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FIELD ENVIRONMENTAL SCIENCE

The Călimani Mountains as a social-ecological system: An Integrated Assessment of State, Dynamics, and System Resilience

SUMMARY OF THE DOCTORAL THESIS

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Key words

Bioeconomy, carbon footprint, Călimani, circular economy, conceptual mapping model, ecological state, ecological value, economic value, ecosystem services, forest fires, global pollution index, greenhouse gas emissions, hysteresis, impact factors, impact index, impact sources, Leopold matrix, life cycle assessment, mineral and balneotherapy waters, mining activity, mountain product, natural protected areas, antural resources, pollution, resilience, risk assessment, social value, social-ecological system, undeserved mountain area, waste deposits, water quality, windthrow.

Abstract

Natural resources constitute a fundamental component of the contemporary global economy, influenced by unstable factors such as inflation, market volatility, and the scarcity of critical goods. In this context, enviromental charactersitics play a key role in determining the value, accessibility and uniqueness of these resources, as well as in providing the associated ecosystem services.

The present thesis relies on the premise that the success of any sustainable development intervention depends on the conxeptualized understanding, tailored to the biogeographical and social specificities of each mountain system, such as the Călimani Mountains.

Social-ecological systems (SESs) are defined by the close and continuous interaction between natural and social systems, includng not only biophysical and economic components, but also cultural, historical and institutional aspects. The analysis of the Călimani social-ecological system, from a methodological point of view, was carried out using methods that target both the quantifiable biophysical components, categorized as the sphere of *in rebus* properties, and the social, economic and cultural relations that determine the response of the system as a whole, and requires other methods of analysis, for example qualitative or mixed. Bosch et al. (2007) argue for a *systems thinking* perspective to natural resource management, proposing an approach that acknowledges the complexity of these interactions and the multiscale decision-making context in which actors operate. Building on this framework, the thesis adapts it to the specific context of the Călimani Mountains by integrating a top-down analysis (focusing on policies, industrial impacts, and natural resources) with a bottom-up exploratin of local community perceptions, values, and identity traits. The aforementioned methodological combination allows not only the mapping of causal relationships between components, but also the identification of transition thresholds and systemic regulation mechanisms, essential for supporting informed and sustainable decisions. The thesis fits into this epistemological framework by proposing a conceptual model applicable to the Călimani social-ecological landscape, which combines quantitative assessments (of natural resources and the impact of their exploitation, population dynamics, the quality of environmental factors, etc.) with a qualitative analysis of the perceptions of the local population, reflecting both systemic trends and the capacity for reorganization and resilience, illustrated by the phenomenon of hysteresis. In Romania, resilience studies applied to mountain systems are scarce, and those that incorporate systemic concepts are generally disconnected from the field of study of social-ecological systems. Furthermore, they fail to offer a systemic modeling framework or an ontological and causal approach, such as the one developed in the following chapters, which emphasizes the originality of the present work.

The central motivation of this work is the development of an organic model for understanding and interpreting the dynamics, states, and behavior of complex systems - a model that allows for a balanced approach between the reductionism specific to case studies and an integrated, holistic perspective.

The working hypothesis is based on the premise that the Călimani social-ecological system can exist in multiple alternative stable states, shaped by both historical and contemporary pressures on resources and population. Its capacity to reorganize and maintina functionality, rather than returning to a previous state, is considered an expression of emergent resilience. Transitions between states are influenced by the intrplay of ecological, demographic, and ontological dimensions.

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♦ In **Chapter 1 of the thesis, "Theoretical landmarks in the field of study. Current state of research"**, the working concepts and relevant theories are presented (the study of social-ecological systems, as a subdomain of the geosystem; the application of systemic thinking and complex systems theory in the sustainable management of natural resources in the Călimani Mountains; the concept of resilience; the hysteresis effect) as well as the working principles (the principle of causality, the cycle of environmental and historical contingencies, ontology, the teleological principle). Chapter 1 reviews several of the works of some reference authors in this field, which offer robust methods for the analysis of socio-ecological systems, applicable in mountain areas (Holling, Folke, Berkes, Cumming and others), as well as a bibliographic analysis that targeted the Călimani Mountains and their area of influence, through the lens of human communities.

♦ **Chapter 2 of the thesis, The Călimani Social-Ecological System: Delimitation and Specificities**, defines the study area, approached as a social-ecological system covering approximately 334,000 hectares. The Călimani Massif serves as the central point of influence, along with the surrounding localities: the communes of Vătava, Deda, Răstolița, Lunca Bradului, and Stânceni in Mureș County; the commune of Bilbor and the municipality of Toplița in Harghita County; the communes of Șaru Dornei and Panaci, and the spa resort town of Vatra Dornei (approximately 30 km from the massif's edge, included in the analysis due to the presence of mofettic manifestations linked to the Călimani volcanic structure) in Suceava County; continuing along the Dorna Valley toward the Tihuța Pass, the communes of Dorna Candrenilor and Poiana Stampei; and in the north-western and western sectors, the communes of Tiha Bârgăului, Bistrița Bârgăului, Josenii Bârgăului, Prundu Bârgăului, Livezile, Cetate, Dumitrița, Șieu, and Șieuț in Bistrița-Năsăud County (see Figure 1).

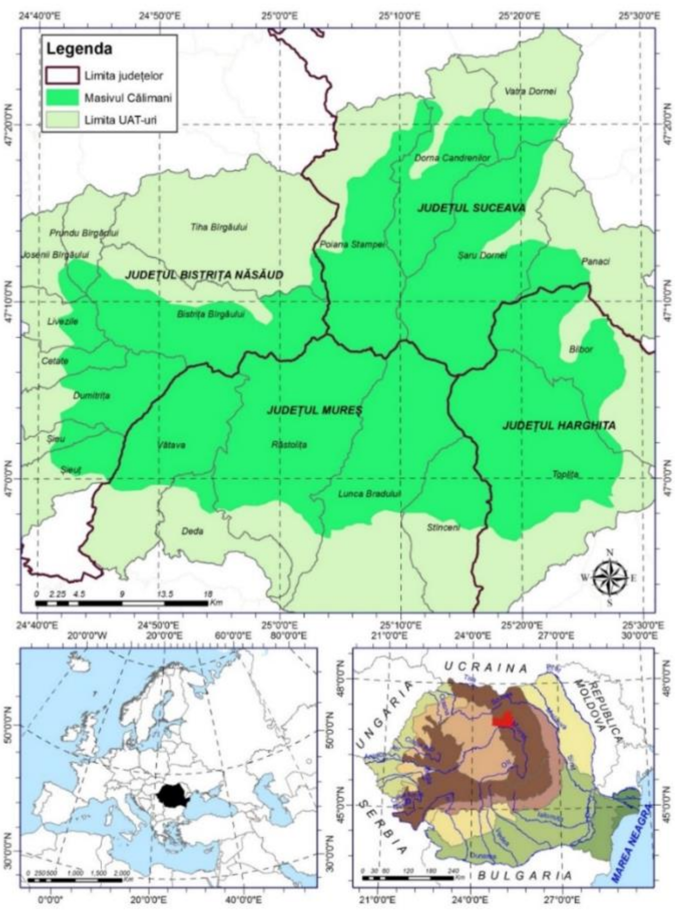


Fig.1. Delineation of the Călimani Mountains social-ecological system according to physico-geographical criteria and in terms of administrative-territorial units

♦ **Chapter 3 „*Research Methods, Materials, and Means Employed*"**

The resilience of a mountain social-ecological system cannot be understood without a historical analysis of its constitutive relationships, the ways in which these have evolved, and the factors that contribute to maintaining the system's identity over time. Accordingly, the methodology proposed in this study aims to provide statistical, qualitative, quantitative, and conceptual tools that capture both the internal dynamics of the system and the historical trajectories that have shaped its current structure..

