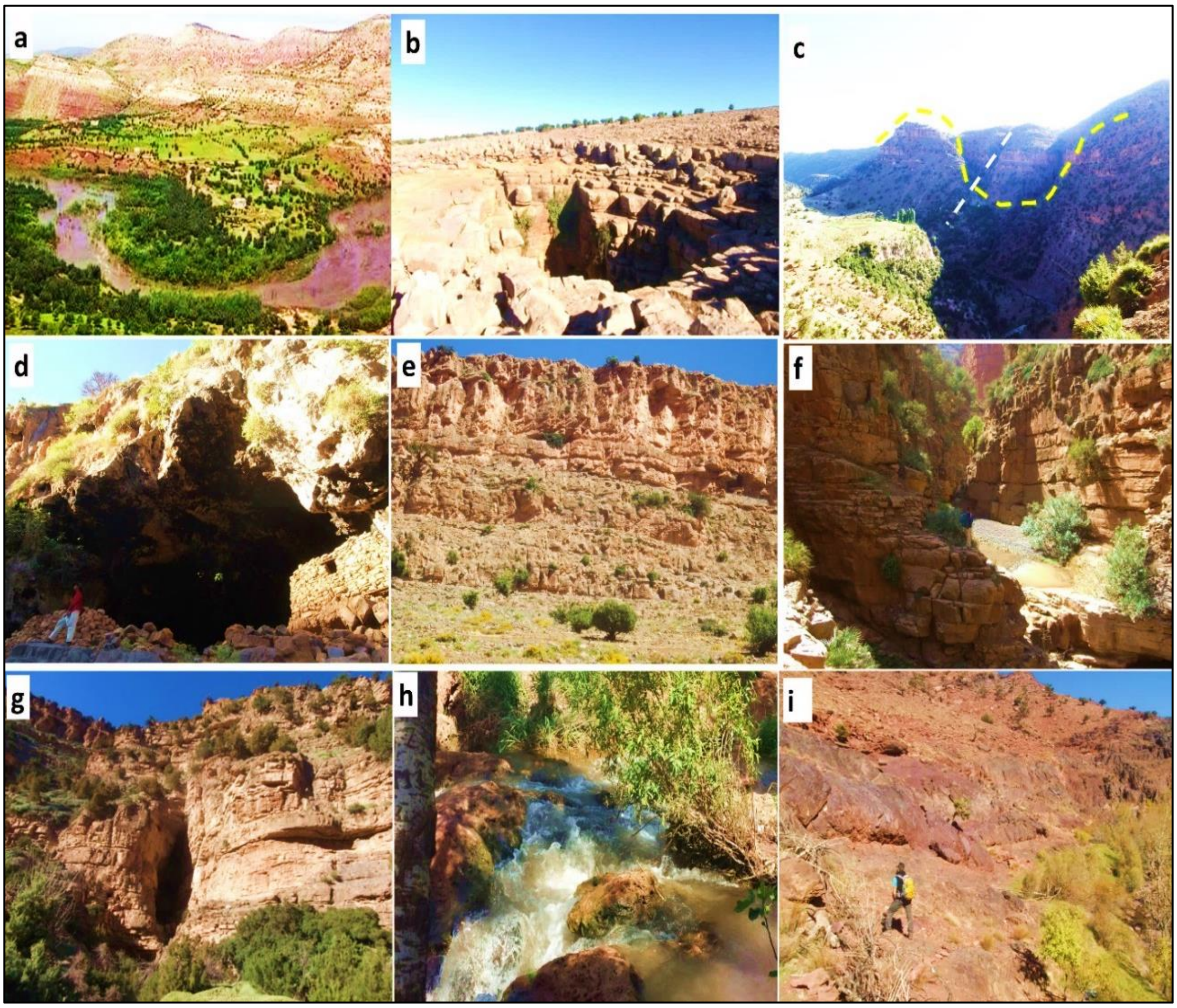

Figure 10. Géopatrimoines représentatifs de la géomorphologie locale par processus morphogéntiques: a- méandre d'Ait Attab, b– gouffre Tabounot, c- plis faille Ait Abdallah, d- maison Troglodyte-Grotte Tabounot, e- Stratification horizontale, f- gradin de suspens

Cependant, on trouve des géopatrimoines non représentatifs de la géomorphologie régionale car ils sont issus des processus très rares comme ceux des couches de basaltes et des géopatrimoines culturels. La moyenne de la rareté atteint 0.66 mais avec des variations d'un site à l'autre. Une excellente rareté (1) est enregistrée pour le site unique « maison de Troglodyte » et la plaine alluviale à magnifiques terrasses agricoles, les cascades d'Ouzoud (0.75) et les grottes de Tabounot et le synclinal d'Ait Attab et aussi le mont évidé et les sources de Tabounot. La majorité des géopatrimoines étudiés ne présentent pas un intérêt paléogéographique dont la moyenne arithmétique est d'ordre de 0.25. Mais, on peut déterminer quelques sites d'intérêt paléogéographique comme celui des cascades d'Ouzoud (0.5) ; les travertins qui sont un indice qui permet la reconstitution des conditions du climat ancien, les coulées basaltiques, la Cuesta d'Ait Attab (0.75), le synclinal d'Ait Attab (0.5) et le mont évidé (0.75 ; Figure 11).

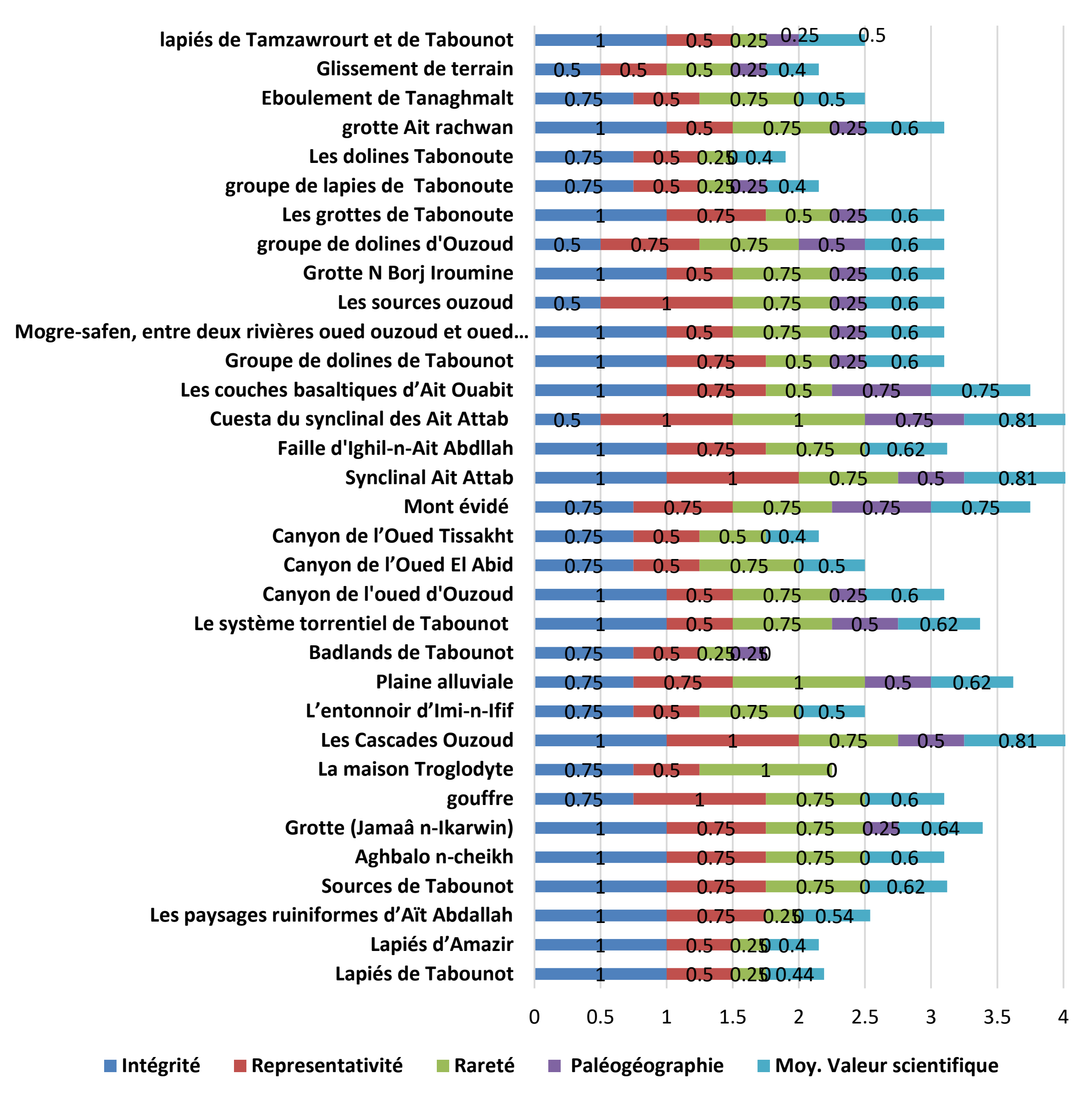

Figure 11. Scores des critères scientifiques et la moyenne de la valeur scientifique centrale

3.2.2. Evaluation des valeurs additionnelles

Les valeurs additionnelles sont évaluées pour tous les géopatrimoines, venant compléter la valeur scientifique, et elles sont particulièrement intéressantes lorsqu'il s'agit des géopatrimoines à forte reconnaissance sociale et culturelle (géomorphosites culturels) ou lorsqu'ils présentent un intérêt pour la conservation et le développement d'espèces floristiques et faunistiques locales, qui peuvent être rares au niveau local, régional, national et international. Parmi ces valeurs additionnelles, la valeur esthétique et scénique fait référence au contexte paysager du géopatrimoine et à la « beauté » du site, évalué à partir de l'extension verticale ou horizontale et des contrastes de couleurs.

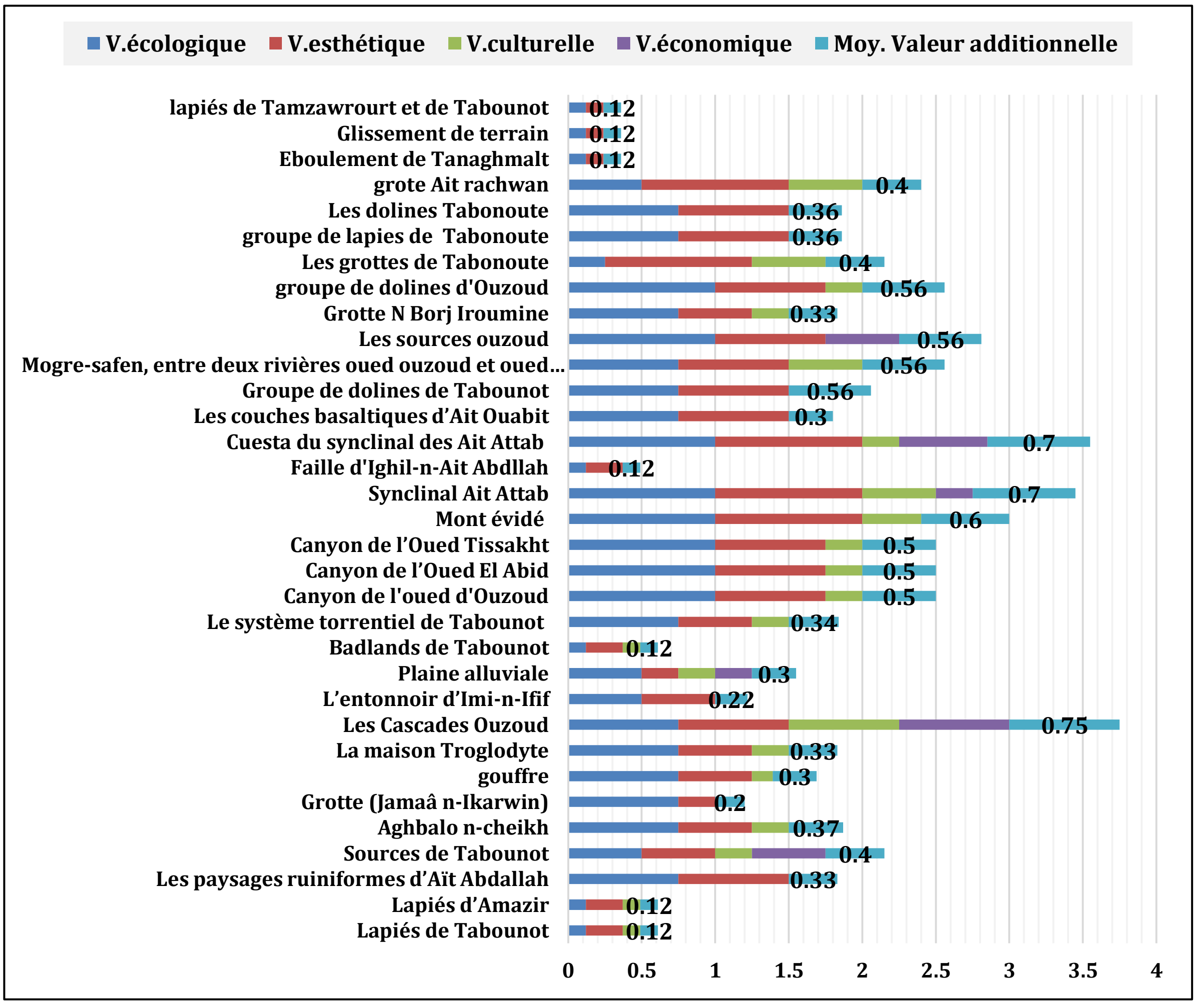

Figure 12. Scores des critères des valeurs additionnelles

La moyenne des valeurs additionnelles, atteignant un score de 0,5. Cela est expliquée avant tout, par le facteur de la valeur esthétique qui est de 0.70 en moyenne, dans une moindre mesure par la valeur écologique (0.54) et très peu, par la valeur socio-culturelle qui est assez faible (0.28 ; Figure 12). L'analyse détaillée des valeurs additionnelles confirme que la plupart des géopatrimoines sont à priori des sites d'intérêt écologique permettant le développement des espèces biologiques (plantes et animaux) diversifiées. La moyenne de cette valeur écologique est importante atteint (0.62). Les canyons présentent des biotopes de grande intérêt écologique car ils participent au développement des animaux dans les parois rocheuses, des oiseaux et des plantes variées comme le cas des canyons de l'oued Tissakht et ceux de l'oued El Abid (1). Les cascades d'ouzoud sont aussi d'importance écologique nationale (0.75) vue l'existence des singes de magots et un espace forestier très riche. La géodiversité est donc un élément soutenant le développement de la biodiversité et la diversité écologique, et pour le fonctionnement des écosystèmes (Crofts, 2019). La morphologie des formes géomorphologiques et leur visibilité et la diversité des couleurs présentent des aspects esthétiques prioritaires dans l'évaluation de ce critère. Plus l'objet géomorphologique est grand est-il dominé le paysage local par rapport à celui de petite grandeur. La variété de couleurs d'un géomorphosite ou géosite est résultante de la diversité des éléments paysagers qui l'entourent. La moyenne de la valeur esthétique est très liée à la dimension paysagère des géopatrimoines, elle est importante avec un score de 0.57 (Figure 13).

