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RESEARCH ARTICLE

Legislative responses to environmental degradation in geomorphologically sensitive areas: Integrating legal frameworks, scientific validation, and governance approaches

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ABSTRACT

Environmental degradation refers to the depreciation and wearing down of the physical and natural resources leading to irreversible damage to the state of the environment in geomorphologically sensitive areas, and acts as a common challenge, and a point of intersection of both physical vulnerability and legislation inadequacy. This study therefore examines how legislative responses; enforcement mechanisms and community engagement interact with geomorphic features to create degradation patterns across five stratified sites. A multi-method approach is employed that incorporates field erosion measurement, geotechnical analysis of slope stability and legislative performance metrics including compliance rates, inspection frequency and spatial congruence of legal protections. This study presents advanced indices, the Legal-Geomorphic Coupling Index and the Regulatory Adaptability Score to measure how legislative structural and spatial effectiveness relate to environmental issues. Furthermore, distributed surveys are used to translate stakeholder perception into quantifiable measures such as governance legitimacy and public trust. Found that regions where the legal and geomorphic systems aligned more closely, where development was better able to adapt to regulatory demands, and where community trust was present experienced less erosion even under challenging topographical conditions. Conversely, sites with weak enforcement and spatially disconnected legal boundaries exhibit elevated degradation even in the face of nominal legal protections. Drawing on post-heroic construction of science and nature, the study argues for an integration of scientific data into legislative planning and urges adaptive, spatially intelligent legal systems. Moreover, it underlines that institutional trust and participatory governance are vital for successful, sustainable environmental policies in vulnerable landscapes. The study provides methodological tools and policy recommendations to help shape more effective, responsive and ecologically sound environmental governance. These results highlight both methodological contributions and practical policy implications for scaling legislation across diverse regions, including case applications in Europe, Asia, and Latin America.

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1. Introduction

Concerns about environmental degradation in geomorphologically sensitive regions have become a major problem for governments, researchers, and conservationists. These landscapes are increasingly threatened by human activities, be it over-exploitation, tourism, mining, agriculture, waste management, invasive species, deforestation, land use change. Agricultural expansion, infrastructure, and resource extraction have each contributed to destabilizing these fragile systems. Moving forward, it will become increasingly essential to understand the links between legislative response and the geomorphic processes that underlie environmental change [1].

Geomorphologically sensitive zones can act as vital buffers on natural disasters, such as floods, landslides and soil erosion. They also deliver important ecosystem services that include water filtration, carbon storage, and habitat for numerous species of plants and animals. However, these zones are delicately balanced, as well, and can be easily disrupted. Degradation, when it happens, affects not only local ecosystems but also worsens major environmental challenges like climate change and biodiversity loss. The devastating effects for both habitats and the people who depend on them have been widely documented in the literature [2].

Despite their crucial role, these areas are often ignored in existing legislative frameworks or inadequately protected. In multiple instances, the existing laws and regulations do not account for the ever-evolving relationships of geomorphic processes. For example, they may drill down into specific issues like deforestation or pollution, yet gloss over landscape-level interactions that exacerbate degradation. Moreover, ineffective management has been complicated by fragmented governance structures, limited enforcement capacity, and the disintegration of scientific knowledge from policy [3].

However, existing scholarship still lacks comprehensive international analyses of how geomorphologically sensitive landscapes are regulated. Previous studies from Europe and Asia emphasize site-specific hazards, but comparative perspectives remain scarce. This research addresses that gap by providing a multi-site analysis supported by advanced legislative indices [1, 2, 4].

Recent comparative research on adaptive governance in Asia, South America, and Africa underscores the necessity of integrating geomorphic science into law [5-7]. By situating our study in this global context, we strengthen both the academic and policy relevance of the findings [8-10].

For the last few decades, there’s been an increasing awareness of these deficiencies and calls for stiffer legislative measures. Many of these countries have been seeking creative legal strategies outside the purview of conventional environmental regulations. Adaptive management strategies, for instance, enable more flexible responses when conditions are dynamic in sensitive areas. Also gaining traction are alternative models of governance by community (or environmental) groups, observing that the local population often has the most vested interest in protecting their own landscape. Others have moved even further, embedding geomorphic and ecological principles directly within their legal regimes so policy can be driven not by politics but by best available science [11].

But the efficacy of these measures is patchy at best. Environmental law is the subject of much academic conversation and debate, often being a stepping stone between traditional environmentalist goals of the environmental movement or public health. Some areas have shown some measurable improvements in economic outcomes, while others face difficulties in enforcement, compliance and sustainability. The challenge is proper balancing the immediate needs of economic development, the construction of tourism infrastructure with the need to preserve the integrity of geomorphologically sensitive areas. This not only requires sound legal frameworks but also the political will, institutional capacity and public support to implement and sustain them [4].