To organize, process, and interpret the data collected in this study, a series of complementary tools were employed—suitable for both quantitative and qualitative analysis, as well as for the conceptual representation of the Călimani social-ecological system. These tools were selected based on the nature of the data, the type of analysis required in each case, and the methodological objectives of the research.

For spatial data analysis, ArcGIS software (ESRI) was used.

For quantitative analysis, applications such as: Microsoft Excel; XLSTAT; Google Colab; Google Forms; Microsoft PowerPoint and Canva were used

Quantitative methods used:

- The assessment of the quality of the environment affected by polluting anthropogenic activities was carried out by calculating the Global Pollution Index**.**
- The ARIMA method (Vasileiadou and Vliegenthart, 2015; Scheffer et al., 2021; Kaur et al., 2023; Dar et al., 2024) is used to examine the relationships between population dynamics and various socio-economic factors, treating each variable as a time series..
- To represent the conceptual resilience of the studied social-ecological system, a potential function adapted from complex systems theory was used, which allows the visualization of the stability of the system in the form of an attraction basin. This method integrates two essential components: the position of the attractor (represented by the proportion of entities that exhibit positive trends – for example, localities in demographic recovery) and a resilience coefficient that regulates the depth of the basin.
- The LCA (Life Cycle Assessment) methodology is an important tool in decision-making by integrating environmental sustainability (Sonderegger et al., 2017).
- Greenhouse gas emissions from agro-zootechnical activity were estimated using the 2006 guide "IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 Agriculture, Forestry and Other Land Use - Chapter 10: Emissions from Livestock and Manure Management".

As a *qualitative method* for an assessment of the effect of anthropogenic intervention on the natural environment and population in the Călimani SSE, in conjunction with the natural pressure factors identified during the study, which have an impact on the development and sustainability of human communities, we opted for the general matrix model for global assessment of environmental impact, the Leopold method (Leopold et al., 1971).

As a mixed method, the questionnaire method (Clifford et al., 2023) was used to explore the perceptions, knowledge and experience of local communities belonging to the study area. The questionnaire was designed to identify both the constraints faced by human communities within the Călimani social-ecological system and the opportunities available to them.

The questionnaires were completed on Google Forms between 15.06.2023 - 11.12.2024 and were processed in XLSTAT.

The conceptual mapping method for social-ecological systems. The *systems mapping* approach was used as a conceptual design tool for modelling social-ecological systems. The method enables the identification and visual representation of the system's key components, the interdependent relationships among them, and the feedback loops that drive internal dynamics. By applying systemic maping, it becomes possible to develop an integrated understanding of social and ecological complexity- an essential step for constructing exploratory scenarios, conducting resilience analyses, or performing systemic impact assessments.

♦ Chapter 4 „Natural resources, defining elements for the resilience of the social-ecological system Călimani"

✓ ***Solid mineral resources***

The mining activity centered in what could be called the heart of the Călimani Massif- for the xtraction and processing of sufur, resulted in the degradatation of all environmental factors as well as of th elocal human communities (acid rain was felt as far as Vatra Dornei). Even now, despite some closure and rehabilitation works having been carried out, residual pollution from this activity can still be observed in the area of its influence.

Despite extractive waste no longer being produced in the Călimani mountain area since 2006, the tailings left behind from the Mining Exploitation Călimani continue to have a significant impact on the environment. Therefor, an impact assessment of the extractive waste deposits- viewed through the lens of their stability as a main risk factor- was carried out by calculating the Global Pollution Index. Its value was found to be 2.80, indicating an environment affected by anthropogenic activities that cause discomfort to living organisms.

Although the extraction activity- and in some cases, the mechanical processing of industrial rocks in crushing stations- is not as polluting as ore mining, it cannot be said that it has no negative impact Beyond the economic benefits it brings to communities- such as job creation and a share of the mining royalties entering the budgets of local administrations where the quarries are located- there are still environmental consequences to consider.

✓ ***Mineral and balneotherapy waters***

The natural mineral water resources in the study area belong to the hydrogeochemical province of mineral waters located within the mophetic aureole of the Neogene volcanic zone of the Călimani-Harghita Mountains. These waters are utilised either as naturally carbonated or non-carbonated mineral waters (brands such as Aqua Carpatica, Bucovina, Dorna, Poiana Negri, Bilbor, Stînceni), or as therapeutic mineral waters in balneotherapy treatments (in locations such as Vatra Dornei).

Still mineral water is bottled directly, as it is suitable for immediate consumption. This indicates an economically viable flow rate at the spring capture points but raises questions about the low percentage of the population with access to a centralized water supply network. A study conducted to analyse the potential anthropogenic impact on the quality of mineral waters in the northern and eastern parts of the Călimani Massif (Ionce & Florea, 2023) highlichted, among other findings, the following: the qualitative characteristics of natural non-carbonated, carbonated, and balneotherapy mineral groundwater in the Călimani SES- specifically on the northern and eastern slopes and adjacent areas- did not reveal significant imprints from the nearby mining sites.

✓ ***Freshwater***

The freshwater resources in the SES Călimani region provide a wide range of ecosystem services, closely tied to their intrinsic value. The ecological status of water bodies directly influences the quality of ecosystem services delivered to the population.

The Neagra Șarului River is the mos tpolluted water body in the SES Călimani, particularly along its course through the Călimani National Park, duet o the historical influence of sulfur mining. We conducted a study on this river, focusing the analysis on the section of the

Neagra Șarului after it receives all tributaries, both the ones carrying polluted waters from the mining area and those conventionally considered clean.

A systemic approach is essential to establish the ling between anthropogenic impact factors and the hysteretic behaviour of water systems in relation to specific quality parameters analyzed in this study, while also accounting for the complex interactions among climate, terrestrial, and aquatic ecosystems. In the Neagra Șarului watershed, these anthropogenic influences in the Călimani Mountains are primarily due to sulfur extraction and processing activities.

Annual average values were used for specific chemical parameters relevant to assessing water quality in the Neagra Șarului watershed, taking into account the mineralogical characteristics of the underlying geological substrate and the analysis of monitored indicators from the watercourse. These parameters include hydrogen ion concentrations (pH), dissolved oxygen, and total iron ions.

As part of the scientific investigation for this case, a series of methodological steps were followed.

- The analysis of water quality in the Neagra Șarului watershed within the mining influence area, during the active exploitation period

Considering that the mining activity took place predominantly during the communist period, when systematic monitoring of the affected environmental factors was lacking and economic indicators were prioritized over ecological ones, the studied conducted after 1989 (followed the political regime change) were used as a reference for the active mining period.

Our analysis data used provided by several public institutions and economic operators in response to our requests: the Institute for Mining Research and Design Baia Mare, the Environmental Protection Agency Suceava, and GEOMOLD SA.