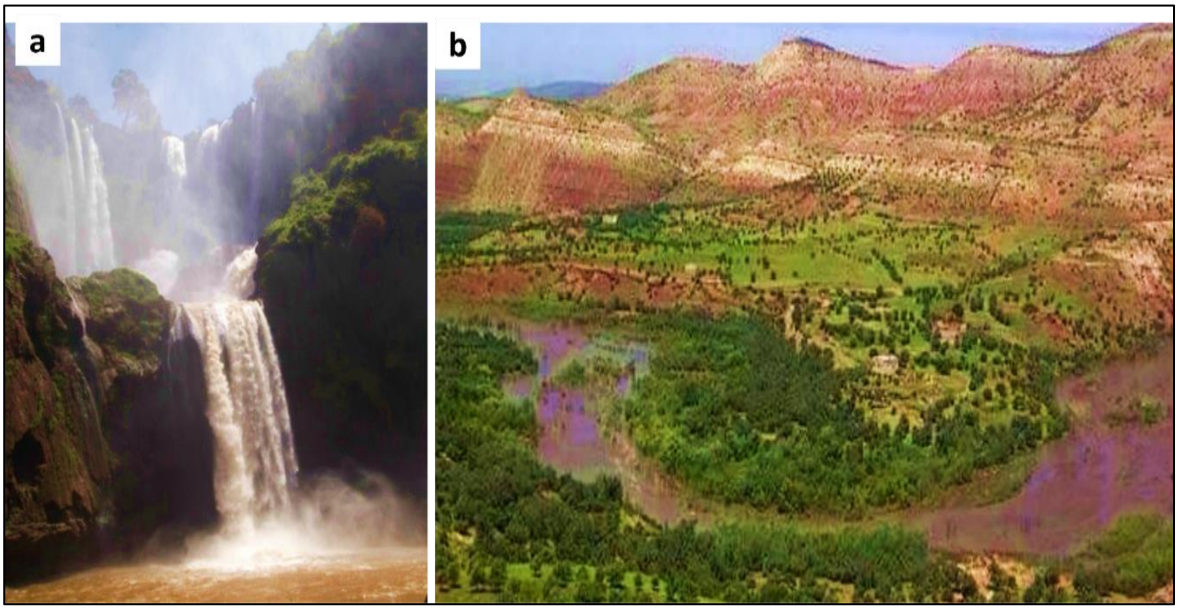

Figure 13. Quelques géopatrimoines d'importance esthétique d'Ait Taguella : a- cascade d'ouzoud, b- méandres de l'oued El Abid dans le synclinal d'Ait Attab

Les éléments du relief avec des éléments culturels (vestiges historiques ou archéologiques, monuments culturels ou religieux, etc.), la valeur géopatrimoniale rejoint la valeur culturelle, et on peut alors parler de sites géoculturels (Reynard, Giusti, 2018). La valeur culturelle moyenne est d'ordre de (0.22). Cependant, il existe des géopatrimoines qui présentent un intérêt socio- culturel comme les cascades d'Ouzoud (0.75) et la maison troglodyte (0.5). La valeur économique est identifiée, avec une moyenne très faible (0.12). Mais un grand intérêt touristique pour le célèbre site d'Ouzoud et ses sources (0.75 ; Figure 14).

3.2.3. Valeur géomorphologique globale

La moyenne de la valeur globale des géopatrimoines étudiés atteint 0,5. Ces résultats montrent qu'un nombre important de sites possèdent des atouts très diversifiés et recèlent un potentiel de valorisation géotouristique certain (Figure 15 et 16).

Figure 14. Excursion d'une journée complète aux cascades d'Ouzoud au départ de Marrakech

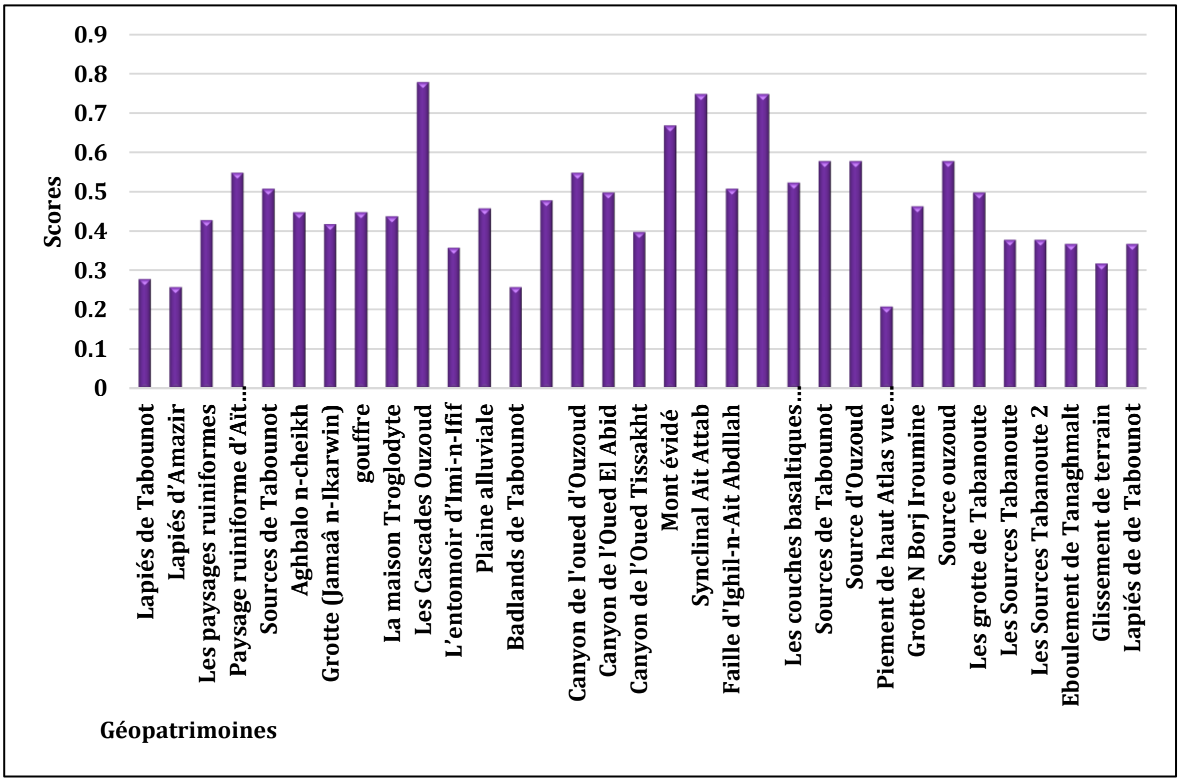

Figure 15. Moyenne de la valeur géomorphologique globale des géopatrimoines inventoriés

3.2.4. Valeur touristique : accessibilité et infrastructure touristique

La plupart des géopatrimoines étudiés possède généralement une bonne accessibilité (0.75). Le réseau routier est de plus en plus devenu dense dans la montagne marocaine et précisément dans Le géoparc M'Goun est en croissance.

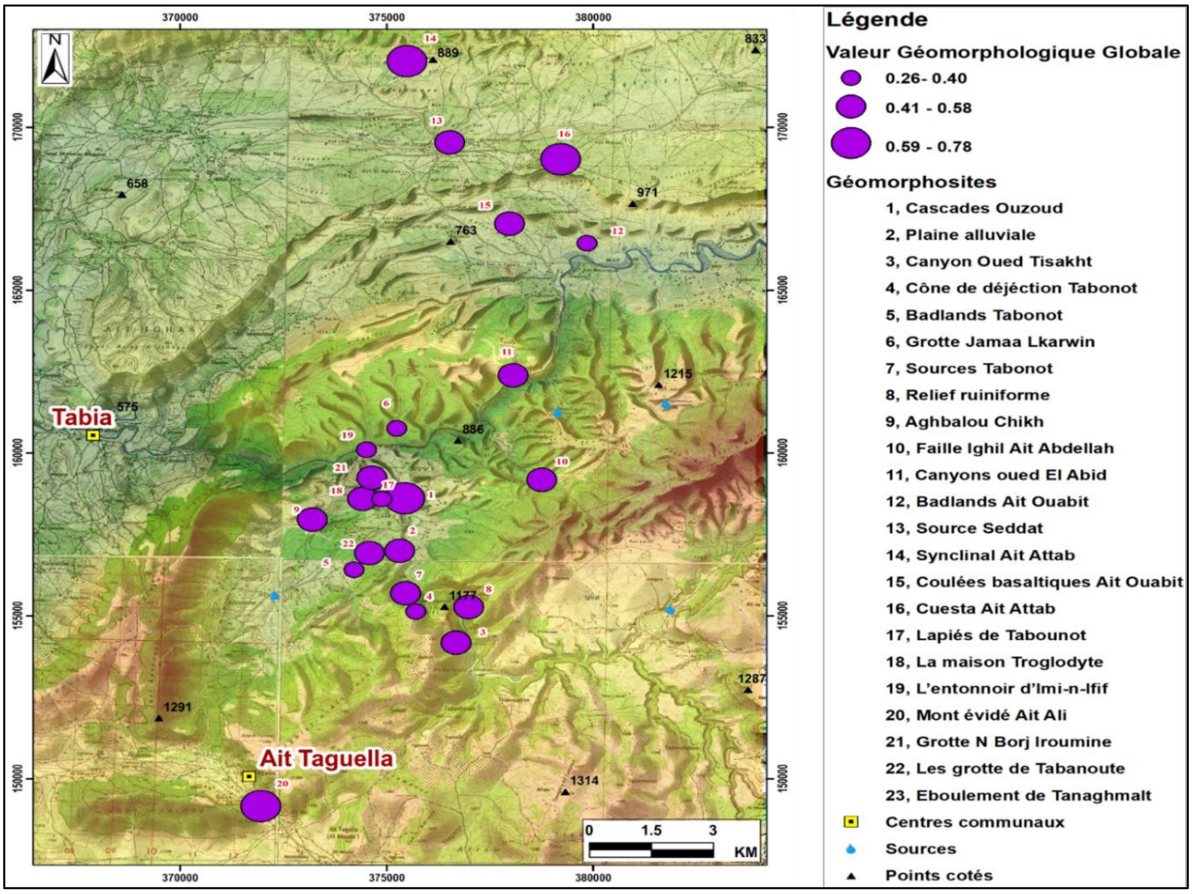

Figure 16. Répartition spatiale de la valeur globale des géopatrimoines étudiés

Cette dynamique touristique et l'intérêt donnée à ce territoire par les organismes internationaux (UNESCO) permettait de résoudre le problème de l'isolement géographique (Figure 17).

Figure 17. Unités d'hébergement (Gites en couleur rose) et les hôtels en couleur rouge.
Source : Google OSM, 2024

Le territoire d'Ait Taguella offre des conditions globalement favorables qui facilitent une visite touristique confortable. Des moyens du transport privés et publics sont divers et des hébergements sont in situ (Figure 18). Or, des contraintes peuvent se manifester et qui peuvent lier à des perturbations météorologiques et des problèmes en réseau de télécommunication.

Figure 18. Infrastructure touristique de la zone touristique Ouzoud : a- camping Zebra, b- Kasbah Oum Hani , c- restaurant et cafés

3.2.5. Menaces des géopatrimoines étudiés

L'analyse des menaces et atteintes s'appuie sur l'observation faite sur le terrain. Des dégradations de l'espace forestier influençant le fonctionnement géomorphologique en résultant des phénomènes d'érosion et des inondations. Le tourisme de masse a des impacts négatifs sur l'intégrité et l'originalité des géopatrimoines et également les habitats bétonnés non réglementaires qui déforment le paysage naturel (Figure 19).

3.3. Valorisation touristique des géopatrimoines

La valorisation de la ressource géopatrimoniale passe par le développement du géotourisme. Celui-ci est défini, dans son sens strict, comme une forme d'écotourisme fondé sur la visite interprétée des géosites (Dowling, Newsome, 2018), et des usages récréatifs et ludo-sportifs (Cayla, 2013).

Figure 19. A- dégradation du milieu forestier, b- impact négatif de tourisme de masse sur les sources Ouzoud

La signalétique des sites touristiques représente un enjeu pour l'image et l'attractivité d'un territoire, en faisant office de levier pour le développement d'une région. La signalétique touristique correspond à l'ensemble des panneaux ou plaques signalétiques, directionnelles, situationnelles ou explicatives indiquant les attraits touristiques d'un lieu (Figure 20).