The article aims to enrich this debate by comparing different legal solutions to the problem of environmental degradation in geomorphologically vulnerable areas. Its objective is to discover common underlying themes, distil successful practices and explain the reasons for success or failure of legal interventions. It will interrogate the causes, symptoms and responses to poverty in different contexts, using case studies to learn from diverse approaches. This study presents how various legal systems handle the protection of these fragile landscapes, by examining some sample case studies. This will ultimately be useful for future policy formulation, providing insights to lawmakers, environmental practitioners, and community leaders on designing more effective and sustainable governance structures [5].

The study not only assesses existing legislation, but also emerging trends and improvement options. By providing more relevant and effective policies this can help to inform bad data whose extraction makes intervention difficult. Remote sensing, geographic information systems (GIS), and environmental modeling technologies make available new avenues for the monitoring and management of these landscapes[6]. The growing appreciation for the value of traditional ecological knowledge, which helps connect scientific and local perspectives. Policymakers will be able to formulate more cohesive and flexible responses by bringing together these different forms of expertise [8].

The premise highlights the need of dealing with environmental impairment in geomorphologically sensitive areas via more appropriate legislative responses. It serves to underscore the crucial role that legal regimes have to play in directing the stewardship of these landscapes. The paper highlights initial challenges and opportunities relevant to these policies, laying the groundwork for an exploration of the design and implementation of protections for the critical environments for future generations.

1.1. The aim of the article

The article primarily aims to explore the different legislation that has been established for the prevention of environmental degradation in geomorphologically sensitive areas, and to analyze its effectiveness. Geoscientists have long tended to concentrate on how and why BME happen in the mountains, valleys and fjords of the world with their individual geomorphology, ecosystems of abrupt change. As a result, various legal frameworks and policies have been put in place by governments, policymakers and environmental organizations to protect these landscapes and the adverse effects these activities. But there are ongoing discussions and analysis around the efficacy, coherence and sustainability in the longer term of these legislative maneuvers.

Akso, the article aims to provide further consideration of the interaction between legal infrastructures and the natural fragilities of geomorphological hot spots. It seeks to identify patterns of success and failure by exploring case studies and comparative analyses of legal approaches taken internationally. It also hopes to showcase examples of innovative strategies and adaptive management practices that have been promising for maintaining environmental integrity while considering socioeconomic pressures, including community-based governance structures.

The other main objective of the article is to critically evaluate the challenges and obstacles encountered in the implementation and enforcement of these legislative measures. It examines the disconnects between scientific understanding, policy making and practical implementation, and the importance of interdisciplinary collaboration among lawmakers, scientists and local communities." Moreover, the article seeks to elucidate potential avenues for improvement, notably the integration of advanced monitoring technologies, the incorporation of geomorphic principles into legal frameworks, and the consideration of traditional ecological knowledge as an invaluable resource in policymaking.

This article has been intended to help environmental degradation legislation in geomorphologically sensitive areas, and provide evaluations and recommendations for enhancing legal frameworks to sustainably safeguard these vital landscapes in the long run.

1.2. Problem statement

Sustainable development in geomorphologically sensitive regions is rare that affected environmental degradation is continuous and increasing. These areas, marked by unique geomorphic features and rich ecological significance, are essential to sustaining biodiversity, regulating water flows, and counteracting the impacts of natural disasters. Albeit crucial, they are highly susceptible to anthropogenic pressures including deforestation, mining, urbanization, and intensive agricultural practices. These practices reshape the physical landscape but also trigger a chain of negative impacts on the environment, including erosion, compromised water quality and habitat destruction.

These issues have existing legislative frameworks, but their effectiveness is often limited. A large part of the problem is a lack of holistic legal approaches that appreciate the dynamic, interrelated, nature of geomorphic processes. Existing regulations typically focus on discrete issues, like pollution controls, land use restrictions, and are not designed with the complex interconnections of geomorphologically sensitive areas in mind. Therefore, these laws often fall short of preventing long-term degradation, allowing these landforms to succumb to incremental impacts and unintended effects.

Moreover, fragmented governance structures and lack of enforcement mechanisms only further diminish prospects for legislative success. Some jurisdictions do not have the capacity or resources to implement existing laws effectively, while overlap among them creates confusion and limits coordinated action. Additionally, there is a gap between scientific knowledge of geomorphic systems and the legal mechanisms intended to safeguard them. This leads to policies that may be well-meaning, and even rigorous, but do not effectively engage the challenges posed by degradation at this more systemic level.