- The analysis of the quality of water bodies in the Neagra Șarului watershed after the cessation of mining activities

The data on surface water quality in the area influenced by the mining parameters (parameters chosen were pH, dissolved oxygen, total Fe) were provided by CONVERSMIN SA, the Siret Water Basin Administration Bacău, the Suceava Water Management System, GEOMOLD SA and the Environmental Protection Agency Suceava.

- The analysis of the correlation between precipitation, hydrogen ions, and iron ion concentration, and hysteresis modelling in the Neagra Șarului River

The analysis of the influence of climatic elements was based on data provided by the National Meteorological Administration and the Suceava Water Management System (Vatra Dornei and the Gura Haitei rain gauge station).

Results of the study

An initial step in the scientific approach involved correlating the data from the sampling points to determine whether observable trends exist and whether the hypothesis of a correlation between water quality parameters and annual precipitation rate holds true. The Pearson correlation coeffiecient was used for this purpose, resulting in the following graphs:

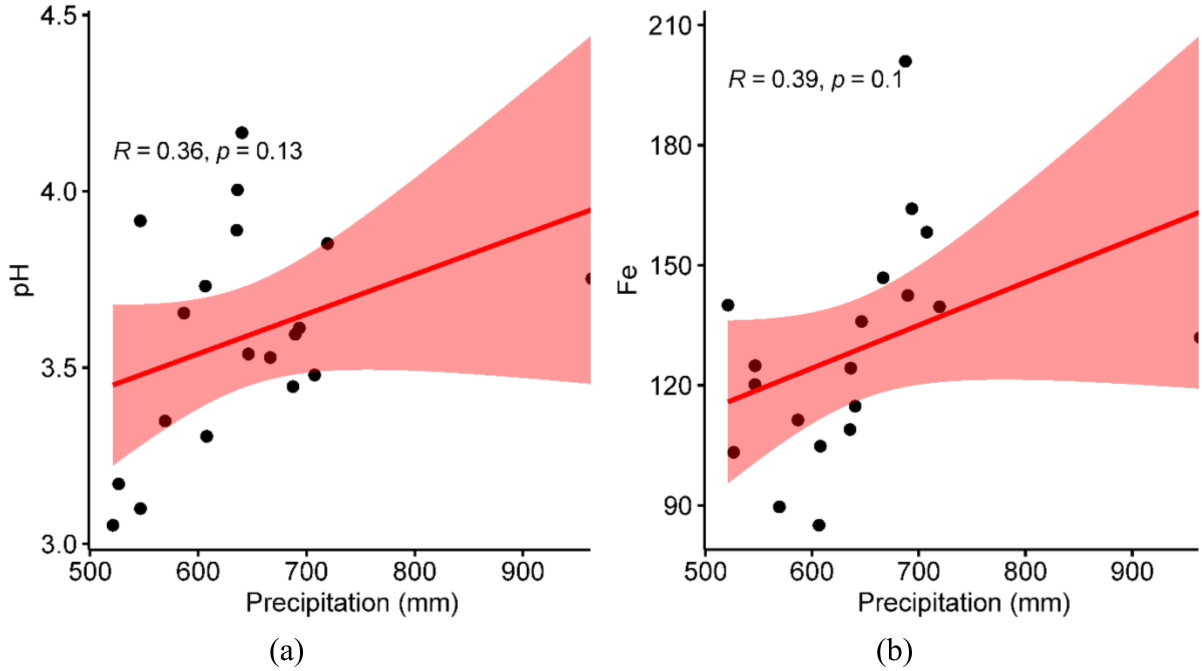
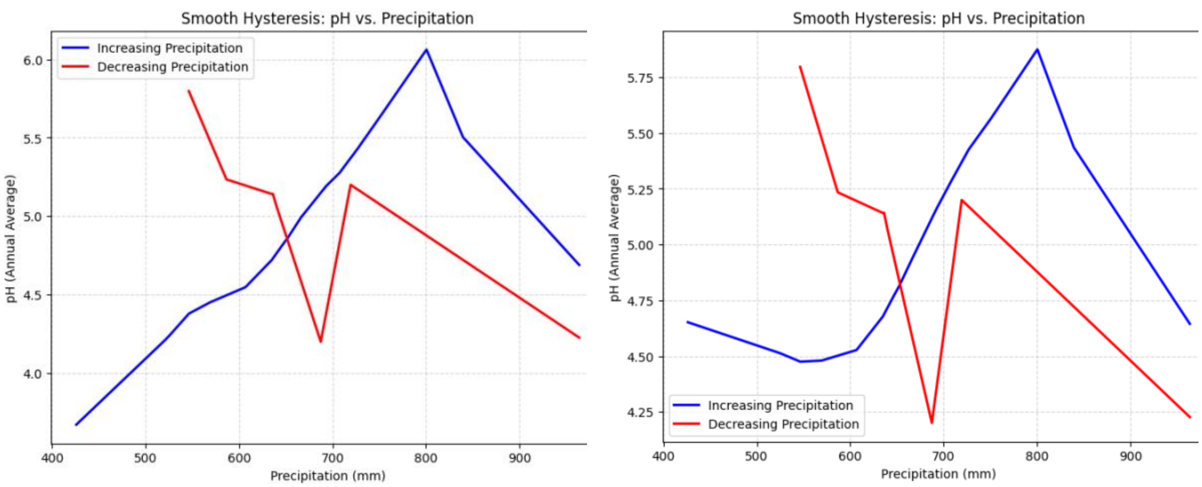


Fig.4.1. (a) Scatter plot for the Pearson correlation coefficient for water pH values and precipitation (mm); (b) Scatter plot of the Pearson correlation coefficient for the correlation between iron ion (Fe) concentration and precipitation

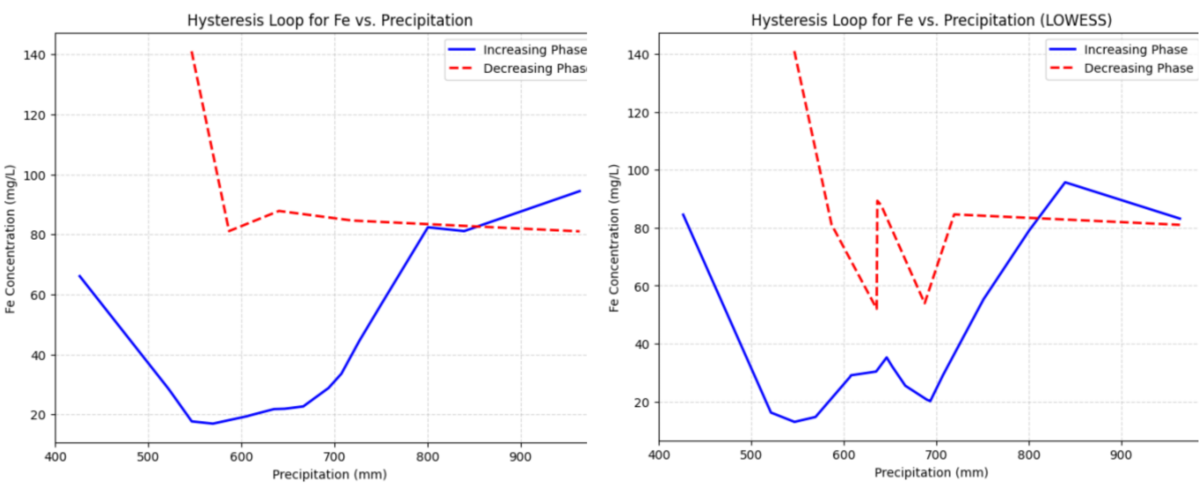
Figure 4.1.(a) shows a correlation coefficient of R=0,36, indicating a moderate positive correlation between precipitation and pH levels. The pH values increase with higher precipitation, a phenomenon that an be explained by the dilution effect duet o additional water input and, consequently, increased flow rate. The trens is clearly positive, with the red area indicating a wider confidence interval at higherl annual precipitation levels, suggesting greater variability. In the case of iron ion concentrations and precipitation, the correlation coefficient of 0.39 (Figure 4.1.(b)) indicates a slightly stronger positive correlation compared to the pH results, suggesting that as precipitation increases, iron ion concentrations may also rise. The trend is similarly positive, with greater uncertainty at higher precipitation levels. This phenomenon can be explained by the fact that precipitation mobilizes iron-rich particles from waste rock deposits and transportrs them into the hydrological network. In both cases, an upward trend is evident, with greater variability obserbed at higher precipitation levels, as indicated by the widening of the confidence intervals. Both graphs suggest a positive relationship between precipitation and the measured variables- hydrogen ion concentration (pH) and iron ion concentration (fe)- and precipitation values (in mm). The increase in variability at higher precipitation levels my indicate hysteretic behaviour in the Neagra Șarului River system.