Figure 20. Un panneau présentant les cascades d'Ouzoud, Ait Taguella

Les affiches touristiques sont des outils de géographie qui représente l'espace qui fait l'objet d'un travail de mise en mots, de mise en signes et beaucoup plus attentifs aux effets structurants des discours sur l'espace (Veschambre, 2005). Nous avons donc réalisé des affiches touristiques pour certains géopatrimoines d'intérêt touristique comme les cascades d'Ouzoud (Figure 21).

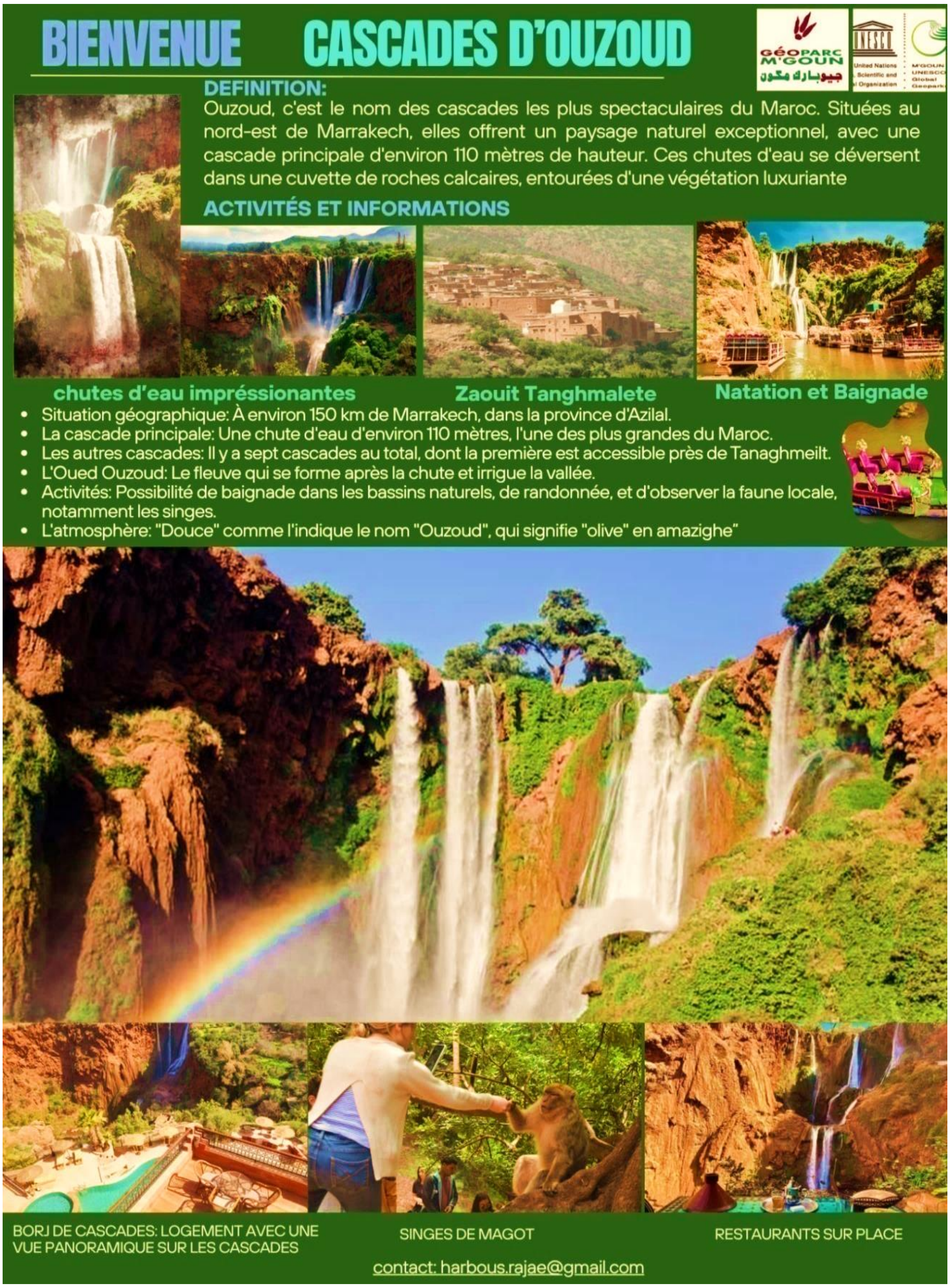

Figure 21. Affiche touristique de la cascade d'Ouzoud, Géoparc M'Goun, Azilal

Tableau 3. Informations pratiques sur le grand sentier touristique d'Ouzoud

Trajet et durée	Ait Attab (El Garage), Centre Ouzoud et Ait Taguella
Distance	50 km (Automobile sur la route provinciale 3105)
Public ciblé	Toutes les catégories
Prix en DH	200 à 500 dh
Hébergement	Les gîtes et les maisons d'hôte, hôtels : Hôtel Borj
Sites visités et activités	Synclinal Ait Attab et Cuesta (El Garage) ; canyons et cascades d'Ouzoud, cascade Hawaï, Imi nifif, grotte, canyon de l'oued El Abid, sources de Tabounot et Zaouiat Tanghmalte - Pin d'Alep (forêt d'Entifa), oxycèdre, genévrier rouge ; Chêne vert, amandier, Singe magot
Instructions	Veuillez apporter une tenue de sport conforme à l'activité pratiquée + une bouteille d'eau pour maintenir l'humidité corporelle ; Amener des biscuits, dattes, fruits (frais, sec)

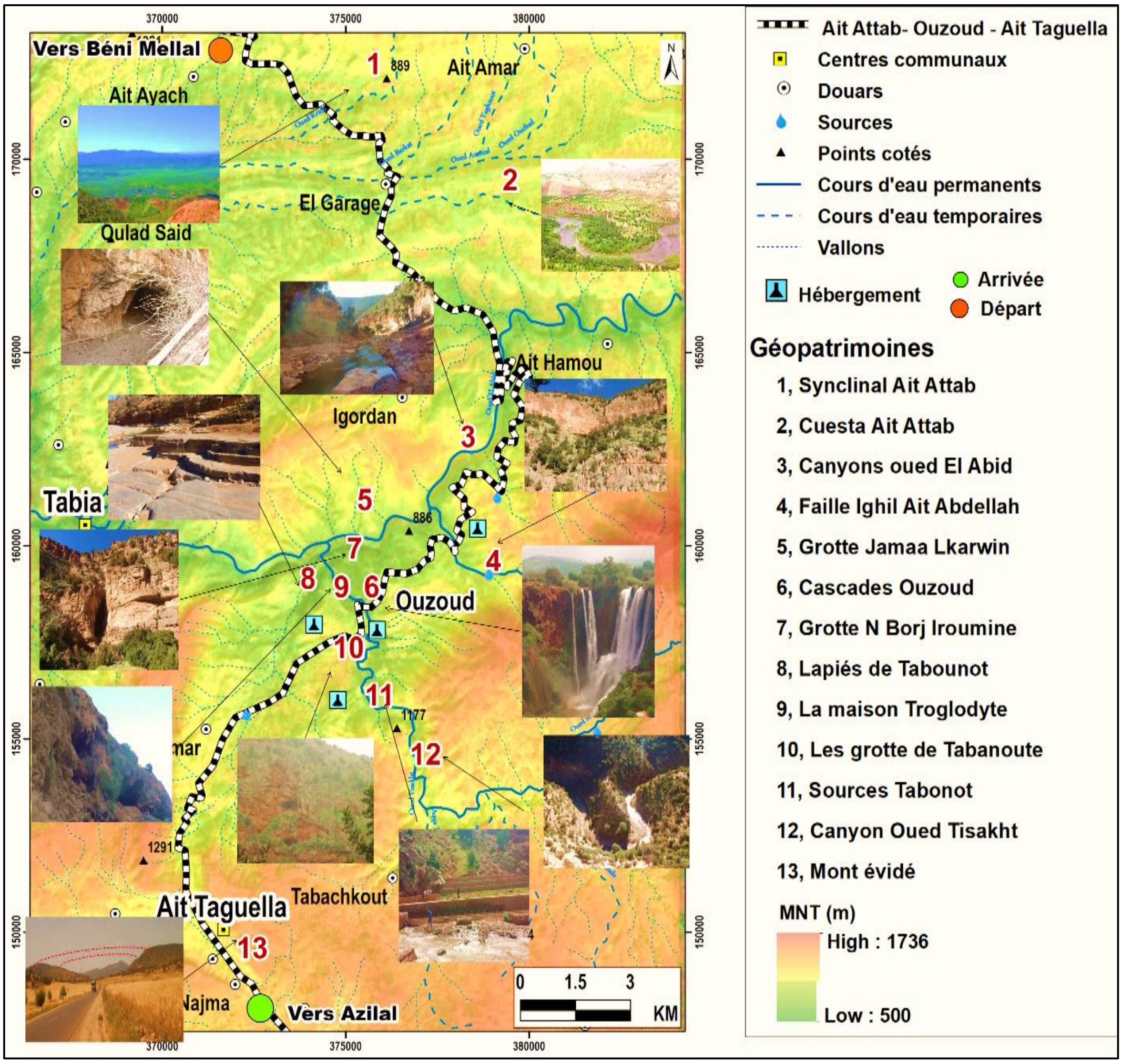

Figure 22. Sentier touristique d'Ait Attab-Ouzoud vers centre d'Ait Taguella
(MNT, 30 m USGS, 2024)

Quant à la cartographie géotouristique des géopatrimoines. Il s'agit d'un outil de médiation offrant des informations spatiales comme les infrastructures et les services locaux ou sur la présence d'autres points d'intérêts. Dans ce cas, les itinéraires et les sites sont visualisés sur une carte MNT et une carte topo (Tableau 3, Figure 22).

4. CONCLUSIONS

Cette contribution avait pour objectif d'identifier le potentiel géoscientifique et géotouristique de la zone d'Ait Taguella à travers une méthode scientifique quantitative développée à l'Université de Lausanne (2016). Cette méthode est rigoureuse et on obtient des fiches d'inventaire complètes qui constituent une base de données très riche. A la base de cette méthode, nous avons inventorié 23 géopatrimoines dans la commune Ait Taguella résultant de cinq processus : structural, fluvial, karstique, gravitaire, anthropique). Tous ces géopatrimoines nécessitent des procédures de gestion, géoconservation et de protection car ils constituent des objets géomorphologiques et géologiques de haute valeur patrimoniale. Cette évaluation des géopatrimoines sélectionnés montre clairement qu'ils ont une pertinence scientifique. Ils ont également un intérêt écologique particulier reflété par la réserve biologique d'Ouzoud. Sur le plan esthétique et scénique les qualités paysagères sont attrayantes liées notamment à la diversité des éléments paysagers avec un contraste de couleurs combinée (la végétation, l'eau, le ciel, la roche, le sol et les constructions). L'étude a également montré que le potentiel d'usage est remarquable à travers le développement des activités économiques et touristiques et le développement des activités sportives et de loisirs. Nous avons enfin abordé quelques pistes de valorisation en espérant que ce potentiel geopatrimonial peut être utilisé une ressource territoriale en avenir (Bétard et al., 2017).

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CINQ CONTINENTS
REVUE ROUMAINE DE GEOGRAPHIE

Volume 16 / Numéro 33
Été 2026
ISSN : 2247 - 2290
p. 109-123

The impact of European Funds in reducing the interregional economic disparities in Romania (2007-2023)

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Citer ce document :

VARGĂ, I. 2026. The impact of European Funds in reducing the interregional economic disparities in Romania (2007-2023).. Cinq Continents 16 (33): 109-123.

Cinq Continents Volume 16, Numéro 33, 2026, p. 109- 123

The impact of European Funds in reducing the interregional economic disparities in Romania (2007-2023)

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Impactul fondurilor europene în reducerea decalajelor economice între regiunile de dezvoltare ale României (2007-2023). Studiul de față abordează problematica decalajelor economice interregionale la nivelul României. Cercetarea acestui subiect ia în considerare perioada între momentul aderării României la Uniunea Europeană (2007) și anul 2023. Scopul acestei cercetări este analiza evoluției economice regionale și impactul absorbției fondurilor europene în reducerea disparităților economice între regiuni. Pentru evidențierea evoluției economice la nivel regional a fost calculat indicele dezvoltarii economice, un indicator agregat creat pe baza a trei indicatori macroeconomici definitorii: contribuția la PIB-ul național total a fiecărei regiuni, rata șomajului înregistrată și diferența între salariul mediu net regional și salariul mediu net național. Pentru elaborarea acestui studiu au fost utilizate următoarele metode: metoda studiului de caz, metoda analizei, metoda comparației, metoda cartografică și metoda analizei multicriteriale. Rezultatele cercetării au relevat o accentuare a ecartului economic între regiunile țării, pe alocuri valorile indicatorilor suferind deprecieri considerabile în raport cu anul 2007. Se constată o incapacitate a regiunilor emergente de a își îmbunătăți considerabil performanțele economice, în timp ce regiunile dezvoltate concentrează cele mai importante și cele mai valoroase activități economice din țară, conducând la amplificarea fenomenului polarizării economice excesive la nivel național.

Cuvinte cheie: decalaje economice, fonduri europene, PIB, regiuni de dezvoltare, România.

The impact of European Funds in reducing the interregional economic disparities in Romania (2007-2023). The current study approaches the economic disparities between the Romanian development regions. The research is taking into account the period between 2007 and 2023. The purpose of this paper is to assess the regional economic evolution and the impact of the European funds in reducing the economic disparities between development regions. In order to realize this desideratum, the economic development index was created, an aggregate index based on three major economic indicators, respectively the regional contribution to national GDP, the differences between regional average net salary and national average net salary, and the unemployment rate. The methodology utilized for this study consisted of case study method, analysis method, comparison method, cartographic method, and multi-criteria analysis. The results have revealed an accentuation of the economic disparities between regions, the indicators' values suffering, in some cases, significant impairments in 2023 compared to 2007. It is noticed a fundamental incapacity of the emergent regions to improve significantly their economic performances, while the already developed regions are getting much more developed, concentrating on the most important and valuable economic activities within the country, leading to amplification of the phenomenon of excessive economic polarization at the national level.