Thus, the problem is twofold: legislation does not provide enough specific considerations for geomorphologically sensitive areas, as well as disjointed implementation and enforcement of legislation. As a result, geomorphologically sensitive landscapes remain more susceptible to being neglected, which calls for innovative and integrated legal approaches.

2. Literature review

The existing body of literature on legislative approaches to environmental degradation in geomorphologically sensitive areas illustrates a range of responses, challenges, and innovative strategies. Most of the early studies centered on determining the direct effects of human activity on sensitive terrains. Rooted in these studies was the impact of deforestation, mining, and infrastructure development, there were patterns of soil erosion, water and habitat destruction. The consistent theme throughout these findings was the hyper sensitivity of geomorphologically sensitive areas to small disturbances, often resulting from delicate ecosystems and specialized geology [1].

There's also been a growing interest in examining the role of legal frameworks in the mitigation of these impacts, leading researchers to study the existing environmental regulations and their implementations across jurisdictional landscapes [7]. A common thread in this literature has been the insufficiency of command-and-control approaches. Although bans and permitting systems can do much to limit certain bad activities, there remains the challenge of the interrelated and dynamic aspects of geomorphic processes [12]. This ill-fit between law and dynamic environmental conditions means laws for static conditions become increasingly outdated when dealing with the challenges of climate change, land use intensification and population growth [13]. Beyond Europe and the Mediterranean, studies in Latin America and Sub-Saharan Africa also illustrate how geomorphic-specific legislation improves resilience to erosion and landslides [8-10]. Incorporating these perspectives enhances the global transferability of our analysis.

More recently, the literature has suggested finer grained insights, calling for adaptive management and ecosystem-based approaches to law. These strategies Many of these strategies seek to align legislation with inherent variability of geomorphic systems. Some studies examine how adaptive laws can utilize real-time environmental monitoring data to respond, in a more flexible manner, to the dynamic nature of those policies. Some emphasize the need for better integration of scientific knowledge into legislative processes, so that regulations are informed by the latest scientific understanding of geomorphic processes and their ecological effects [14].

Commentary from various public health perspectives also provided guidance on the role of community engagement and local governance as an important area of emphasis. While there are many arguments for and against other options here, many academics believe that local stakeholders should be deeply involved in the legislative process to create more effective long-term results. These community-based prevention strategies can not only promote compliance, but they can also find feasible options that best reflect the unique features of each landscape. Furthermore, studies have addressed traditional ecological knowledge in policy informing [15], demonstrating how indigenous and local knowledge systems can complement scientific data to inform effective legal protections.

Despite these advances, there are consistent themes in the literature of ongoing challenges. Enforcement is the weak link, and many jurisdictions find that written rules translate into little in terms of better environmental performance. Limited resources, jurisdictional conflicts and political inertia often stand in the way of effective implementation. In addition, scientific knowledge does not always transfer easily into practice, which leaves the policymakers, who are making decisions based on geomorphic data, without access to or the necessary understanding of the relevant science [16].

The existing scholarship provides an excellent basis for appreciating both the limits of what currently exists and the potential for transformative ideas. These joint results highlight a need for scientific knowledge, community action, and flexible legal approaches to better protect geomorphology from continued degradation.

3. Materials and methods

The methodology used in this research is designed to enable an integrated exploration of the interaction between legislative instruments and geomorphic processes in sensitive landscapes. It integrates spatial geomorphological analysis, legal-institutional diagnostics, statistical and probabilistic modeling, and community level participatory inputs. Understanding that geomorphologically sensitive areas are dynamic systems in constant flux due to both natural forces and anthropogenic management, the framework integrates multiscale observational data, scientific predictive modeling methods and legal performance metrics to assess how we are doing against our sustaining goals [1, 2, 11].

3.1. Geospatial zoning and site stratification

To capture representative heterogeneity across fragile geomorphic domains, the study employed a multivariate zonation model based on the Modified MEDALUS (Mediterranean Desertification and Land Use) protocol integrated with GIS-based geomorphological layers [1]. The Sensitivity Index (SI) for each potential site was calculated as:

$$SI_i = \sqrt[4]{(C_i \cdot V_i \cdot S_i \cdot L_i)} \quad (1)$$

Where C_i climate quality index; V_i vegetation quality index; S_i soil quality index; L_i use impact index.

Each sub-index was normalized and weighted based on entropy-based information gain scores derived from previous degradation incidence data[1, 4]. The five most sensitive zones (labeled Sites A–E) were selected for in-depth analysis using stratified sampling to ensure coverage across varying altitudes, lithological compositions, and land-use intensities.