For the next methodological step and based on our conclusions, we chose to analyze sampling points 16 (located after the confluence with the Dumitrelu stream, which carries infiltration from the Dumitrelu tailings pond) and 21 (on the Neagra Șarului River upstream of its confluence with the Bistrița River, after receiving a significant flow of clean water from the Sărișor, Haita, and Călimănel streams.



(a) (b)

Fig. 4.2. (a) Hysteresis graph for sampling point 16- water pH value and precipitation (mm); (b) Hysteresis graph for sampling point 21- water pH value and precipitation (mm)



(a) (b)

Fig. 4.3. (a) Hysteresis graph for sampling point 16- total iron (Fe) concentration in water (mg/L) and precipitation (mm); (b) Hysteresis graph for sampling point 21- total iron (Fe) concentration in water (mg/L) and precipitation (mm)

The hysteresis graphs illustrating the relationship between pH and precipitation suggest a dynamic and non-linear response of the river's water chemistry to changes in precipitation levels. During the rising phase of precipitation (blue line), the following observations were made:

- As precipitation increases, the pH also rises, indicating that a greater water input leads to the dilution of acidic components in the river. This aligns with the expectation that higher flow rates reduce the concentration of hydrogen ions, resulting in a pH closer to neutrality.
- The smooth upward trend suggests that the mixing of surface water and grounwater helps buffer acidity as precipitation increases

Regarding the decreasing phase of precipitation (the red line), the following observations can be made:

• When precipitation begins ot decline, the pH does not immediately follow the same trajectory back. A lag effect is observed, with the pH dropping more sharply after reaching its peak.

• The divergence between the rising and falling phases of precipitation confirms hysteresis, indicating a memory effect in the river's chemistry, where previous hydrological conditions influence present responses.

The asymmetry in the hysteresis graphs indicates that the river exhibits a self-purification mechanism under increasing precipitation conditions, but gradually returns to a more acidic state when precipitation decreases, highlighting a negative feedback mechanism in the natural river system.

Based on the results for Fe ion concentrations and the obtained graphs, a delayed response can be observed in the fluctuations of Fe ion concentrations relative to precipitation input. The difference lies in the fact that Fe appears to increase with precipitation, similar to pH, however, in this case a positive feedback mechanism can be observed for Fe ion concentration. The possible explanations can be summarised as follows:

• Differenc iron mobilization mechanisms: increased precipitation intensifies slope erosion of waste rock deposits and the subsequent transport of sediments.

• Delayed storage and release: iron ion can accumulate in sediments or groundwater and be gradually released after certain precipitation thresholds are reached, causing hysteresis.

• Other possible human or natural influences: if this pattern is consistend annually, it may reflect natural geochemical cycles. If the dynamics of iron ions have changed over time, external factors (e.g., changes in land use, pollution, or climate variability) could play a role

✓ Biological resources

The most exploited natural resource in the SES Călimani has been, and remains, the forest.

After the fall of the communist regime in the 1990s, there was a period of massive logging, partly illegal. Large quantities of wood waste (on the order of hundreds of thousands of cubic meters) were found in abandoned mining areas, but especially along the banks of mountain watercourses. Only three bark and sawdust deposits were regulated from an environmental standpoint: Chilia, Bodnăraș, and Poiana. The calculation of the Global Pollution Index for these three deposits indicated an environment affected by anthropogenic activities, but within the permissible limits established by legislation. The emergence of large-capacity biomass heating plants and the financial incentives for the production of pellets and briquettes have led to the utilization of wood waste.

The existence of a large area in the Călimani Mountains under special ecosystem protection, along with the implementation of the forest management certification system by forestry directorates for state-owned public forest land (still the majority), a system that private owners have also begun to adopt, has led to the implementation of measures for the sustainable conservation of forest biodiversity.

Local agro-pastoral activity, ranked second in importance among the activities in SSE Călimani, is supported by the existence of a very large area of high natural value pastures. It is largely a subsistence activity but is showing an upward trend due to the support provided by the National Agency for the Mountain Area, through the granting of the 'mountain product' certification.

Considering Considering that SSE Călimani has approximately 58% of its area covered by forests and forested land (which absorb over 1,043 thousand tonnes of CO_2 per year), as well as 2,358 hectares of water surfaces and wetlands, the impact of greenhouse gas emissions from the (subsistence) livestock farming practiced in SSE Călimani can be considered very low.

♦ Chapter 5. The dynamics, modelling and resilience of the social-ecological system Călimani

Based on the data gathered regarding the interdependence between the natural resources of the Călimani Mountains and the sustainability of human communities, a series of steps were followed in modelling the social-ecological system:

⋙ Using the ARIMA statistical method, the historical trajectory of the Călimani SES is analyzed- a method useful for determining whether there are not only correlations but also causal relationships between population dynamics and various variables. The analysis shows that common trends were identified for all the localities studied, suggesting that the populations experienced an initial growth followed by a sharp decline during the 2000- 2005 period. After this decline, some regions show signs of recovery or stabilization, but do not return to their pre-decline population levels, which may indicate that a hysteresis phenomenon is present in the observed population dynamics.

Given the specific characteristics of the Călimani SES and based on the analysis of population dynamics, a series of variables specific to agro-pastoral practices (bovines and ovines husbandry) in this area were introduced in order to analyze whether certain common trends and variations also occur here.

The conclusion of the analysis points out that as the human population in the Călimani SES increases, the resources and means of agricultural production, including livestock farming, expand proportionally, indicating the long-term stability of this practice regardless of population changes. With additional temporal data and the inclusion of other influencing factors in the statistical analysis, this type of approach has the potential to become an extremely useful tool for forecasting future trends in social-ecological systems and for identifying causal relationships within these systems.

⋙ Pentru o evaluare a efectului intervenției antropice asupra mediului natural și populației din SSE Călimani, coroborat cu factorii de presiune naturali identificați pe parcursul studiului (analizați în Chapterul 4), care au impact asupra dezvoltării și sustenabilității comunităților umane, am optat pentru o evaluare calitativă: modelul matriceal Leopold. Au rezultat patru matrici, cu reprezentarea indicelui de impact.