Keywords: development regions, economic disparities, European funds, GDP, Romania.

1. INTRODUCTION

The interregional economic disparities inside a country represent a current important topic in the European context, but not only. This concern regarding reducing the economic disparities between regions is confirmed by the important budget allocated by the European Union in order to solve this issue among European countries (Polster, 2021; Nyikos, 2022; Spilioti, Anastasiou, 2024; Oprea et al., 2025).

These interregional inequalities can have various causes, from objective factors such as natural barriers (mountain ranges, large rivers, etc.) to subjective factors, respectively the lack of strategic programs for regional development in common collaboration between regions.

These problems have been previously studied in the literature by different scientists from different fields, such as economy, geography, and sociology, at both national and international levels. The various case studies chosen by the authors, covering approximately all the European space (Central Europe, Eastern Europe, Western Europe, Southern Europe), show that this issue is not particular to a specific geographical area or a specific country. The common character of these economic inequalities is caused, usually, by the objective factors, especially the natural framework, which often prevents the interconnection of different regions through large and complex infrastructure network systems, namely highways and railways (Surubaru, 2020; Pietak, 2024; Moldovan, 2025; Kurek et al., 2026; Frangiamore et al., 2026;).

In Romania's case, this type of analysis is appropriate, especially for the emergent states located in the former Soviet space, due to the fact that there is a common background, which has generated similar economic and social deficiencies. These issues, caused by the same communist regime, have strongly delayed the economic transition of these states compared to the Western states, which led to a huge economic gap between Western and Eastern states (Dominy et al., 2026).

This study can provide an objective perspective of the trajectory that a new European Union member can have after 16 years, especially for the emergent states such as Republic of Moldova, Albania, North Macedonia, and others.

The purpose of this article is to assess objectively the impact of the European funds in reducing the interregional economic disparities in Romania. For achieving this desideratum have been established three relevant objectives for this analyze, respectively the regional contribution to national GDP, the unemployment rate, and the difference between the regional average net salary and the national average net salary. These objectives have been directly related to the absorption rate of European funds for each region in the current multiannual financial framework, 2021-2027.

The study has revealed direct connections between the absorption rate of European funds and the regional level of economic development throughout the time.

2. METHODOLOGY

The study analyzes the economic situation of Romania's development regions, which have only a role in providing statistics to the European Union's institutions. The eight development regions overlap approximately on the historical regions of Romania, respectively Transylvania (Centru region), Banat (Vest region), Moldova and Bucovina (Nord-Est region), Dobrogea (Sud-Est region), Oltenia (Sud-Vest Oltenia region), and Maramureș (Nord-Vest region).

The article highlights Romania's evolution from 2007 to 2023, divided into three main periods of time, entitled at the European Union's level multiannual financial framework: 2007-2013, 2014-2020, and 2021-2027 (European Parliament, 2026).

In order to elaborate this analysis were utilized the following methods: case study method, comparison method, and multi-criteria analysis (Greene et al., 2011; Chandio et al., 2012; Malczewski, Liu, 2014; Mrak, 2024). The multi-criteria analysis consisted of selecting three economic indicators, calculating specific rates for each region and then cumulating the results into an economic development index.

These three economic indicators selected for this study were: regional Gross Domestic Product (GDP), the differences between regional average net salary and national average net salary, and the unemployment rate. The regional GDP represents one of the most important indicators in creating an economic analysis, expressing the entire economic productivity of the region; the regional average net salary reflects the current economic status of the regions related to the national economy and the consumer spending power; the unemployment rate indicates the capacity of the region to integrate and capitalize current labor force in local economy (Breaz et al., 2025; Savariapitchai, Chaurasia, 2026).

For better understanding of the impact of the European Union funds in the national economy has been realized, a comparison between the total amount of money absorbed from the European Union and the total amount of investments with national funds has been realized. The sums have been transformed into a percentage share of national GDP. In order to convert the resulting sums in euro have been utilized the archive database provided by the National Bank of Romania for 2007-2023.

Based on these three economic indicators presented previously have been calculated the economic development index, in order to determine the economic evolution for each region (Table 1). These indicators were assigned different weights regarding their economic importance (Table 2). The highest weight was assigned to the regional GDP indicator (50%), followed by the indicator related to the difference between regional average net salary and national average net salary (30%), and the unemployment rate (20%).

Subsequently, each region was assigned a mark from 1 to 10 according to the value class regarding each indicator. Later, every result was calculated to the weight value assigned for each indicator, and then all the values resulted have been cumulate into one value, representing the economic development index.

These values were transposed into different maps, utilizing QGIS 3.28.3, in order to highlight the evolution between 2007 and 2023.

Table 1. Criteria utilized for the multi-criteria analysis and the scoring system

Criterion	Weight	Justification	Category (%)	Mark
Regional GDP	50%	Indicates the entire economic productivity of the regional economic activities	5 - 10	2.5
			10.1 - 15	5
			15.1 - 20	7.5
			20.1 - 25	10
Difference between regional average net salary and national average net salary	30%	Indicates the financial value of the economic activities and the consumer spending power	-15 - -10	2
			-10.1 - -5	4
			-5.1 – 0	6
			0.1 - 25	8
			25.1 - 38	10
Unemployment rate	20%	Indicates the capacity to integrate and capitalize the labour force	7.6 - 10	2.5
			5.1 – 7.5	5
			2.6 - 5	7.5
			0 – 2.5	10

Table 2. The scores resulted for each economic indicator

Region	Regional GDP		Net salary differences		Unemployment rate		Economic development index	
	2007	2023	2008*	2023	2007	2023	2007	2023
NORD-VEST	2.5	2.5	0.6	1.8	1.5	1.5	**4.6**	**5.8**
CENTRU	2.5	2.5	0.6	1.2	0.5	1.5	**3.6**	**5.2**
NORD-EST	2.5	2.5	0.6	1.2	1	1	**4.1**	**4.7**
SUD-EST	2.5	1.25	1.2	0.6	0.5	0.5	**4.2**	**2.35**
SUD-MUNTENIA	2.5	2.5	1.2	1.2	0.5	0.5	**4.2**	**4.2**
BUCUREȘTI-ILFOV	5	5	3	3	1.5	1.5	**9.5**	**9.5**
SUD-VEST OLTENIA	1.25	1.25	1.8	1.2	1	0.5	**4.05**	**2.95**
VEST	1.25	1.25	1.2	1.8	1	1.5	**3.45**	**4.55**

* unavalaible data for 2007

3. RESULTS AND DISCUSSION

In the period of the multiannual financial framework 2007-2013 European Union allocated Romania funds in total of 40,254,230,000 euro. Romania has absorbed 36,685,400,000 euro of this total amount of money (91.13%; Table 3).

In the following multiannual financial framework, 2014-2020, Romania has recorded a higher rate of funds absorption, 98.21%, contracting European projects in the amount of 51,571,190,000 euro out of a total sum of 52,509,170,000 euro.

In the current multiannual financial framework 2021-2027, the absorption rate is the lowest one considering previous financial periods, with only 31.55% absorbed of the total amount of money allocated by the European Union (50,531,330,000 euro).

Alongside these three major financial frameworks created by the European Union's institutions, it can be added the NextGeneration EU 2021-2023 project. Romania has benefited from 6,525,240,000 euro out of a total amount of 17,007,160,000 euro (Ministry of Finance, 2026).

In the period of 2007-2026 Romania has absorbed European funds in a total amount of 110,726,640,000 euro from a total amount allocated of 160,301,890,000 euro, representing an average absorption rate of 69.07%.

In the same period of time, Romania has contributed to the European Union's budget with 36,644,910,000 euro. Considering this financial contribution, it results in a net balance in Romania's favor of 74,081,730,000 euro in 2007-2026 (Ministry of Finance, 2026).

Table 3. The financial report of Romania, considering the EU funds received until 28.02.2026 (million euro)

Period of time	EU funds received	EU funds allocated for Romania	Absorption rate %
2007-2013	36,685.40	40,254.23	91.13
2014-2020	51,571.19	52,509.17	98.21
2021-2027	15,944.81	50,531.33	31.55
NextGeneration EU 2021-2023	6,525.24	17,007.16	38.37
Total (I)	110,726.64	160,301.89	69.07
Romania's contribution to EU budget 2007-2026 (II)	36,644.91	-	-
Net balance (I-II)	*74,081.73*	-	-

Source: Ministry of Finance, 2026

In the multiannual financial framework 2021-2027 European Union allocated to Romania 11,503,720,724 euro for financing the regional programs. The highest amount of money was distributed to the Nord-Est region (1,760,457,242 euro), and the lowest amount of money to the Vest region (1,179,093,826 euro). The other regions have received, on average, approximately 1,400,000,000 euro each (Table 4).

It is noticed low absorption rates especially for the regional projects, the average value recorded being 17.11% (Figure 1). The highest absorption rate is recorded in the Nord-Vest region, 24.94%, while the lowest rate is found in the Sud-Est region, 13.78% (Ministry of Investments and European Projects, 2026).

Table 4. EU funds received by each region in the multiannual financial framework 2021-2027 (euro)

2021-2027	EU funds allocated	Absorption rate %
PR NORD-EST	1,760,457,242	13.92
PR SUD-MUNTENIA	1,576,796,471	15.21
PR SUD-EST	1,488,071,059	13.78
PR NORD-VEST	1,437,252,471	24.94
PR CENTRU	1,384,456,339	15.95
PR SUD-VEST OLTENIA	1,211,128,522	15.73
PR VEST	1,179,093,826	19.91
PR BUCUREȘTI-ILFOV	1,466,464,794	20.35
Total	11,503,720,724	17.11

Source: Ministry of Investments and European Projects, 2026

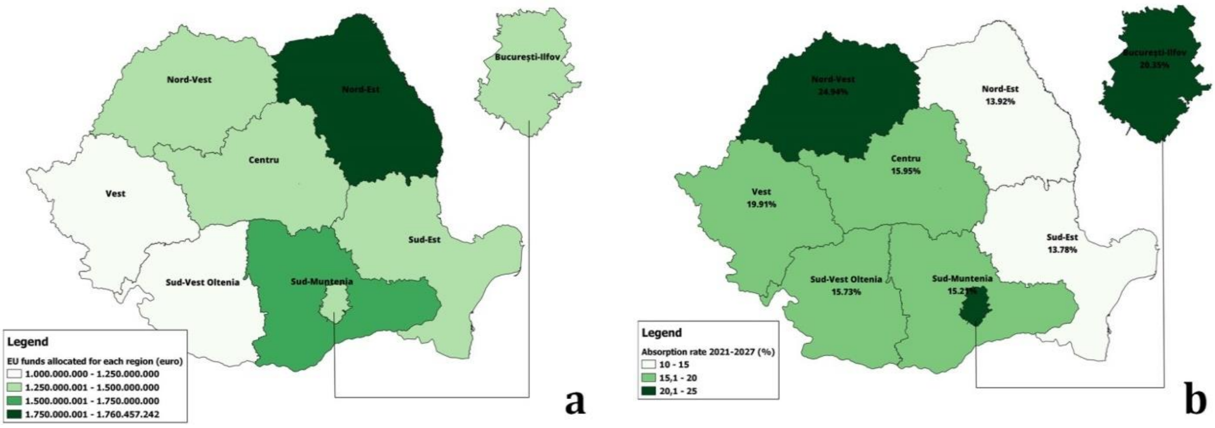

Figure 1. European funds allocated to each region (a) and their absorption rate (b)
Source: Ministry of Investments and European Projects, 2026

For better understanding of the importance and the economic dimensions of these amounts of money that Romania has benefited from, a comparison was made with investments realized from national funds in the same period of time (Table 5). Also, the sums invested were transformed into percentage points of the national GDP for each multiannual financial framework.

The economic analysis has revealed that investments made by European funds from 2007-2013 were 2.92 times higher than the investments made by national funds. In 2014-2020, the European funds absorbed were 3.27 times higher and, in 2021-2027, 1.39 times higher than national investments (National Institute of Statistics, 2026; Ministry of Finance, 2026).

In 2007-2026, the European investments have represented, on average, 2.60% of the national GDP, while the national investments have represented 1.29% of the national GDP (National Institute of Statistics, 2026; Ministry of Finance, 2026).

Table 5. Total investments realized with EU funds vs. total investments with national funds (billion euro)

Period	EU funds investments	% of national GDP	Investments with national funds	% of national GDP
2007-2013	36.6	3.86	12.5	1.32
2014-2020	51.5	3.92	15.8	1.20
2021-2027	15.9	1.88	11.4	1.35
NextGeneration EU 2021-2023	6.5	0.77	-	-
Total	110.7	-	39.7	-

Source: National Institute of Statistics, 2026; Ministry of Finance, 2026

In order to display the evolution of economic productivity to each Romania's development region, the regional GDP was calculated and related to the national GDP, in an attempt to observe precisely the contribution of each region (Table 6, Figure 2).

In 2007, the highest contribution to national GDP was recorded by the București-Ilfov region, 24.13%, while the Sud-Vest Oltenia region recorded the lowest contribution, only 7.99%. In 2007, excepting the București-Ilfov region, the other regions had an average contribution of 10.82% to national GDP, which means 2.22 times less than the value recorded by the București-Ilfov region (National Institute of Statistics, 2026; Figure 3).