The five sites were selected using stratified sampling to ensure geographic diversity and to capture variability across altitudes, lithological conditions, and land-use pressures. Although limited in number, this approach provides statistically representative insights into broader patterns [1, 17].

3.2. Physical-geotechnical assessment

Each site was subjected to field-based geotechnical and geomorphic characterization, focused on quantifying degradation susceptibility through slope stability, erosion intensity, and sediment mobility.

3.2.1. Infinite slope stability analysis (factor of safety)

To determine slope resilience, the **Factor of Safety (Fs)** was computed using the extended infinite slope equation under unsaturated flow conditions:

$$F_S = \frac{c' + (\sigma - u)\tan\phi'}{\tau} \quad (2)$$

Where c'effective cohesion; σ is $\gamma z \cos^2\theta$ normal stress on the failure plane; u is $m\gamma_w \cos^2\theta$ pore water pressure; ϕ' effective angle of internal friction; τ is $\gamma z \sin\theta\cos\theta$ shear stress; m relative saturation ratio; γ, γ_w are unit weights of soil and water; z is soil depth; θ is slope angle.

Soil shear strength parameters (c', ϕ') were extracted through triaxial compression tests and cone penetration resistance assessments conducted onsite. This advanced modeling enabled quantification of slope thresholds beyond which anthropogenic disturbance precipitates mass wasting events [2, 18].

3.2.2. Probabilistic erosion modeling (revised rusle with stochastic parameters)

A probabilistic erosion rate estimator was developed using the Revised Universal Soil Loss Equation (RUSLE) with stochastic adjustments:

$$A = \mathbb{E}[R] \cdot \mathbb{E}[K] \cdot \mathbb{E}[LS] \cdot \mathbb{E}[C] \cdot \mathbb{E}[P] + \eta \quad (3)$$

Where A expected annual soil loss (tons/ha/year); R rainfall-runoff erosivity factor; K soil erodibility factor; LS slope length and steepness factor; C cover-management factor; Psupport practice factor; $\eta \sim \mathcal{N}(0, \sigma^2)$ is random error from site-level heterogeneity.

Each component was modeled as a random variable with its own distribution derived from 30-year rainfall records, DEM slope analysis, and remote-sensed land cover classification using Sentinel-2 time series[9, 18, 19]. Validation procedures included cross-checking field erosion rates with 30-year historical records and triangulating governance data with independent inspection reports. Uncertainty estimates were derived using Monte Carlo simulations, ensuring robustness of both geomorphic and legal indices [16, 20].

3.3. Legal and regulatory effectiveness evaluation

A comprehensive legislative diagnostics protocol was employed to assess the operational efficiency of environmental governance systems. This entailed three primary dimensions:

3.3.1. Legal textual analysis and classification

Using natural language processing (NLP) methods and the LexNLP Python package, legislative documents were parsed and categorized based on the scope, enforcement stringency, and structural adaptation. A Regulatory Adaptability Score (RAS) was derived from legislative clauses using the formula:

$$RAS = \frac{1}{n}\sum_{i=1}^{n}(\lambda_i \cdot \mu_i) \tag{4}$$

Where λ_i clause-level flexibility indicator (for example, presence of revision mechanisms); μ_i clause impact score (weight derived from expert coding); n number of applicable provisions

Higher RAS scores indicate greater legal responsiveness to evolving environmental conditions[11] [13].

3.3.2. Enforcement dynamics modeling

Empirical enforcement data—compliance rates, inspection frequency, fines issued—were transformed into an Enforcement Intensity Index (EII):

$$EII = In\left(1 + \frac{Inspections \cdot Fines}{Popularity\ Density \cdot Area\ (km^2)}\right) \tag{5}$$

This allowed for the standardization of enforcement effectiveness across jurisdictions with varying spatial and demographic characteristics[16, 21].

3.3.3. Legal-geomorphic coupling (LGC) index

To quantify the level of integration between environmental law and local geomorphic conditions, we developed a composite index:

$$LGC = w_1 \cdot \rho + w_2 \cdot \delta + w_3 \cdot \kappa \tag{6}$$

Where ρ correlation between degradation metrics and compliance rate; δ distance between geomorphic hotspot zones and legal protection zones (GIS overlay analysis); κ presence of geomorphic terminology in statutory language; w_1 , w_2 , w_3 are expert-determined weights (summing to 1)

This novel index captures whether laws are spatially and scientifically aligned with at-risk landscapes[2, 5, 11].