For Matrix I – *Physico-chemical characteristics of the Călimani SES*, a significant impact index was obtained for: soil (due to intensive forestry operations, both for the exploitation of timber resources and as a consequence of deforestation associated with the construction of the sulfur mining site); surface waters (pollution caused by emissions within the Călimani mining perimeter, the discharge of domestic wastewater – considering that only about 38% of the Călimani SES population benefits from a sewerage network with a treatment plant –, the presence of industrial or household waste deposits, compounded by the still-prevalent practice of dumping waste along riverbanks).

For Matrix II – Biological conditions of the Călimani SES, a significant impact index was recorded for: woody vegetation (affected by windthrows which, from 1995 to the present, have damaged more than 900 thousand cubic meters of timber, compounded by insect infestations);

aquatic biota, impacted by both the construction of small hydropower plants on watercourses and by pollution.

For Matrix III – Cultural factors of the Călimani SES, the impact index is significant for: natural landscapes, protected natural areas, and rare species and habitats (affected by extractive waste deposits from sulfur mining); residential areas (the construction of the Colibița Reservoir led to the displacement of the village settlement).

For Matrix IV – Ecological relationships in the Călimani SES, a significant impact index was recorded for trophic chains, in cases of habitat modification and the presence of extractive waste deposits. According to the Călimani National Park Management Plan (2022), the diversity of small mammals (*Chiroptera*) is very low in the Neagra Șarului hydrographic basin, particularly in the area of the sulfur quarry and waste dumps, and the long-term viability of bat species is significantly affected.

» **Analysis of perceptions and knowledge: the ontological sphere of the Călimani SES.**

Within this analysis, a questionnaire was applied as the main tool for investigating the level of awareness regarding the available natural resources among the local population, as well as their perception of the limitations imposed by living in a mountainous area.

The questionnaire was completed online by respondents during the period June 2023–December 2024.

» One of the main contributions of the present work is the development of a conceptual design model or conceptual mapping ("systems mapping") (Barbrook-Johnson & Penn, 2022a) of social-ecological systems, which facilitates, at a first glance, the understanding of the relationships, functions, and dynamics of the system. In the case of the Călimani social-ecological system, a fundamental principle for establishing boundaries is the dependence of the communities in the Călimani mountain area on the geological resources and the ecosystem services provided by the Călimani Massif.

Since this is an analysis of complex social-ecological systems, a very large input of data is required- data that needs to be sorted, validated, and classified, to which the important element of uncertainty and unknown variables is added. A balance between reductionism and holism is always necessary, in order to study certain phenomena in isolation, but also to analyze them in their functional context. To achieve this balance, I propose a teleological modeling approach, that is, a model built on general working principles, adapted to the final purpose of the study. Depending on this final purpose, simplification occurs, reducing the system to the relevant elements and details, without losing the overall perspective. For the Călimani social-ecological system, the teleological principle in conceptual mapping involves the inclusion of relevant elements and their representation in relation to the whole. In this way, the coherence and cohesion among the elements can be perceived, both in relation to each other and to the system as a whole, and, implicitly, the resilience of the system when these functions and relationships are affected.

Also, because the anthropic sphere, alongside the natural one, is a main and defining element of the social-ecological system, I propose the introduction of an ontological component, which should include the immaterial elements related to what is essentially human—thought and intellect, ethos and collective mentality, ritual and culture. The ontological sphere includes the general characteristics of the system's existence.

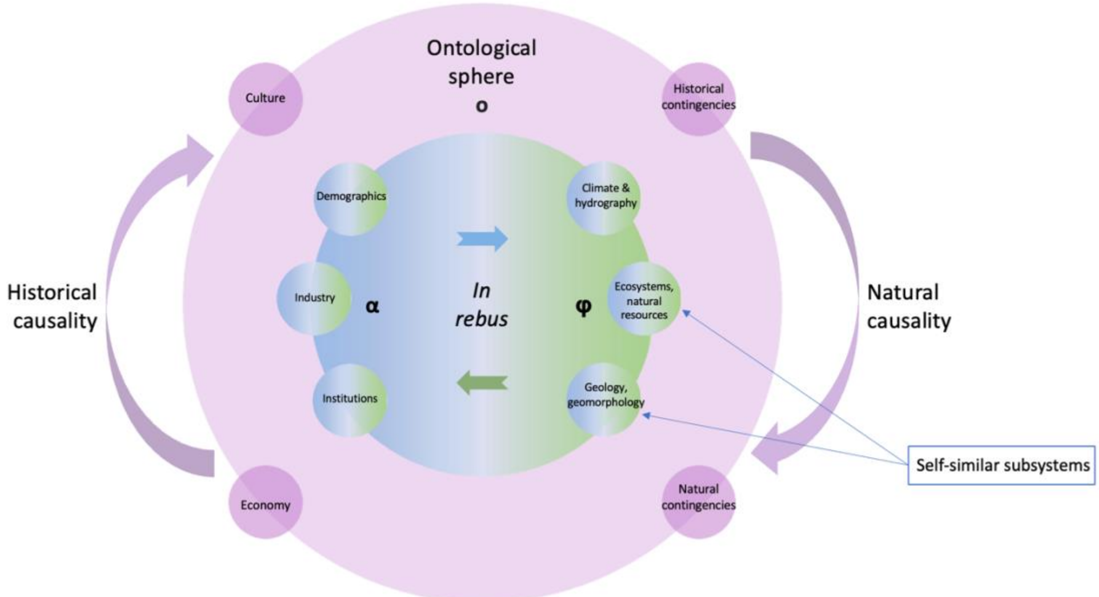


Fig.5.1. Conceptual modeling of the Călimani social-ecological system

The cell-type modeling of the Călimani SES is based on the following principles:

- **The principle of self-similarity (Mandelbrot, 1983):** the parts of a fractal structure resemble the entire structure, regardless of scale; as fractals, each discrete element resembles the system as a whole, meaning that each element within the sphere of *in rebus* properties (quantifiable, tangible) resembles the whole and is itself a social-ecological system by the nature of the relationships and functions it fulfills, proportional to the scale at which it is found;
- **Teleological principle:** the elements and boundaries of the system are determined on the basis of observed physico-geographical characteristics and selected according to the intentionality and purpose of the study; for example, in the case of the Călimani SES study, the boundaries were determined according to the administrative-territorial units that are in contact with and depend on the resources of the Călimani Massif;
- **The part–whole relationship principle (Preiser, 2018):** the whole is composed of distinct parts or discrete elements, which can be studied separately; for example, the study of the hysteresis phenomenon in the Neagra Șarului River, where the hydrographic network can be treated as a social-ecological system in itself and may have a systemic impact on the northern area of the Călimani SES, due to its dense hydrographic network;
- **The principle of proportionality:** the temporal dynamics of certain subsystems will be directly proportional to the temporal dynamics of other subsystems (for example, population variations will have a proportional impact on the local economy, while variations in precipitation will have a proportional impact on the concentration of certain pollutants in the hydrographic network)
- **The principle of symmetry:** both at the level of the system as a whole and at the level of discrete elements, there is a dichotomy between the anthropic and the natural sphere, whose boundary is diffuse ("fuzzy") due to their interdependent relationship and balanced causality.