In 2023, only two development regions increased their contributions, respectively Nord-Vest region (+0.26 percentage points) and București-Ilfov region (+4.85 percentage points). All the other regions have decreased their values between 0.22 and 1.73 percentage points compared to 2007. Sud-Vest Oltenia and Vest remained the economic negative poles, with the lowest recorded values, down compared to 2007, respectively -0.33 percentage points less, in the case of the Sud-Vest Oltenia region, and -0.88 percentage points, in the case of the Vest region. The biggest drop was recorded by the Sud-Muntenia region, -1.73 percentage points (National Institute of Statistics, 2026).

In 2023, excluding the București-Ilfov region, the other regions produced, on average, 10.14% of national GDP, representing 2.85 times less than the value recorded by the București-Ilfov region (28.98%).

The unemployment rate recorded percentage reductions in 2023 compared to 2007 in five of eight regions. The greatest improvements were recorded in the Vest region, -50%, and Centru region, -48.86%, while the Sud-Vest Oltenia region recorded the biggest rise in the unemployment rate, +25% (Table 7, Figure 4).

Table 6. The contribution of each region to the national GDP (million lei)

Region	2007		2023	
	Regional GDP	% of national GDP	Regional GDP	% of national GDP
NORD-VEST	51,229.1	12.03	195,580.5	12.29
CENTRU	50,452.4	11.85	179,095	11.26
NORD-EST	46,061.8	10.82	168,565.3	10.60
SUD-EST	45,984.3	10.80	150,855.2	9.48
SUD-MUNTENIA	52,803.9	12.40	169,747.9	10.67
BUCUREȘTI-ILFOV	102,709.8	24.13	461,034.7	28.98
SUD-VEST OLTENIA	34,016.8	7.99	121,820.7	7.66
VEST	42,057.9	9.88	143,150.3	9.00

Source: National Institute of Statistics, 2026

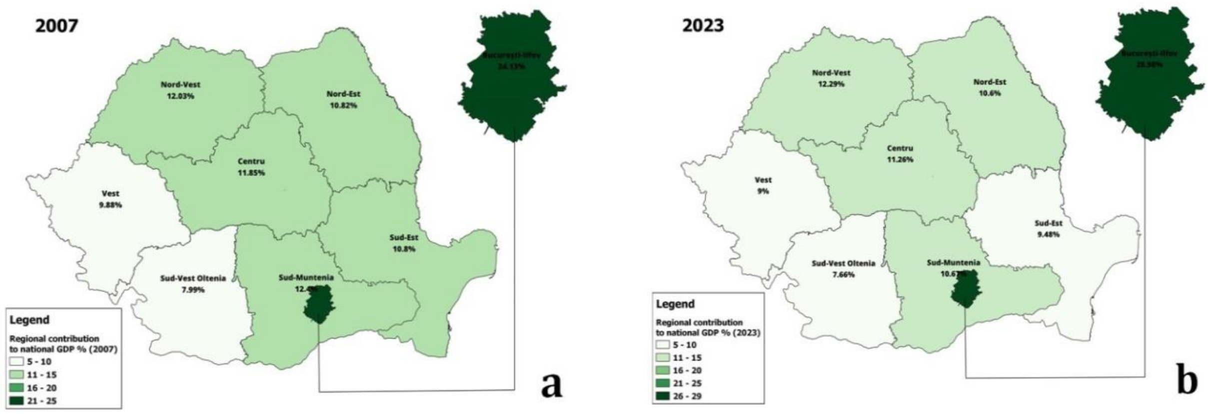

Figure 2. The contribution of each region to the national GDP, 2007 vs. 2023
Source: National Institute of Statistics, 2026

It is observed a direct correlation between high values of the unemployment rate and low values of the regional GDP. The highest unemployment rates were recorded in 2023 (higher than in 2007), in the Sud-Est region (9.1%) and the Sud-Vest Oltenia region (9%), the regions with two of the lowest contributions to the national GDP (National Institute of Statistics, 2026).

There are drawn two diametrically opposed development patterns of evolution between the inner regions which overlap to the historical regions of Transilvania, Banat, and Maramureș, and the regions from the Old Kingdom, respectively Oltenia, Muntenia, Moldova, and Dobrogea. The regions of Centru, Nord-Vest, and Vest have reduced the unemployment rate, on average, by 43.82% compared to 2007. The rest of the regions, excluding the București-Ilfov region, have raised their unemployment rate, on average, by 7.71%.

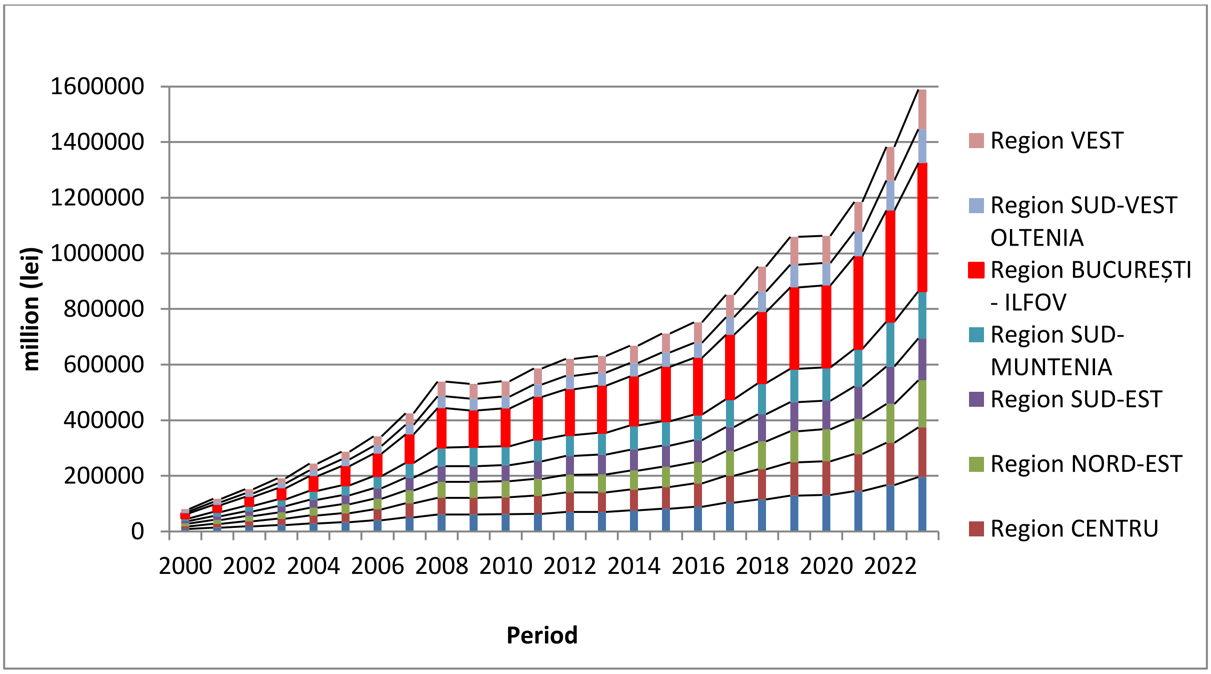

Figure 3. The evolution of regional GDP, 2000-2023
Source: National Institute of Statistics, 2026

Table 7. The unemployment rate recorded in each region

Region	2007	2023	Evolution %
NORD-VEST	4.6%	3.1%	-32.61
CENTRU	8.8%	4.5%	-48.86
NORD-EST	5.5%	5.9%	+7.27
SUD-EST	8.8%	9.1%	+3.41
SUD-MUNTENIA	8.3%	7.9%	-4.82
BUCUREȘTI-ILFOV	4.3%	2.8%	-34.88
SUD-VEST OLTENIA	7.2%	9.0%	+25.00
VEST	5.8%	2.9%	-50.00

Source: National Institute of Statistics, 2026

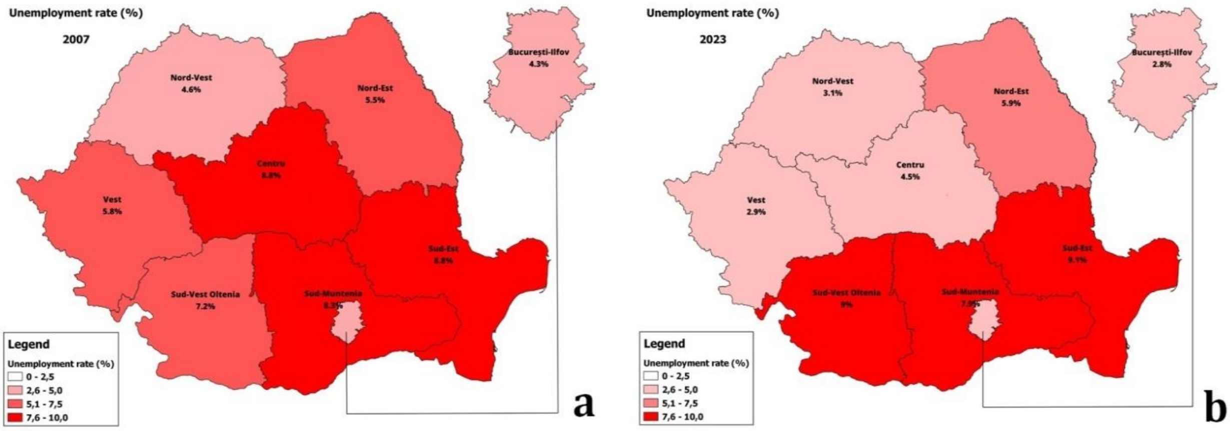

Figure 4. The unemployment rate in each region, 2007 vs. 2023
Source: National Institute of Statistics, 2026

The national average net salary has recorded major value increases in each development region in 2023 compared to 2008[1] (Table 8, Figure 5). The national average net salary has risen by 237%, representing a total sum of 4412 lei in 2023, 3103 lei more compared to 2008, 1309 lei (National Institute of Statistics, 2026).

Between 2008-2023, the regional average net salary has increased its value either. The greatest wage improvements were recorded in the Nord-Vest region, 274.43%, Centru region, 255.57%, while the Sud-Vest Oltenia has recorded the lowest increase among all regions, 202.62% (National Institute of Statistics, 2026).

In 2023, the greatest regional average net salary was recorded in the București-Ilfov region, 5842 lei, and the lowest was recorded in the Sud-Est region, 3733 lei.

In 2008, the București-Ilfov region recorded a net salary of 38.27% higher than the national average value. All the other regions recorded values below the national average value, and this situation continues in 2023.

In 2023, the economic disparities increased in the following regions: the Sud-Vest Oltenia region (from -3.74%, in 2008, to -13.58%, in 2023), the Sud-Est region (from -9.09%, in 2008, to -15.39%, in 2023), and the Sud-Muntenia region (from -6.80%, in 2008, to -11.67%, in 2023).

Table 8. Regional average net salary (lei)

Region	2008	2023	Evolution %
NORD-VEST	1119	4191	+274.53
CENTRU	1150	4089	+255.57
NORD-EST	1155	3914	+238.87
SUD-EST	1190	3733	+213.70
SUD-MUNTENIA	1220	3897	+219.43
BUCUREȘTI-ILFOV	1810	5842	+222.76
SUD-VEST OLTENIA	1260	3813	+202.62
VEST	1207	4250	+252.11

Source: National Institute of Statistics, 2026

Considering the economic indicators that have been calculated previously, the economic development index has been calculated in order to display precisely the evolution of each region from 2007/2008 to 2023 (Figure 6).

It can be observed a general improvement of the economic parameters at the national level, except for the particular cases of the Sud-Vest Oltenia region and the Sud-Est region, which have recorded major decreases in 2023 compared to 2007. The Sud-Vest Oltenia region has recorded a decrease of 27.16%, in 2023, and the Sud-Est region has recorded a decrease of 44.04% in the same year.

[1] unavailable data for 2007

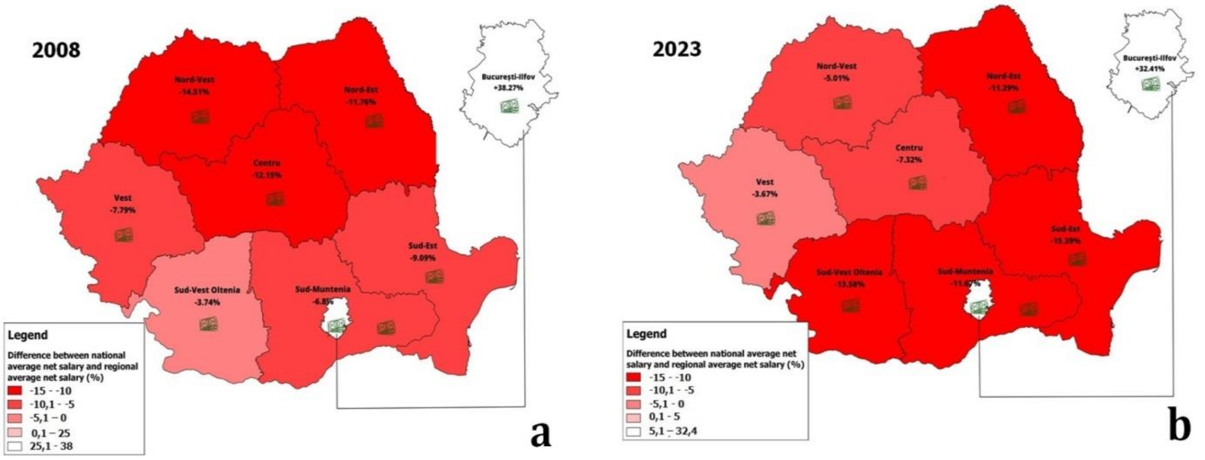

Figure 5. The difference between the regional average net salary and the nation average net salary, 2008 vs. 2023
Source: National Institute of Statistics, 2026

The regions Sud-Muntenia and București-Ilfov have stagnated, while the Nord-Vest, Centru, Nord-Est, and Vest regions have improved their index value.

The greatest index improvement was recorded by the Centru region, 44.44%, followed by the Vest region, 31.88%, then the Nord-Vest region, 26.08%, and the Nord-Est region, with a raise of 14.63%.