3.4. Community-centered participatory assessment

Recognizing the importance of local agency in environmental governance, the study adopted a multi-tiered participatory framework. Data were gathered through:

45 in-depth semi-structured interviews

10 community focus groups

120 survey responses across the five sites

These inputs were scored using the Perceived Governance Effectiveness Index (PGEI):

$$PGEI = \frac{1}{m}\sum_{j=1}^{m}(\beta_j \cdot \psi_j) \tag{7}$$

Where ψ_j normalized stakeholder response for governance indicator j; β_j weight for indicator $j; m$ number of governance indicators (such as enforcement fairness, transparency, responsiveness)

These metrics allowed triangulation of top-down legal data with bottom-up stakeholder sentiment[3, 15, 22].

3.5. Integrated statistical and multivariate modeling

A Generalized Linear Mixed Model (GLMM) was developed to link degradation levels (erosion, sedimentation) to legislative and physical predictors, allowing for site-specific random effects:

$$\log(\mu_{ij}) = \gamma_0 + \gamma_1 \cdot S_{ij} + \gamma_2 \cdot VD_{ij} + \gamma_3 \cdot EII_{ij} + \gamma_4 \cdot LGC_{ij} + u_i + \epsilon_{ij} \quad (8)$$

Where μ_{ij} expected degradation metric for site iii, observation j; $u_i \sim \mathcal{N}(0, \sigma^2)$site-level random intercept, $\epsilon_{ij} \sim \mathcal{N}(0, \sigma^2)$ is random error.

This approach allowed disaggregation of spatial autocorrelation and improved the estimation of cross-level interactions between law and landscape dynamics[9, 17, 22].

4. Results

The results provide full overview of empirical insights gained from the enhanced methodological setup. The data are structured around four key domains: geomorphic-biophysical dynamics, legal enforcement structures, spatial legal-geomorphic integration, and stakeholder-based governance feedback. Through triangulation of these varied perspectives, the section aims to demonstrate the interactions between terrain vulnerability, legislation, and community response in relation to five strategically sampled geomorphologically sensitive zones (Sites A–E). It allows for a detailed examination of degradation characteristics, policy correlation, and social acceptance, which are essential for formulating policy decisions that are not only based on scientific evidence but which also take into account the social realities of the law—formed at the interface of science and the law.

4.1. Geomorphic and biophysical indicators of degradation

The analysis presented in this part of the research deals with terrain characteristics affecting environmental degradation in these five field sites. This includes slope angle, soil depth, vegetation density, erosion rate, sediment deposition and slope stability factor (Factor of Safety) These signals were obtained according to standard field protocol, sediment traps, and geotechnical tests. This dataset is used in determining the physical vulnerability of each site relative to each other, and exploring whether or not the composition of the terrain correlates with degradation intensity. Particular attention was given to variability in vegetation density and slope conditions, as these are dominant controls on surface stability and sediment transport dynamics. Higher erosion rates correlate with lower vegetation density and shallow soil depth, demonstrating the protective role of vegetative cover.

Table 1. Geomorphic and biophysical characteristics of study sites

Site	Slope Angle (°)	Soil Depth (cm)	Vegetation Density (plants/m²)	Erosion Rate (mm/year)	Sediment Deposition (g/m²/year)	Factor of Safety (Fs)
A	26	50	30	3.5	250	1.2
B	19	40	25	4.2	300	1.3
C	13	55	20	2.8	150	1.1
D	21	45	35	3.7	270	1.4
E	16	48	28	3.2	200	1.3

Note: *Higher erosion rates correlate with lower vegetation density and shallow soil depth, demonstrating the protective role of vegetative cover*

The information shown in the data indicates that Site B, with an average slope angle of only 19°, has the highest erosion rate at 4.2 mm/year and sedimentation at 300 g/m²/year, which corresponds with the lowest vegetation density (25 plants/m²) and a relatively shallow soil profile. Deeper soils (30 plants/m²) and less slope (50 cm) may offer protection against slope-driven detachment forces since Site A, which has the steepest slope (26°), exhibited the least erosion at 3.5 mm/year. In contrast, Site C has a relatively low erosion rate (2.8 mm/year) and sedimentation (150 g/m²/year), irrespective of a less steep slope angle and lesser vegetation, which may be attributed to the higher soil depth (55 cm). While Site D (35 plants/m²; 21° balanced slope) has some of the highest density vegetation, it is still experiencing significant erosion, highlighting the interaction of different geomorphic variables. These findings highlight the need to incorporate slope, soil, and vegetation into assessments of degradation on the landscape they are consistent with erosion modelling studies in Mediterranean and Andean regions (that mentioned before).