The color code was chosen in order to better differentiate between the spheres of influence, which, in turn, facilitate the analysis of causality and the interdependence relationships among the elements and phenomena that determine the identity of the Călimani SES:

- Purple is used for the ontological sphere **(ο),** which encompasses the abstract notions that provide the general characteristics of the system: ethos, culture, information, historical and natural contingencies
- Green is used for the natural sphere (φ – abbreviation of the Greek word *physios*, meaning "nature");
- Blue is used for the anthropic sphere (α – abbreviation of the Greek word *anthropos*, referring to man, the human being).

It should be noted that, although it may be considered an abstract notion and not a physical entity, the economy was included in the sphere of *in rebus* properties, because it is quantifiable and can be studied through statistical and scientific methods, just like the other elements belonging to the same sphere.

Unlike classical logical models, the cell-type conceptual model allows for an organic representation of the system, in which the interactions between endogenous and exogenous phenomena are integrated in a way that reflects intrasystemic relationships and extrasystemic influences. In a logical scheme, linearity is fundamental, whereas this model highlights complex, flexible, and dynamic relationships. Thus, this conceptual diagram facilitates the understanding of social-ecological systems through analogies with structures and fractals observed in nature (the atomic model, the biological cell model), offering an overview that includes discrete elements, phenomena, and interdependence and feedback relationships.

The resilience of the Călimani SES depends on maintaining the functions and relationships, and the system's coherence, within the three main spheres: anthropic, natural, and ontological. Associated with the principle of causality is the notion of contingency (that is, events or factors that may act upon the system only at the level of potentiality and do not necessarily materialize—for example, the probability of an acute drought event, an earthquake, etc.), which involves a cycle of historical (anthropic) and natural contingencies that play an important role in the probabilistic analysis of the system's dynamics over a certain period of time (an example would be risk analysis for certain natural and anthropic hazards). The following principles apply:

- **Efficient cause**: associated with anthropic causality, referring to agency and intentionality, and thus linked to historical contingencies (e.g., decisions of local actors with environmental implications, initiation of activities with systemic impact such as natural resource exploitation);
- **Material cause**: contextualized and simplified to refer to natural contingencies and natural, environmental causality (including all phenomena related to natural cycles and natural hazards);
- **Final cause:** in the present study, the final cause refers both to the dynamics of the system—as the cause that describes the intention of the agent or efficient cause (man)—and to the way of thinking in the teleological modeling of the Călimani social-ecological system, for the final purpose of the study, through the elements that are included and those that are neglected.

The complex behaviors of social-ecological systems include phenomena such as non-linearity, positive and negative feedback, the existence of thresholds, as well as the capacity to shift between equilibrium states (alternative stable states). These systems have the ability to self-organize into new states of dynamic equilibrium, depending on the interactions between internal processes and external factors, which allows them to transition through multiple alternative stable states according to the conditions and influences in their environment. Thus, a disturbance of social-ecological systems caused by anthropic and/or natural factors leads to internal changes that are qualitatively different from the initial state and to a transition toward new alternative stable states. The natural environment possesses regenerative capacity, especially regarding biological resources, but only within the limits of the system's program: the contingencies of alternative stable states depend on the genetic and material resources of the social-ecological system, since the system itself is subject to entropy. Any anthropic intervention determines a trajectory of historical dependence on an initial perturbing event (the hysteresis effect); therefore, any ecosystem or social-ecological system may have alternative stable states in a natural condition (prior to anthropic intervention) and in a semi-natural condition (human–nature interdependence). As presented in subchapter *4.3.2.2. Historical pollution and the hysteresis phenomenon*, the hysteresis effect is fundamental for understanding the way in which systems transition from one stable state to another and the temporal trajectory between these states.

The Călimani SES "oscillates" between different equilibrium states that exist in potential form and toward which the system gravitates depending on certain basins of attraction. Alternative stable states refer to the ability of a system to exist and persist in multiple configurations or states that can be drastically different from one another. These alternative states are triggered by the feedback mechanisms of systems, and the transitions between them can have profound consequences for the structure and functions of the ecosystem in question (Beisner et al., 2003; Folke et al., 2004). Transitions between these states are often non-linear, triggered by gradual changes that exceed a critical threshold, and are irreversible in the dynamics of the system. For example, mining activities produced structural and functional changes in the natural environment, leading to the alteration of certain watercourses and underground hydraulics, as well as the pollution of the hydrographic network through the discharge of pollutants from waste dumps; the landscape has been irreversibly altered, but rehabilitation works following the cessation of mining activities, together with natural mechanisms such as the self-purification of rivers through pollutant dilution, may in time lead to a new equilibrium state, although functionally and structurally different from the previous one.

The Călimani SES, being located in a mountain area, is, due to its geographical particularities, similar to other mountainous zones and areas, a system generally considered disadvantaged and vulnerable in the face of environmental and social changes. This vulnerability is due to the fragility of mountain ecosystems and the exposure of local communities to a series of internal and external factors.

Within the Călimani SES, alternative stable states result from the complex interactions between ecological processes (e.g., variation of the hydrological regime, climate change, etc.) and social structures (e.g., local administrative structures, modes of exploitation and use of natural resources and ecosystem services). These interconnected dynamics imply that regime shifts are not purely ecological or purely social phenomena, but are deeply rooted in social processes and decision-making contexts. A system may shift from an equilibrium state, such as sustainably managed resource capital, to a degraded regime characterized by the loss of ecological integrity and the decline of social well-being. Returning to the equilibrium state often requires human intervention, in order to enhance the a priori natural feedback mechanisms.

››› The resilience of the Călimani social-ecological system

The resilience assessment of the Călimani social-ecological system was carried out through an integrated approach, combining qualitative and quantitative methods from the previous chapters, designed to capture both the internal dynamics and the current states of the system. Based on the data obtained during the scientific endeavor—population dynamics, water hysteresis, the ecological condition of mining sites (IPG), and the impact induced by woody waste—a resilience coefficient was calculated for each category. To capture the integrated resilience of the analyzed social-ecological system, a conceptual model of the stability landscape was constructed. This model is based on two key indicators: demographic trends (represented by the normalized score of population dynamics) and ecological trends/states, calculated as the average of the resilience coefficients for five representative cases: Călimani Mining Site, Dealu Rusului, Chilia woody waste deposits, Bodnărași and Poiana, and the Neagra Șarului River (for which the hysteresis phenomenon was investigated).

The resulting composite index was calculated by assigning equal weight to the demographic component (50%) and the ecological component (50%), reflecting a balanced approach between anthropic and biophysical factors. The resilience coefficient for the composite stability landscape of the *in rebus* properties sphere of the SES is x=0.55, which reflects a moderate balance. Thus, the model indicates a system that, although strongly supported by ecological components (well-conserved environmental factors or those showing clear tendencies of recovery/hysteresis), remains conditioned by population dynamics, whose stagnation or decline may limit long-term processes of self-organization and adaptation. Overall, the model provides a clear and holistic representation of the composite resilience state of the Călimani SES, supporting the hypothesis of the existence of an emerging alternative stable state, situated at the intersection of environmental functionality and the adaptability of local communities.