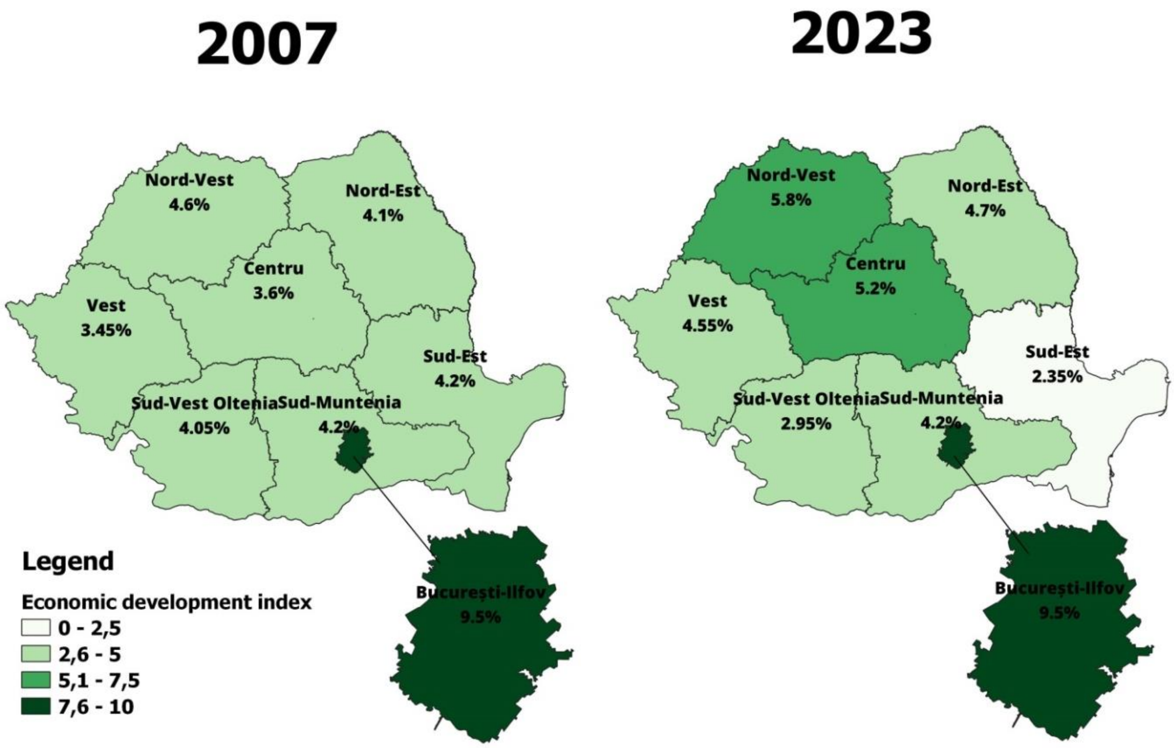

Figure 6. The economic development index comparison between 2007 and 2023
Source: own elaboration

4. CONCLUSIONS

It can be observed a direct correlation between the absorption rate of European funds and the level of improvement of the economic indicators taken into account for the analysis. This fact is confirmed by the positive trajectory of the regions as Centru, Vest, and Nord-Vest, which, despite the fact that they have benefited from considerably fewer funds for implementing regional projects in 2021-2027 compared to other regions, have reached better results due to the better absorption rate and the better use of these funds.

The study reveals a general improvement of the economic condition at the regional level, but it displays the accentuation of the interregional economic disparities throughout the time. The București-Ilfov region has increased its economic importance and clarified its role as the major economic pole at national level to the detriment of the other regions and other major cities.

It is noticed a precarious economic condition especially in the regions that are under the Bucharest's influence, such as Sud-Muntenia, Sud-Vest Oltenia, and Sud-Est. These regions record the lowest economic values on each indicator assessed, and, more important, these record a strong decrease in economic terms.

The major economic disparities between the București-Ilfov region and the rest of the regions highlight fundamental issues within the settlement system of Romania. University urban centers, excluding the capital city, cannot fully accomplish their territorial and economic role of assuring the territorial balance at the national level. These major cities cannot act as real urban poles in order to attract strong, diversified, and high-value economic activities in order to reduce the migration and to attract the young categories inside the surrounding counties to the city. This incapacity of developing their economic potential leads directly to intensifying the capital's congestion and increasing the level of hypertrophy. The demographically unbalanced territorial distribution contributes later to these economic disparities between regions.

The study reveals the fact that regional development fundamentally depends on the high rate of European funds absorption, considering the low amounts of money allocated for investments from the national budget. The dependency is confirmed by the situation in the current multiannual financial framework (2021-2027), where the regions with the lowest economic performances (Sud-Vest Oltenia, Sud-Muntenia, and Sud-Est) could not compensate for the low absorption rates with national funds for investments.

Therefore, it can be concluded that the European funds have represented essential financial instruments in the evolution of each development region since the beginning, helping in real terms to improve the general economic context. Nevertheless, these funds could not avoid the raising of the economic disparities between regions.

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CINQ CONTINENTS
REVUE ROUMAINE DE GEOGRAPHIE

Volume 16 / Numéro 33
Été 2026
ISSN : 2247 - 2290
p. 124-145

The dynamics of industrial activities in Galați, Romania

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Sommaire :

Citer ce document :

AJDER, Ș.-S. 2026. The dynamics of industrial activities in Galați, Romania. Cinq Continents 16 (33): 124-145.

The dynamics of industrial activities in Galați, Romania

Ștefania-Silvia AJDER

Dinamica activităților industriale în municipiul Galați, România. Dinamica dezvoltării industriale în România a fost puternic afectată de efectele negative ale procesului de dezindustrializare post-comunistă, remarcându-se dificultăți de redresare economică. Scopul acestui articol este de a analiza evoluția industriei municipiului Galați în perioada post-decembristă și impactul acesteia asupra dezvoltării economice și sociale a orașului. Metodologia de analiză a inclus prelucrarea datelor statistice și demografice privind evoluția populației și structura economică a municipiului Galați, precum și analiza informațiilor referitoare la dezvoltarea principalelor ramuri industriale reprezentative. Rezultatele au evidențiat o scădere semnificativă a activităților industriale după 1990, însoțită de pierderea locurilor de muncă și de transformări sociale importante în municipiul Galați. Concluziile analizei arată faptul că procesul de dezindustrializare a condus la șomaj de lungă durată și declin socio-economic, fiind necesare noi investiții și dezvoltare durabilă a economiei locale.

Cuvinte cheie: industria siderurgică, dezindustrializare, industria navală, dezvoltarea economică durabilă, Galați.

The dynamics of industrial activities in Galați, Romania. The dynamics of industrial development in Romania have been strongly affected by the negative effects of the post-communist deindustrialization process, highlighting significant difficulties in economic recovery. The aim of this article is to analyze the evolution of industry in the municipality of Galați during the post-1989 period and its impact on the city's economic and social development. The methodology included the processing of statistical and demographic data regarding population trends and the economic structure of the municipality of Galați, as well as the analysis of information related to the development of the main industrial branches. These were completed by field observations of representative industrial sites. The results highlight a significant decline in industrial activities after 1990, accompanied by job losses and major social transformations in the municipality of Galați. The conclusions of the analysis indicate that the deindustrialization process has led to long-term unemployment and socio-economic decline, making new investments and the sustainable development of the local economy necessary.

Keywords: steel industry, deindustrialization, shipbuilding industry, sustainable economic development, Galați.

1. INTRODUCTION

A degraded environment is defined as a natural area composed of elements such as water, air, soil, and living organisms, whose characteristics have been altered due to anthropogenic interventions, thereby affecting the ecosystem's ability to function optimally (Iojă, 2013; Zia-ur-Rehman et al., 2016). The imbalances thus created within ecosystems are an imminent consequence of environmental degradation and represent a major issue faced by 21st-century society. On one hand, economically developed countries aim to improve this situation by embracing the concept of sustainable development, which involves meeting the current needs of society without compromising the ability of future generations to meet their own (Brundtland Commission, 1987). On the other hand, however, these same countries continue to base their national economies on consumerism and heavy or extractive industries (highly polluting sectors) by significantly increasing investments in primary sector activities that involve the exploitation of natural mineral resources (Wei et al., 2020).

As a result of global population growth and the continuous development of human civilization, particularly in technological and economic terms, environmental issues have become increasingly pronounced. These include climate change, the depletion of natural resources, pollution, and the disruption of geospheres balance (Sodiq et al., 2019; Manzoor et al., 2025). The scale of these challenges lies in the fact that they are not confined to specific regions of the world, but are instead the cumulative outcome of local anthropogenic actions. When such actions become more frequent and impactful, their consequences can escalate to national, regional, and even global levels (Tal, 2025). In response to these challenges, the United Nations (2025) has established the Sustainable Development Goals (SDGs), which serve as a global framework for addressing environmental, social, and economic issues. Notably, *SDG 12 – Responsible Consumption and Production* outlines key actions such as achieving the sustainable management and efficient use of natural resources, reducing the release of harmful chemicals into the environment, and promoting awareness of sustainable development and lifestyles in harmony with nature (United Nations, 2023). Furthermore, SDG 12 is closely interconnected with other goals that address environmental integrity and biodiversity, including *SDG 13 – Climate Action, SDG 14 – Life Below Water,* and *SDG 15 – Life on Land*. Together, these goals emphasize the need for integrated and coordinated efforts to ensure the long-term sustainability of natural systems and the well-being of future generations.

Limestone quarrying practices vary significantly across the globe, influenced by factors such as a country's economic development, mining legislation, and the geological characteristics of the deposits (Carrasqueira et al., 2024). As noted by Oates (1998), the majority of limestone extraction is conducted through open-pit operations. In economically advanced nations like Poland, commonly employed methods include excavation, drilling, and blasting. These traditional techniques are increasingly integrated with modern technologies, such as digital mapping using Geographic Information Systems (GIS), and the implementation of comprehensive reclamation plans designed for post-extraction site restoration (Kaźmierczak, Strzalkowski, 2019). In the United Kingdom, collaborative initiatives between geoconservationists and the mineral extraction industry further enhance sustainable practices, ensuring that geoconservation is considered throughout the quarrying lifecycle, from initial development to final restoration (Prosser, 2018).

Brazil, although classified as a middle-income country, serves as a notable example of integrating biodiversity offset strategies within limestone quarrying operations (Souza, Sánchez, 2018). The country combines conventional extraction methods with advanced technologies such as controlled blasting and diamond wire cutting. The latter is particularly valued for its precision and reduced environmental impact and is supported by favorable tax policies under Brazilian law (The Federal Government of Brazil, 1992). In contrast, developing countries like Algeria, where limestone quarrying plays a vital role in economic development, continue to rely heavily on traditional methods involving large-scale blasting and drilling machinery. As a result, Bendouma and Vapur (2020) advocate for the adoption of sustainable development principles to mitigate the environmental consequences associated with these practices.

Based on this premise, it becomes evident that, in Romania and beyond, a pressing environmental issue is the exploitation of natural resources without adequate consideration for their impact on the geospheres or the principles of sustainable development. Among the most frequently exploited and utilized solid mineral resources at the national level is limestone, which holds a long-standing history in Romania. The limestone extraction and processing industry reached its peak during the communist regime, largely due to the material's wide range of uses in everyday life and its economic value (Ministry of Geology and Geology and Geofizic Institute, 1983; Fodor, Georgescu, 2023; Carrasqueira et al., 2024). According to the most recent statistical data published by the European Union regarding the total number of limestone quarries across member states, there were 26,449 quarries recorded in 2012. Among EU countries, Romania ranked 10th, with a total of 1,225 limestone quarries (Eurostat, 2012).

The process of limestone extraction in Romania varies according to the physical and geological characteristics of the rock, as is showed in other studies regarding the rock characteristics (Carrasqueira et al., 2024). In the case of underground mining, limestone is obtained through conventional mining techniques, whereas surface quarrying typically involves the use of explosives to dislodge the material (Ministry of Environment Waters and Forests, 2020). As such, both the extraction and processing of limestone entail not only economic considerations but also significant social and environmental ramifications. Behind the economic benefits associated with limestone extraction lies the environmental cost of polluting an entire geographical area, encompassing both the quarry perimeter and its surrounding landscape. Pollution may occur not only during the active phase of exploitation but also persist after operations have ceased (Manea et al., 2014; Fodor, Georgescu, 2023). In Romania, it is common for quarries to be abandoned once extraction is halted, whether due to economic non-viability, natural events that hinder operations, or the depletion of the resource (Buta al., 2019). Although national legislation provides for a formal decommissioning and land restoration process to be undertaken by the operator, the effective implementation of these measures requires systematic monitoring and the enforcement of penalties in cases of non-compliance (Romanian Parliament, 2003).

Accordingly, the present study was conducted with reference to the local context, focusing on the Bistrița limestone quarry located in Vâlcea County, Romania. This site was selected as the research area in order to identify the issues related to the exploitation of natural limestone resources, as well as the ecological imbalances and adverse effects on the local community. Within this framework we focused on two main objectives: (1) to assess the environmental impact of limestone quarrying, with a focus on both natural environmental components and the anthroposphere, and (2) to explore potential sustainable solutions for environmentally degraded areas resulting from extractive activities.

2. METHODOLOGY

2.1. Study area

For the present study, the selected research area is the Bistrița-Costești limestone quarry, located in the northern part of Costești commune, Vâlcea County, Romania. The quarry is situated on the southern slope of the Arnota Massif, which lies in the southeastern sector of the Căpățânii Mountains, part of the Parâng Mountain Group within the Southern Carpathians. The Arnota Massif is primarily composed of Jurassic limestone, while its foothills feature Cretaceous and Paleogene sediments, indicating the presence of significant limestone resources (Ministry of Environment Waters and Forests, 2016). The quarry is located adjacent to the southern boundary of Buila-Vânturarița National Park, a nationally protected natural area classified as an IUCN Category II site, established in 2004. This park overlaps with Natura 2000 Network ROSCI0015 Buila-Vânturarița and ROSPA0025 Cozia-Buila-Vânturarița (Figure 1), as well as with several designated nature reserves (Romanian Government, 2004).