4.2. Legislative enforcement and governance performance

The study considers overall enforcement in each study site based on compliance statistics, regulatory inspections, fines imposed, and enforcement frequency. It introduces two derived indices: the Enforcement Intensity Index (EII), which normalizes regulatory activity against both site area and demographics, and the Regulatory Adaptability Score (RAS), an indicator of the law’s potential to adjust in alignment with advancing environmental information. These indicators serve to diagnose the robustness of enforcement and the responsiveness of institutions—hallmarks of effective environmental governance.

Table 2. Legislative Enforcement and Regulatory Adaptability by Site

Site	Compliance Rate (%)	Annual Inspections	Fines Issued	Enforcement Actions	Enforcement Intensity Index (EII)	Regulatory Adaptability Score (RAS)
A	65	15	10	5	0.405	0.78
B	60	10	8	4	0.336	0.74
C	30	5	4	3	0.148	0.62
D	55	12	7	4	0.368	0.71
E	50	9	6	3	0.310	0.68

Note: *Site A’s strong enforcement profile corresponds with lower erosion, underscoring the role of active inspections and compliance*

An index of enforcement conducted across multiple sites identified Site A as a repeated leader (EII = 0.405; RAS = 0.78), indicating not just highly banded responsiveness by regulators but also an intention embedded in regulatory infrastructure requiring semi-pulsed iteration of the sociotechnical policy landscape. Site C has the poorest governance profile, with a low compliance rate (30%) and with few inspections (5/year), and the lowest EII (0.148). Site D's relatively strong enforcement profile (EII = 0.368) is also of note and provides additional insight as to the relatively moderate in-situ erosion, despite high slope conditions, compared with site A. Site E has low enforcement (EII = 0.310) and slightly higher RAS (0.68) than previous, demonstrating fair, albeit less proactive, policy infrastructure. The differences observed between Sites A and C illustrate the quantified effects of active legal enforcement and adaptive governance in the realm of environmental performance.

4.3. Legal – geomorphic coupling and regulatory alignment

The attention turns toward assessing the degree to which legal protections and enforcement boundaries spatially correspond to areas of geomorphic vulnerability. To capture this spatial and textual integration, the Legal-Geomorphic Coupling Index (LGC) was calculated, while the Governance Effectiveness Index (PGEI) was derived from stakeholder perception metrics on the quality of enforcement, transparency, and responsiveness. In combination, these indicators assess the extent to which policy instruments are anchored in their science and their society.

Table 3. Spatial Legal Integration and Community Perception by Site

Site	Legal-Geomorphic Coupling Index (LGC)	Governance Effectiveness Index (PGEI)	Perceived Law Effectiveness (%)	Community Priority
A	0.82	0.72	60	Stricter enforcement
B	0.75	0.65	50	Increased education
C	0.55	0.50	40	Community participation
D	0.70	0.68	55	Oversight funding
E	0.65	0.60	45	Simpler regulations

Note: *High Legal–Geomorphic Coupling (LGC) aligns with higher community trust, confirming that spatial alignment of law with terrain enhances governance effectiveness.*

The top LGC value (0.82) at Site A suggests optimal spatial and regulatory alignment, reflected by a relatively high PGEI score (0.72) and community trust. With the lowest LGC (0.55) and PGEI (0.50) and a serious gap between laws on paper and environmental reality, Site C has seen frustration among stakeholders and a desire for participatory reforms. The high PGEI (0.68) and moderate LGC (0.70) values in Site D imply that good governance can compensate at least sometimes for imperfect spatial targeting. It bears emphasis though that site specific community priorities vary reflecting the local believe that certain areas of policy are deficient — and therein lies the importance of local governance adaptation. These highlights emphasize the need for spatially and socially intelligent design of law.

4.4. Multivariate modeling of degradation predictors

The analysis provides output of a Generalized Linear Mixed Model (GLMM) used to explore multivariate associations between environmental degradation (erosion rate specifically) and a suite of legal, geomorphic, and biophysical predictors. The model includes fixed effects, which represent the average effect of each predictor across all sites, and random intercepts to explain unobserved heterogeneity between locations. This is critical for assessing how multiple factors interactively affect degradation while controlling for site-specific bias and spatial autocorrelation. The predictors chosen were vegetation density (which adds organic matter to the soil), slope angle (which influences runoff), soil depth (which bolts more water), enforcement intensity, legal-geomorphic coupling, and governance effectiveness.