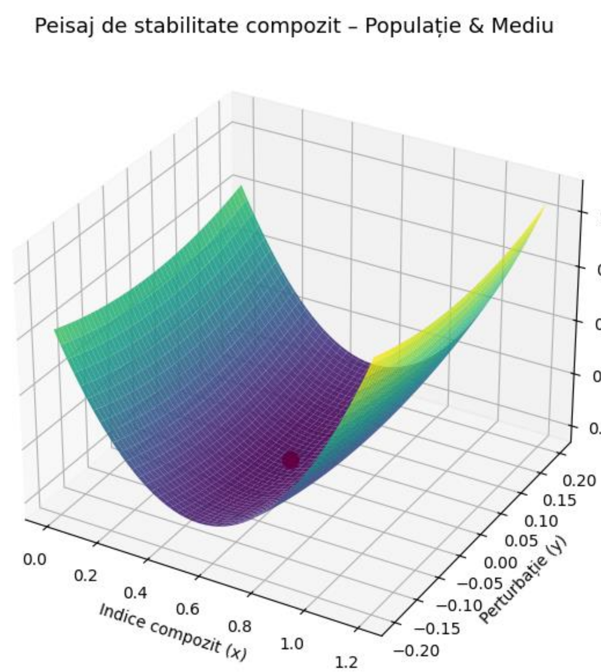


Fig. 5.2. Composite stability landscape for the in rebus sphere of the Călimani SES

The analysis of perceptions collected through the questionnaire and represented graphically in the form of radar charts highlights, first of all, a clear alignment between rural and urban residents regarding the perceived benefits of the natural environment in the Călimani SES. Both rural and urban communities assign high importance (over 85%) to essential resources such as drinking water, timber, useful rocks, clean air, the ecological functions of forests, and the recreational value of the mountain environment. These convergences indicate the presence of well-defined ontological attractors that support the identity resilience of the system. Moreover, these elements represent a common perceptual bridge between different social categories, serving as a cultural and ecological stabilizer. At the territorial level, the analysis of responses differentiated by county reveals a series of structural vulnerabilities. Thus, the counties of Mureș and Harghita stand out with high proportions in the perception of harsh living conditions and conflicts with wildlife, which indicates stronger anthropic pressures and more pronounced administrative limitations. These perceptions differ significantly from those in Suceava, where pressures are felt less acutely, suggesting different local resilience levels influenced by administrative and infrastructural contexts. By correlating uniformly perceived benefits with territorial differences in constraints, a complex picture of the system's ontological dynamics emerges: common attractors- founded on the valorization of natural resources- ensure symbolic coherence of the system, while divergent pressures may generate tendencies of fragmentation or gaps in functional resilience.

The stability landscapes, constructed on the basis of composite resilience indicators (including pollution, demographic trends, and anthropic pressures), highlighted the system's capacity to remain in an alternative stable state, with a positive trend.

The model I have developed is not a deterministic one, but rather a structured form of representing systemic tendencies, using composite indicators based on real data and aligned with resilience theory. Its purpose is not to predict exact outcomes, but to highlight recurrent patterns, causal relationships, and critical thresholds within the Călimani SES. Looking ahead, I intend to improve this model by applying differentiated weights, detailing the variables, and calibrating it using time series or methods sensitive to feedback. Nevertheless, in its current stage, the model succeeds in demonstrating that the Călimani social-ecological system, although subjected to profound structural changes, manages to maintain its functional identity—suggesting a transition toward a qualitatively new but resilient state, with a positive trajectory of reorganization and adaptation, despite a considerable population decline.

The ontological sphere includes the symbolic and perceptual dimension of the system, reflecting mental representations, perceptions, local knowledge, and the values attributed to the environment. This was analyzed through the application of a semi-structured questionnaire addressed to the local population, with the aim of identifying the level of awareness regarding environmental opportunities and constraints, as well as the ways in which these perceptions influence the relationship between humans and the environment. Since in this study the method for evaluating perceptions and knowledge related to the living environment was based on the semi-structured questionnaire, I selected those items where the responses showed clear polarization, with the rural/urban or county-level proportion exceeding a chosen threshold of 85%. From this, the system's attractors can be deduced, meaning the elements in the collective perception of major importance on which the ontological stability of the system depends.

The selected responses were then visually represented through radar charts, using Google Colab.

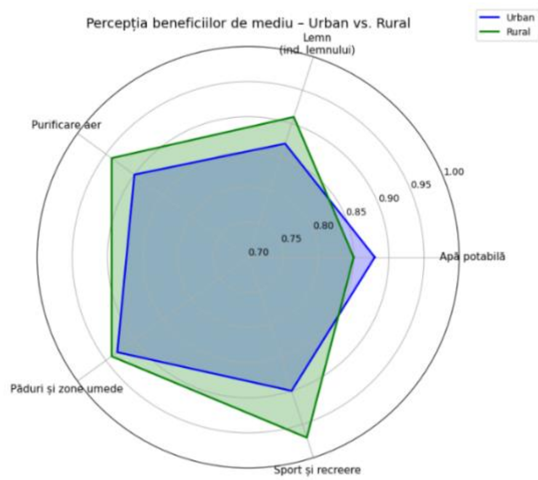


Fig.5.3. Radar chart of urban versus rural population perceptions regarding the benefits of living in a mountain area

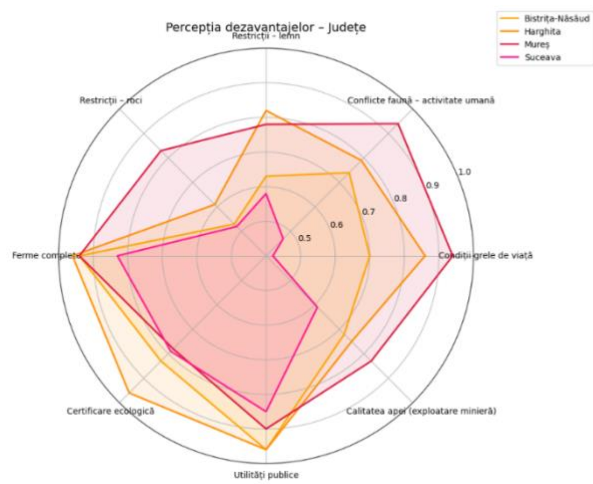


Fig. 5.4. Radar chart of the perceptions of populations from the four counties belonging to the Călimani SES regarding the disadvantages of living in a mountain area

The analysis of perceptions collected through the questionnaire and represented graphically in the form of radar charts highlights, first of all, a clear alignment between rural and urban residents regarding the perceived benefits of the natural environment in the Călimani SES. Both rural and urban communities assign high importance (over 85%) to essential resources such as drinking water, timber, useful rocks, clean air, the ecological functions of forests, and the recreational value of the mountain environment. These convergences indicate the presence of well-defined ontological attractors—factors of symbolic and functional connection between communities and the ecosystem—that support the identity resilience of the system. Moreover, these elements represent a common perceptual bridge between different social categories, serving as a cultural and ecological stabilizer. At the territorial level, the analysis of responses differentiated by county reveals a series of structural vulnerabilities. Thus, the counties of Mureș and Harghita stand out with high proportions in the perception of harsh living conditions and conflicts with wildlife, which indicates stronger anthropic pressures and more pronounced administrative limitations. In Mureș County, for example, 100% of respondents consider the provision of public utilities to be “very important,” while in Harghita 79% of residents indicate problematic interactions with wildlife. These perceptions differ significantly from those in Suceava, where pressures are felt less acutely, suggesting different local resilience levels influenced by administrative and infrastructural contexts. By correlating uniformly perceived benefits with territorial differences in constraints, a complex picture of the ontological dynamics of the system emerges: common attractors—based on the valorization of natural resources—ensure the symbolic coherence of the system, while divergent pressures may generate tendencies of fragmentation or gaps in functional resilience. Thus, these interpolations between perceptions and realities may contribute to anticipating systemic transitions, offering valuable insights for the development of differentiated policies for adaptation and community support.