According to Făulete (1977), limestone extraction at the Bistrița-Costești quarry began in 1942, initiated by a private enterprise that installed a crusher for mosaic and filler production, sourcing raw material from the surrounding massif. The crusher was powered by a water turbine and operated by a team of 12 workers, producing approximately 8 tons of mosaic daily. In 1954, systematic extraction and processing of limestone commenced at the quarry, and by 1957, the operations were mechanized. Automation led to a reduction in the workforce by half, an increase in production capacity, and the expansion of mosaic distribution at the national level. The quarry was officially established in 1960 by order of the communist regime, which at the time prioritized the development of primary sector industries such as agriculture, heavy industry, and extractive activities. The primary objective of the quarrying operations was the extraction and processing of limestone for local use, particularly in the chemical industry, construction (e.g. limestone mosaic, filler), and asphalt mixtures. In 1965, the quarry was taken over by a state-majority-owned company, which succeeded in increasing production between 1970 and 1974. From 1976 to 1980, further investments were made in equipment and machinery to enhance production capacity (Figure 2).

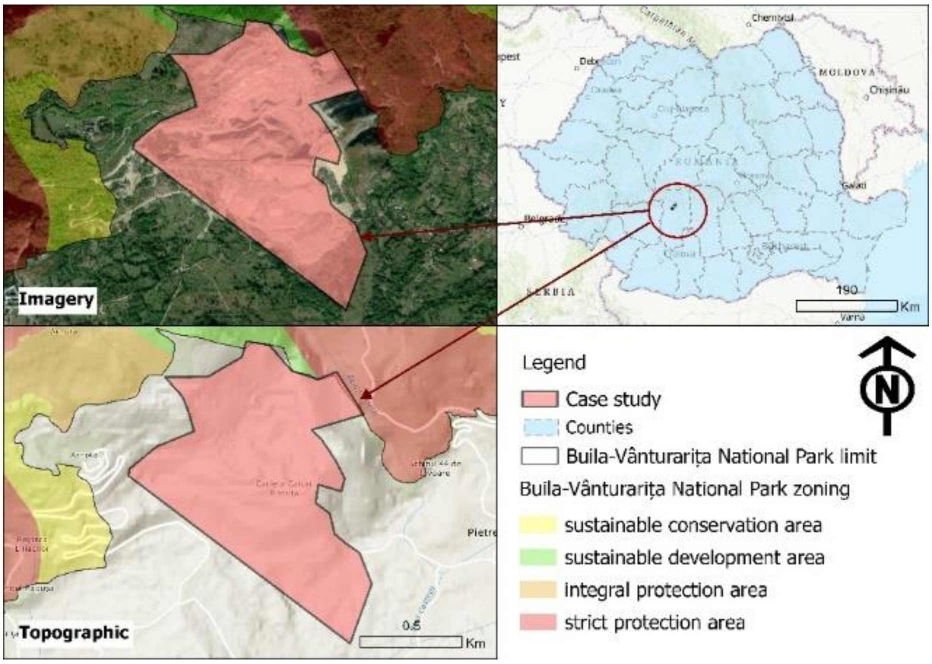

Figure 1. Location of Bistrița limestone quarry – study area

According to the former administrator of Buila-Vânturarița National Park, at the time of the park’s establishment, the quarry was operational and partially overlapped with the park’s territory. The extraction activities were conducted under an authorization issued in 2000 (Table 1).

However, following the designation of the new protected natural area, operations within the park boundaries were suspended. Subsequently, upon the expiration of the operating permit in 2020, the quarry ceased all activity entirely, as the exploitation costs were no longer economically viable (Kogayon Association, 2016).

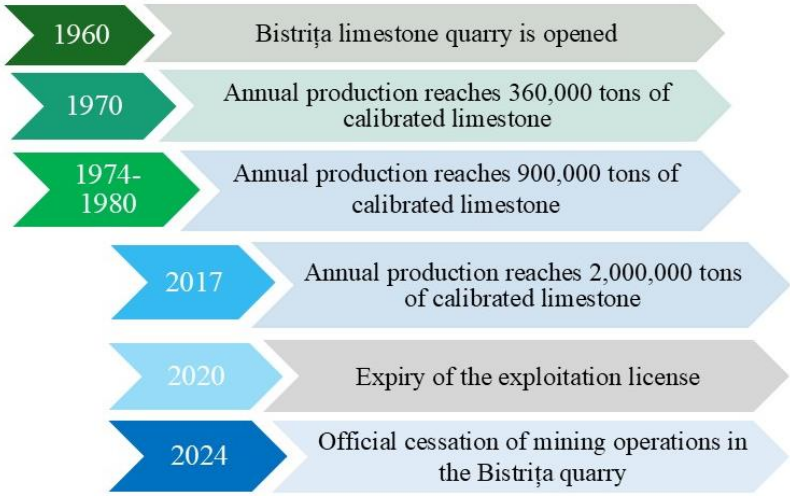

Figure 2. Exploitation evolution for Bistrița limestone quarry
Source: post-processing after Făulete (1977) and Costești Local Council (2024)

Table 1. The legal framework for the operation of mining exploitation of Bistrița limestone quarry

N°	Legal document issuer	Legal document	Document name
1.	Romanian Government (2000)	Government Decision no 652/2000	Regarding the approval of the Exploitation License no. 633/1999 issued by the National Agency for Mineral Resources
2.	Romanian Parliament (2003)	Law no 85/2003	Mining Law, as amended and supplemented
3.	Romanian Government (2003)	Government Decision 1208/2003	On the approval of the Norms for the application of the Mining Law No. 85/2003
4.	National Agency for Mineral Resources (2014)	Technical Norms	In the field of mineral resources exploitation

Source: post-processing after Kogayon Association (2016)

2.2. Study design

In order to achieve the proposed objectives, a methodology was applied that focused on three main types of activities: (1) content analysis of documents from the academic literature (scientific articles), public administration sources (official documents, legislation, reports, ordinances), and media outlets (online press articles);

(2) a comparative analysis of the environmental, economic, and social impacts before and after the quarry's exploitation activities; and (3) field observations aimed at data collection and validation of findings identified through document analysis, where relevant.

The documents were identified using keyword searches conducted via the Google search engine and the ScienceDirect database. The keywords used included: "Bistrița-Costești quarry", "limestone exploitation Bistrița-Costești," and "environmental impact limestone quarry", in both Romanian and English. Based on the search results, the materials were reviewed, and relevant information was extracted through content analysis. Documents whose subject matter did not align with the scope of the research were excluded from the analysis.

From the perspective of content analysis, several key aspects relevant to the study were identified, namely: *part 1 impact assessment*: (a) the domain affected (environmental, economic, or social); (b) the type of impact (positive, negative); (c) the duration of the impact (temporary, permanent); and (d) a description of the impact and *part 2 sustainable solutions*: (a) potential solutions, (b) description of the solutions, (c) advantages of the solutions and (d) disadvantages of the solutions. The analysis was conducted on 30 scientific articles, 14 public administration sources and 5 press articles. In addition, other data sources (both spatial and statistical) were used to support and complement the analysis (Table 2).

Table 2. Data sources used in the study

N°	Data	Year	Type of data	Source
1.	Protected areas limits	2024	Spatial	Ministry of Environment Waters and Forests (2024b)
2.	Species and habitat distribution	2024	Spatial	Ministry of Environment Waters and Forests (2024)
3.	Limestone quarry limits	2020	Spatial	National Agency for Cadastre and Real Estate Advertising (2020)
4.	Statistics about the industry of quarrying in the European Union	2012	Statistical	Eurostat (2012)

Also, the present study relied on direct field observations, photographic documentation, and field notes to identify and describe the visible environmental impacts caused by limestone extraction activities. These qualitative records provided valuable insights into the degradation of the natural landscape, the disruption of local ecosystems, and the presence of pollution indicators (the type, duration and description of the impact). Field visits for conducting direct observations were carried out during the period of March-April 2025. The collected data were compiled and processed using Microsoft Excel, while graphical elements were created with Microsoft PowerPoint (Microsoft, 2019). For map production, ArcGIS Pro 3.2.1 software was employed (ESRI Inc., 2023).

3. RESULTS

The analysis of the impact generated by quarry exploitation focused on the three main pillars of sustainability (environment, economy and society) detailing the specific aspects that comprise each one of them (Table 3). Furthermore, in the context of sustainable development, the United Nations has established a framework for assessing sustainability through key issues, represented by the Sustainable Development Goals (SDGs). In our study, the analysis is centred on *SDG 12*, which is closely linked to natural and environmental implications and how these are affected. Additionally, three other SDGs are considered complementary within our analysis, based on the identified impacts: *SDG 13, SDG 14,* and *SDG 15.*

Table 3. Key aspects for assessing impact of limestone quarry exploitation

N°	Impact	Domain	Type	Duration	Description
1.	Changes in the relief	Environment	Positive	Temporary	Calcareous substrate, raw material
2.	Exokarst	Environment	Positive	Permanent	Karst valley with gorges, limiting the area of exploitation
3.	Landslides	Environment	Negative	Permanent	Stripping, blasting and excavation, land instability, tailings dumps
4.	Soil pollution/ degradation	Environment	Negative	Permanent	Silica (SiO_2), alkaline dust, sulfur oxides (SOx), nitrogen oxides (NOx), tailings dumps, infertility
5.	Water pollution	Environment	Negative	Permanent	Turbidity, pH, methane (CH4), sulphur oxides (SOx), phenols, zinc (Zn), copper (Cu). lead (Pb)
6.	Air pollution	Environment	Negative	Permanent	Particulate matter ($PM_{2.5}$, PM_{10}), carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), silica (SiO_2), nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), ammonia (NH_3)
7.	Noise pollution	Environment	Negative	Temporary	Explosions, heavy machinery
8.	Vibration pollution	Environment	Negative	Temporary	Explosions, heavy machinery
9.	Proximity	Environment	Negative	Permanent	Exploited area (1,161 km^2 and 200 m

N°	Impact	Domain	Type	Duration	Description
					depth)
10.	Conflicts	Environment	Negative	Temporary	Functional incompatibility with the national park and Arnota monastery
11.	Biodiversity	Environment	Negative	Permanent/ Temporary	Loss of species and habitats, reduction in the range of species and habitats, damage to the conservation status of species and habitats
12.	Production capacity	Economic	Positive/ Negative	Temporary	From 360,000 tons per year in 1970 to 900,000 tons per year in 1989 and to 2 million tons in 2017, permanently closed in 2024
13.	Local investments	Economic	Positive	Permanent	Developed infrastructure through railways, road network for transporting products
14.	Funds to the local budget	Economic	Positive	Temporary	Payment of local taxes and fees
15.	Job reduction	Economic	Negative	Temporary	Approximately 400 people were laid off
16.	Affected communities	Social	Negative	Temporary	Approximately 30,000 people were affected
17.	Illnesses	Social	Negative	Permanent	Silicosis, respiratory diseases

From the environmental point of view, the results of the study indicate that limestone exploitation at the Bistrița quarry has significantly degraded environmental components, including biodiversity, water, air, soil. The Vâlcea County Local Action Plan (Vâlcea Environmental Protection Agency, 2021) reports major ecological alterations in the Arnota Massif, with the quarry spanning 161 hectares and reaching depths of 200 meters. Tailings make up approximately 40% of extracted material, leading to landscape transformation and visual pollution.

Anthropogenic disturbances, such as blasting and excavation, have triggered erosional and gravitational processes, increasing land instability and the risk of landslides (Adevărul, 2010; Stringfield, Rapp, 1976; Ekmekci, 1993; LaMoreaux, Powell, LeGrand, 1997), notably in 1970 and 1972. These events altered the course of Costești Creek, necessitating hydraulic regulation. In 2024, stabilization of hazardous tailings dumps was undertaken (Făulete, 1977). Unstable tailings dumps have been identified as potential contributors to such hazards. In response, stabilization works were undertaken in 2024 to mitigate these risks (Costești Local Council, 2024).

Pollutants from quarrying operations, including silica, SO_x, NO_x and alkaline dust, contribute to soil degradation (altering pH and reducing fertility) and water contamination (pH, turbidity, chemical composition) (Chenot et al., 2018). Disruption of hydrological and physicochemical conditions affects biodiversity and human health

(Fugiel et al., 2017). Water and soil quality are further compromised by chemical emissions such as CH_4, phenols, Zn, Cu, and Pb. The impact is not only at local level, but regional because of the potential of the contamination of soil and then the infiltration to the groundwater which has effects to a higher zone than the exploited one (Mouloudi et al., 2025).

Quarrying processes, including blasting, crushing, excavation, and transportation, also contribute to air pollution that is exacerbated by emissions of CH_4, CO_2, CO, particulate matter ($PM_{2.5}$, PM_{10}), and various nitrogen compounds (European Environment Agency, 2024). Noise from drilling and transport, as well as vibrations from blasting, disrupts local fauna (Oggeri et al., 2019; Nesticò et al., 2024). Blasting operations in quarries affect the environment in five distinct ways: through the propagation of seismic waves, air shock waves, the ejection of fragmented rock, the release of dust, and the emission of gases (Fodor, 2006).

Ecologically, quarrying reduces photosynthetic activity and biomass production, degrades habitat quality, and threatens protected species such as plants, herpetofauna (*Bombina variegata*), chiropters and large mammals (*Ursus arctos, Lynx lynx, Canis lupus* - Figure 3; Kogayon Association, 2016; Ministry of Environment Waters and Forests, 2016). Studies showed that this kind of activities have a medium impact on plants and faunal population (Pop et al., 2025). Sustainable management practices are imperative to mitigate these impacts and uphold biodiversity conservation within national and international frameworks.