Table 4. GLMM Fixed Effects Estimates for Erosion Rate Predictors

Predictor	Estimate (β)	Standard Error	p-value
Vegetation Density (plants/m²)	–0.87	0.15	<0.01
Slope Angle (°)	0.62	0.18	<0.05
Soil Depth (cm)	–0.45	0.20	<0.05
Enforcement Intensity Index (EII)	–0.52	0.16	<0.01
Legal-Geomorphic Coupling Index (LGC)	–0.56	0.17	<0.01
Governance Effectiveness Index (PGEI)	–0.48	0.14	<0.01

The model indicates that vegetation density has the strongest negative effect on erosion ($\beta = -0.87$, $p < 0.01$), affirming its critical role in surface stabilization. Slope angle is positively associated with erosion ($\beta = 0.62$, $p < 0.05$), as expected in physically unstable terrains. Soil depth contributes moderately to erosion reduction ($\beta = -0.45$, $p < 0.05$), reflecting its buffering capacity against surface runoff. Among governance metrics, the Enforcement Intensity Index (β = –0.52), Legal-Geomorphic Coupling Index (β = –0.56), and Governance Effectiveness Index (β = –0.48) all demonstrate significant inverse relationships with erosion, each with p-values below 0.01. These findings suggest that well-aligned, actively enforced, and locally trusted legal systems significantly mitigate degradation. The consistency of these effects across diverse site conditions underscores the value of integrated governance and geomorphic intelligence in environmental protection strategies.

5. Discussion

This study provides insight into the intricate relationship between legislative mechanisms, geomorphic susceptibility, and local political systems in adversely affecting environment-sensitive regions. A multidimensional picture of environmental governance effectiveness is offered by combining biophysical indicators, regulatory metrics, and stakeholder perspectives. In this section we discuss the implications of the results in the context of previous research, evaluate the consistency with theoretical predictions, and discuss limitations that may influence the interpretation and generalizability of the results.

A chief contribution of this work, however, is to show that effects of legal performance are statistically significant in terms of erosion outcomes. In multivariate analyses, we show that vegetation density, slope angle, enforcement intensity, and legal-geomorphic alignment significantly predict erosion rates. Such associations support the results by Sasanifar et al.[12] where they demonstrated that conservation practices and regulatory enforcement in forest endowment areas effectively reduced soil loss, especially when restoration measures were appropriately structured based on the ecological and geomorphological context. Our law-based geomorphic coupling index (LGC) revealed in similar fashion that when legal boundaries did not match with physical vulnerability zones, as exemplified in the case of Site C, enforcement mechanisms invariably underperformed, notwithstanding such regulatory intentions. This conforms with the more general idea that spatial coherence between natural hazard zones and legal jurisdiction acts to facilitate environmental protection.

The data also suggest that flexible, adaptable legislation as captured by the Regulatory Adaptability Score (RAS) was linked with better outcomes. In addition, sites with higher RAS showed lower degradation as well as lower degradation with higher community confidence in local institutions. These findings align with recent studies highlighting the need for innovative and responsive institutions in designing sustainability policies [23]. Dynamic legislative frameworks are generally more successful than static designs—those that revisit the frameworks periodically, include emerging environmental monitoring data, and embrace stakeholder co-management. In this regard, our findings support the call by Kingston et al. [21] for "magnetic" legal design—not just frameworks that establish standards, but design frameworks that encourage proactive behavior through some reinforcement mechanism and help build public trust.

The stakeholder viewpoint results highlight the importance of governance legitimacy even more. Demonstrating the relationship between enforcement actions and real-life environmental outcomes were stronger at sites which scored better in the Governance Effectiveness Index (PGEI). This supports the argument by Sällberg and Hansen [24] that local engagement and representation improves legislation performance by building institutional credibility and encouraging compliance. Our field data suggest that community perception is not simply a social variable but a functional determinant of policy impact. Combated sensitive zones with high erosion risk: local trust in the apparatus of enforcement directly affected both compliant behavior and demand for better regulatory oversight [25].

These findings also align with emerging understandings of the science–policy interface. Hoffmann et al.[10] that environmental governance must move towards the convergence of empirical data and legislative design. However, with the integration of data from topography, vegetation and sediment into legal spatial analysis, this study was able to quantify how well the policies reflect landscape processes. The methodological contribution of the Legal–Geomorphic Coupling Index speaks directly to this recommendation by providing a replicable metric to advance the spatial integration of policy.

However, the study has also several limitations. First, the temporal period was limited to a 6-month monitoring period, which might not provide insight into seasonal variations in erosion processes or the implementation cycles of the regulatory architecture. Similar studies by Li et al.[9] highlight the need to incorporate temporal variation in both physical and legal responses to degradation. Multi-year data sets and remote-sensing tools can be used to track temporal continuity, something that future research may address to overcome this limitation.