Based on the modeling carried out in this research, several relevant conclusions can be drawn regarding the resilience and dynamics of the Călimani SES. The stability landscapes, constructed on the basis of composite resilience indicators (including pollution, demographic trends, and anthropic pressures), highlighted the system’s capacity to remain in an alternative stable state, with a positive trend. The depth and shape of the basins of attraction were used to express systemic stability: the deeper and more well-defined the valley, the more the system tends to maintain its balance in the face of shocks. In parallel with this conceptual approach, the perceptual analysis was integrated through radar representations of the most relevant ontological attractors (perceived environmental benefits) and systemic pressures (perceived disadvantages). The questionnaire data show a high level of consensus between urban and rural communities regarding the importance of natural resources (water, timber, clean air, forests, recreation), indicating the existence of stable socio-cultural attractors that contribute to maintaining the identity and functionality of the system. By contrast, the perceived pressures vary significantly between counties, reflecting the different administrative and infrastructural contexts and suggesting differentiated territorial vulnerabilities. Overall, the integration of 2D and 3D graphic representations allows for outlining a robust perspective on the dynamic stability of the Călimani SES. These visual models provide not only a method for qualitative and comparative evaluation, but also a foundation for future quantitative refinements and specific weightings aimed at predicting systemic transitions.

Conclusion

The structure of the thesis is conceived as a logical succession of methodological approaches that progressively build the argumentation, providing the necessary foundations so that, in the final stage, the modeling of stability landscapes can be achieved. The thesis is articulated in two complementary parts: the first part is dedicated to the evaluation of resources within the Călimani SES and the analysis of the impact generated by their exploitation on the environment and quality of life; the second part focuses on the dynamic character of the system, including the conceptual and graphical modeling of the Călimani social-ecological system, with the purpose of interpreting the current equilibrium state.

The natural resources of the Călimani Mountains have represented a fundamental pillar in the formation and maintenance of the surrounding communities, but also with a significant impact on the natural environment, the most considerable being caused by sulfur mining. Although the mining activities ended in 2006, residual pollution persists, especially due to the waste dumps. The hysteresis graph for the polluted water collector from the mining perimeter, the Neagra Șarului River, for the relationship between hydrogen ions and precipitation, highlights a non-linear and dynamic behavior: during the increase phase of precipitation, the pH gradually rises, suggesting dilution of acidity, while during the decrease phase, the pH drops sharply, indicating an ecological memory effect. In the case of iron ions, a different behavior is observed—the concentrations increase with precipitation, but with a delay, suggesting positive feedback and complex mechanisms of mobilization, erosion, and delayed release. Thus, the aquatic system reacts differently to external stresses, and geochemical recovery, although slow, is evident after 1996.

The assessment of the connection between quality of life and the ecosystem services provided by water, corroborated with the responses obtained through the questionnaire, revealed that freshwater resources are the most important for the population of the Călimani SES.

With regard to biological resources, the forest remains the most important bioeconomic resource, providing services of climate regulation, hydrological protection, and raw material. Recent measures of forest certification and investments in bioenergy have led to a more sustainable management of timber resources. However, non-timber resources remain undervalued, and the degradation of alpine pastures through grazing abandonment contributes to ecosystem losses.

Agro-zootechnical activity, supported by the National Agency for Mountain Areas and through the certification of the "mountain product," is on the rise.

The resilience assessment of the Călimani social-ecological system was carried out through an integrated approach, combining qualitative and quantitative methods from the previous chapters, aimed at capturing both the internal dynamics and the current states of the system, providing a comprehensive picture of the types of pressures and of the affected components of the system. The aspects addressed in Chapter 5, the elaborated conceptual model, were presented at the ESEV Conference (Earth Systems and Environment Journal Annual Meeting), 28–30.04.2025, Istanbul, Turkey. The presentation "*An organic design model for studying complex social-ecological systems and their resilience. A case study for the Călimani Mountains, Romania*" (Ionce and Redeker), was awarded as the best paper in the section: *Environmental Earth sciences, environmental processes and systems.*

Through ARIMA modeling of population dynamics, significant trends, potential thresholds, and transition trajectories were identified, contributing to the understanding of historical processes and the adaptive capacity of communities. In addition, the concept of hysteresis was used to highlight the potentially irreversible nature of certain regime shifts in the system, suggesting that returning to a previous state is not always possible, even under similar external conditions.

The resulting model highlights the relative position of the system within a conceptual stability landscape, suggesting its tendency to return to a state of equilibrium under the influence of disturbances. The resilience coefficient for the composite stability landscape of the *in rebus* properties sphere of the SES reflects a moderate balance. Thus, the model indicates a system which, although strongly supported by ecological components (well-conserved environmental factors, or those showing clear tendencies of recovery/hysteresis), remains conditioned by population dynamics, whose stagnation or decline may limit long-term processes of self-organization and adaptation.

Based on the modeling carried out in this research, several relevant conclusions can be drawn regarding the resilience and dynamics of the Călimani SES. The stability landscapes, constructed on the basis of composite resilience indicators (including pollution, demographic trends, and anthropic pressures), highlighted the system's capacity to remain in an alternative stable state, with a positive trend.

The Călimani social-ecological system presents an intrinsic capacity to transition between different alternative stable states, along an irreversible temporal trajectory. These new states of dynamic equilibrium are determined by complex series of interpolated causalities, both anthropic (such as the exploitation of natural resources, decisions of local institutions, modification of community ethos and traditional practices) and natural (climate change, variations of the hydrological regime, seasonality, and cyclical environmental processes). The triggering phenomena (anthropic or natural causes) represent concretizations of historical and natural contingencies. Although they require separate analysis for practical reasons, the observed effects are almost always the result of an interaction between the social and the ecological sphere.

In a future stage of the research, I intend to refine the constellation of methods used and to apply differentiated weights for the elements contributing to the modeling of stability landscapes, according to their relevance and systemic influence. This stage will include both the introduction of new qualitative and quantitative variables, as well as the extension of the analysis period through the use of longer time series that are more sensitive to the feedback mechanisms characteristic of social-ecological systems. The modeling of resilience will be recalibrated by testing a variety of coefficient ranges and by exploring parametric values that can more faithfully highlight the structure, dynamics, and critical points of the analyzed system. Additionally, the integration of exogenous factors- disturbances external to the system- is envisaged, which, although currently having a reduced influence on internal stability, may generate significant medium- and long-term effects on the functions and relationships among the analyzed subsystems. Even though in its current form the studied system proves to be more vulnerable to endogenous pressures (demographic, ecological, or related to community perception), without being deeply affected by external economic or political factors, it is essential to monitor their evolution, especially in the context of global climate change. Subtle exogenous transformations may alter the proportionality and coherence of relationships among system components, thereby influencing its long-term resilience.

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