From the economic point of view, limestone extraction at the Bistrița quarry has fostered notable development in the Costești commune, particularly through improved transportation infrastructure (roadway and railway). Production increased from 360,000 tons in 1970 to 2 million tons by 2017 (Costești Local Council, 2024), that created several key benefits include revenue generation, budgetary contributions, and affordable construction materials. However, these gains entail considerable environmental costs. Pollution has extended beyond the quarry, and conflict has arisen due to its proximity to Buila-Vânturarița National Park and Arnota Monastery. A proposed 2008 expansion, requiring reclassification of 29 hectares, highlighted this tension (environmental conflicts), leading to partial rezoning as a sustainable development area (Kogayon Association, 2016; Mitrache, 2018). The ongoing unsustainable use of non-renewable resources underscores the need for responsible practices. Operationalizing SDG 12 through localized initiatives is crucial to ensure long-term environmental equity and resilience for future generations.

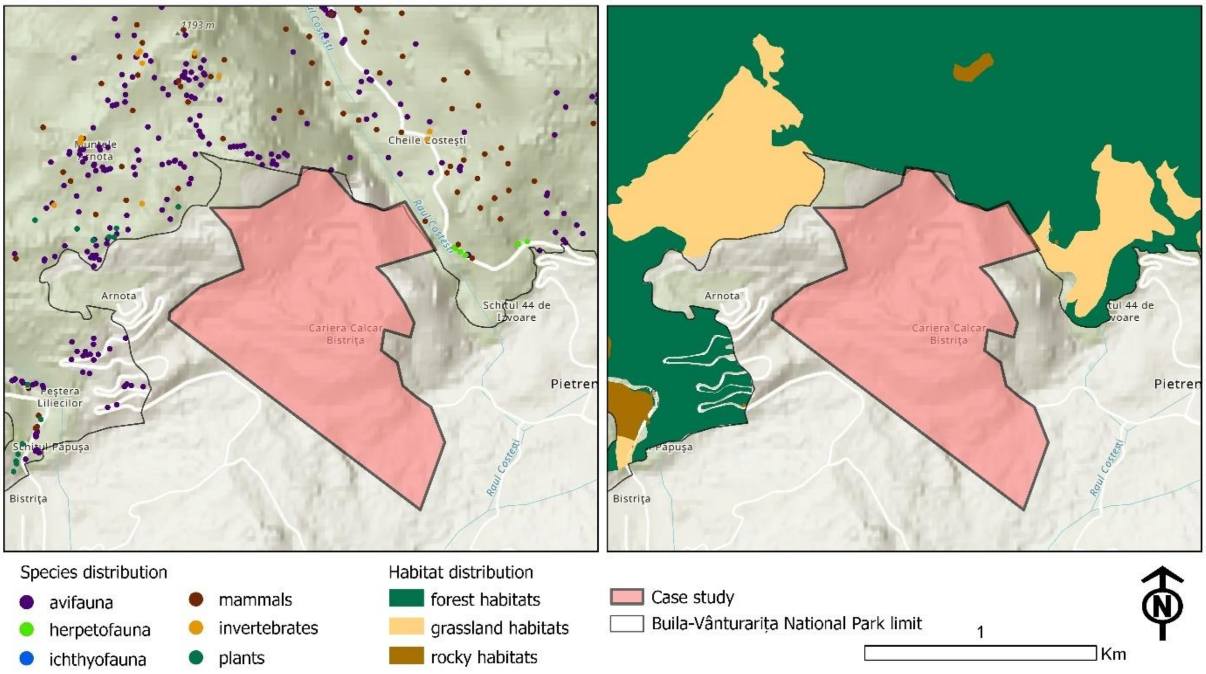

Figure 3. Species and habitat distribution in Buila-Vânturarița National Park near the case study

From the social point of view the results show that limestone exploitation at the Bistrița quarry has had more adverse than beneficial effects on the local population of Costești (Poiană, 2024). Sociological surveys confirm the significant socio-economic impact of the quarry's closure, both at the local and county levels. The cessation of operations resulted in widespread job losses among direct employees and subcontractors, affecting approximately 30,000 individuals when including their families (Befu, 2017).

Beyond economic repercussions, the quarrying activities have also had serious public health implications. Airborne particulate matter (dispersed by wind or released during the transportation of limestone) has posed long-term health risks to the local population (Costești Local Council, 2024; Poiană, 2024). Prolonged exposure to fine dust particles containing silica has been linked to severe respiratory illnesses (Fugiel et al., 2017; Nesticò et al., 2024). According to a former quarry worker numerous of his colleagues have reported suffering from pulmonary conditions, with silicosis being the most prevalent disease attributed to the inhalation of silica-laden dust.

4. DISCUSSION

Considering the European and the national legislation, we need to have an Environmental Impact Assessment (EIA) for any kind of resource exploitation. As Lee et al. (2024) show in their study, the quarry lifecycle creates a cause-effect chain, that is not limited only on the environmental aspects such as noise, pollution, aesthetics, geomorphology, air, water, soil etc. but also have implication on the human wellbeing ecosystem (healthy, safety, infrastructure).

All of the sustainability domains are impacted mostly negative and for a long term by the quarry exploitation practices, but we need to take in consideration to improve this kind of activity if we want a more positive impact rather than a negative one (Nesticò et al., 2024). When we cannot improve the exploitation and we are in the last cycle of the exploitation we should use different kind of solution to make it sustainable and with less impact on the environment.

The current state of the quarry indicates an abrupt closing of operations, with the potential for resumption pending license renewal. The site presents an evident contrast to the natural wooded landscape of the southern Arnota Massif, now severely altered by extensive excavation from base to peak. The barren, industrial terrain is visually unappealing, with only sparse pioneer vegetation. The southern slope appears as a scar on the Căpățânii Mountains, reflecting the profound environmental impact of human activity. The Bistrița quarry is characterized by unstable tailings dumps that pose a risk of collapse onto adjacent roads. A conveyor belt runs alongside the road, emphasizing ongoing limestone processing. Although access to the exploitation zone is restricted, heavy machinery is visible at multiple levels (Figure 4).

Rainfall leads to water accumulation in excavated areas due to the permeability of limestone. Active geomorphological processes include runoff, gravel collapse, and occasional landslides or seismic activity. According to the Administration of Buila-Vânturarița National Park (Kogayon Association, 2016; Ministry of Environment Waters and Forests, 2016), the quarry lies in a tectonically active zone with steep fault planes and mylonite zones, increasing the risk of slope failure and landslides involving both carbonate and sedimentary rocks beneath the waste dump.

Figure 4. Field photos of the Bistrița limestone quarry

The abandoned Bistrița limestone quarry forms a unique landscape where technological and environmental heritage intersect, creating a form of patrimonial pluralism that calls for innovative protection and valorisation strategies. According to Talento et al. (2020) quarry recovery approaches can be categorized by intended use: naturalistic, recreational, cultural, educational, or productive. The proposed solutions (Table 4), adapted from the literature to this case study, require long-term investment and comprehensive analysis and monitoring. Implementation must align with the 'polluter pays' principle and comply with the EU Regulation on Nature Restoration (European Parliament and Costești Local Council, 2024), part of the European Action Plan for Nature, aiming to balance economic development and environmental protection by 2050.

The scientific literature shows that there are different approaches for sustainable practices on quarry exploitation that involve ecological restoration, rehabilitation, reforestation and even reconversion of the land. *Ecological restoration* refers to the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed, aiming to return it to its original structure, function, and biodiversity (Fan et al., 2025). *Ecological rehabilitation* involves improving the ecological integrity of a degraded ecosystem without necessarily restoring it to its original state. It focuses on re-establishing key functions and processes to support biodiversity and ecosystem services (Osterkamp, Hupp, 2010). *Reforestation* is the process of replanting trees in a deforested or degraded area, typically using native or ecologically appropriate species, to restore forest cover and associated ecological functions (Pragya et al., 2017). *Reconversion* refers to the transformation of land from one use to another, a former extractive site to ecological, agricultural, or recreational purposes, through planned interventions that support sustainable land use, social and environmental recovery (Talento et al., 2020).

In this particular context, the integration of the proposed solutions may serve as a medium to long-term strategy for reshaping both economic and environmental frameworks. However, the active engagement and consensus of local stakeholders remain essential in determining the priorities and requirements for future generations. These solutions collectively support the achievement of *SDG 12*, while also contributing to *SDG 13, SDG 14,* and *SDG 15.* Quarry exploitation practices can be environmentally, economically, and socially sustainable both during their operational phase and, more importantly, following closure provided that comprehensive and forward-thinking approaches are implemented.

Table 4. Identified solutions for the degraded environment as a result of limestone quarrying

N°	Solutions	Description	Advantages	Disadvantages	Reference
1.	Ecological restoration of the relief	Restoration of the natural topography in the southern Arnota Massif quarry area, integrating it with the surrounding landscape through terrain reshaping. This process involves slope stabilization and may require topsoil replacement.	Promotes naturalistic restoration of the quarry site; Mitigates morphological impacts of excavation; Reduces vulnerability to natural hazards; Enhances potential as a habitat for avifauna; Improves visual and ecological landscape quality.	Demands a cost-intensive ecological assessment to guide appropriate technical interventions; Requires sustained, long-term financial investment; May involve heavy machinery, contributing to environmental degradation through vibrations and NOx emissions from diesel combustion.	Rosiere et al. (1989) Mouflis et al. (2008) Talento et al. (2020) Legwaila et al. (2020)
2.	Reforestation	Artificial reforestation of the degraded site using native species, alongside *Populus alba*, *Quercus rubra*, and *Rosa canina*, which act synergistically to support partial restoration of key ecosystem functions.	Supports naturalistic quarry restoration; Mitigates natural disaster risks; Contributes to microclimate regulation; Reduces soil erosion; Enhances watershed stability; Restores habitats for native species; Promotes biodiversity recovery and enhancement; Improves landscape aesthetics.	Requires a cost-intensive and complex ecological assessment to inform appropriate vegetation strategies.	Talento et al. (2020) Semeraro et al. (2021)
3.	Ecological rehabilitation	Partial restoration of key ecosystem functions involves soil decontamination, land reshaping and stabilization, soil rehabilitation, revegetation with native species, and, if necessary, reintroduction of native fauna	Facilitates naturalistic quarry restoration; Promotes biodiversity recovery and enhancement; Reduces susceptibility to natural disasters.	Requires a cost-intensive, in-depth ecological assessment of the site; Long-term monitoring may also entail significant financial investment.	Burger (2008) Zhang et al. (2024)
4.	Reconversion	Enhancing the rehabilitated area's appeal to promote ecotourism, including its integration into a	Creates opportunities in both ecological and economic sectors; Supports the development of	Tourism-related activities may lead to environmental pollution, potentially impacting all	Gandah and Atiyat (2016) Talento et al. (2020)

N°	Solutions	Description	Advantages	Disadvantages	Reference
		sustainable tourist trail. This approach leverages the site's overlap with Buila-Vânturarița National Park and its proximity to cultural landmarks such as the Arnota and Bistrița Monasteries and the Cave of Grigore Decapolitul.	ecological tourism.	ecosystem components.	Ivasyshyna (2024)

Regarding the limitations of the present study, it is important to note that the authors did not have access to confidential data provided by the mining company. Quantitative information on the annual limestone extraction from the Bistrița quarry was obtained from historical sources, some of which date back to the communist period (1947–1989). Due to the lack of publicly available official extraction reports, the authors were unable to verify these figures through direct consultation of primary sources and the information was used with caution, acknowledging that this limitation could affect the accuracy and depth of the study's findings.

In addition, a significant limitation of the present study lies in the absence of direct environmental measurements and laboratory analyses concerning the quality of air, water, and soil within the limestone quarry area, which restricts the ability to comprehensively assess the ecological impact of extractive activities.

5. CONCLUSIONS

In conclusion, the exploitation activities at the Bistrița limestone quarry have exerted a considerable impact on various environmental components, leading to imbalances within the microecosystem of the Arnota Massif, as well as socio-economic repercussions for the local community. Despite the existence of numerous European directives and national legislation aligned with sustainable development goals, the area remains in a state of degradation due to insufficient implementation of environmental measures. The solutions proposed in this study may serve as a foundation for future research aimed at identifying favourable conditions and assessing the feasibility of ecological rehabilitation, not only for this specific case study but also for similar quarry sites.

The present study underscores the dual nature of limestone exploitation, which entails both advantages and disadvantages, depending on the perspective from which it is evaluated. Over the course of approximately 78 years, human activity within the

Arnota Massif has resulted in the extraction of millions of tons of limestone, employing methods that have significantly impacted the environment. These practices have led to the transformation of the natural landscape, the disruption of local ecosystems, and the pollution of the environmental components. The consequences have also extended to the social and economic domains, particularly affecting nearby communities that have experienced sustained economic growth, at the expense of environmental integrity.

Achieving sustainable exploitation of limestone resources requires the prior completion of comprehensive studies and the development of appropriate documentation to assess the impact on all environmental components. This process must be followed by responsible spatial planning of extraction sites and the continuous monitoring of both extractive activities and their associated pollution effects. The measures proposed in this study aim to protect, conserve, and sustainably valorize the natural heritage of the Arnota Massif, especially in areas affected by previous quarrying operations.

Ultimately, the study highlights the necessity of integrating sustainable development objectives into the field of mineral resource exploitation. It also advocates for the active involvement of local communities, not only in resource extraction and processing, but also in monitoring environmental impacts and contributing to the restoration of degraded areas. Promoting community engagement and raising public awareness regarding the environmental consequences of industrial activities are essential steps toward ensuring a just transition to sustainable mineral resource management.

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