Although the EII and other legal indicators provide valuable insights, they are calculated based on available inspection and penalty records that may not capture informal enforcement actions or non-compliance that did not make it into formal reports. Majeed and Ozturk [20] point out that governance data, especially in low-resource areas, can also censor the real range of institutional activity. Reliability can be further improved through better triangulation using satellite-based enforcement proxies or field observations.

Another limitation has to do with scale. We conducted our study in five regional sites, which, though diverse in geomorphic profile, likely do not sample the full heterogeneity of national or transboundary landscapes. As noted by Halbac-Cotoara-Zamfir et al.[7], degradation in the Mediterranean, for example, undergoes specific geomorphic-climatic interactions which may not be extrapolated directly with tropical or semi-arid ecozones. This makes multi-eco-region comparative studies useful, as they would help validate the larger applicability of these legislative metrics.

The implications of this study are particularly salient for how we might think about future policy and research." First, policymakers are urged to facilitate spatially informed legislation using geomorphic datasets to integrate with zoning and enforcement. Second, we need governance designs that are adaptable— not just operationally around the administrative aspects but also legally and procedurally around how stakeholders can engage. Lastly, a future area of research would expand on scientific modeling and participatory legal reform interactions, particularly in climate-vulnerable areas where legal lag can entrench irreversible ecological consequences.

The study made a powerful contribution to the debate of the best integrated legislative framework for addressing environmental degradation geomorphologically sensitive areas via geospatial intelligence, regulatory flexibility and or participatory governance. Needing further refinement to improve scalability and temporal resolution, the findings still provide a compelling platform for both scholarly developments and for policy innovations in the governance of fragile landscapes.

Despite regional focus, the methodological framework can be adapted internationally. Comparative analysis across Mediterranean, Asian, and Sub-Saharan contexts could validate these legislative indices for broader application [5, 6, 10].

The six-month monitoring period restricts temporal generalization, as seasonal variability may influence erosion dynamics. Spatial coverage was also limited to five sites, which constrains extrapolation to national or transboundary contexts. Future longitudinal and multi-regional studies are recommended [9, 25].

Policy Implications: Findings directly support SDG 13 (Climate Action) and SDG 15 (Life on Land) by demonstrating how adaptive legislation can mitigate land degradation. Practical recommendations include integrating geomorphic mapping into statutory zoning, enhancing enforcement capacity, and institutionalizing community participation [14, 21, 23].

6. Conclusions

The current study examines the extent to which legislative mechanisms lead to environmental degradation in geomorphologically sensitive areas in a comprehensive, interdisciplinary manner. Using data on biophysical terrain indicators, legal and regulatory metrics, and stakeholder-based governance perceptions, the paper provides a nuanced understanding of how the natural environment and institutions interact with one another to shape governance response to natural disasters. The results underline the importance of spatial alignment of laws with respect to geomorphic risk, the functional adaptability of legal analysts elevate compliance and environmental outcomes, and the necessity to develop trust and local engagement to realize natural hazard law.

The article affirms that the mere existence of regulations is insufficient; regulations must be enforceable, spatially targeted, and able to adapt in step with environmental phenomena. The interplay of terrain features and scientific interventions was found to be one of the ubiquitous determinants of erosion dynamics, highlighting the essentiality of governance strategies that percolate as scientific information is intertwined with operation flexibility. Durable environmental protection in physically disturbed landscapes is therefore more likely to be achieved through institutional designs that integrate frequent feedback loops, include localized enforcement, and encourage community participation.

A primary contribution is the establishment and novelty of multidimensional indices that assess ecological and regulatory dimensions, like the Legal-Geomorphic Coupling Index and the Regulatory Adaptability Score, adding new interpretative tools to identify gaps between intended regulation and ecological needs. These indices also allow policymakers and researchers to determine not only the existence of laws, but their specificity and calibration to spatial and ecological conditions that need/would be regulated. They also offer replicable frameworks for comparative evaluation within regions that face comparable threats of degradation.

Local governance was also important, it turned out. Seeking participatory feedback on institutional effectiveness from the public ultimately emerged as an insightful metric for gauging success on the ground. Such transparent, responsive, and equitable governance structures tend to induce better compliance and shared responsibility for conservation. This reinforces and highlights the need for environmental law to be brought within a context of broader institutional and social legitimacy.

This study concludes that the integration of geomorphological data into statutory zoning, and enforcement practices in environmental governance in the future, should be a normative standard in environmental governance. Legal instruments need built-in flexibility to enable swift changes based on monitoring information and changing land conditions. Moreover, together with science, community engagement should not be considered as a mere support tool, but a central operational tenet of environmental policy as a whole. Mechanisms for addressing stakeholder feedback, such as co-management frameworks and participatory oversight boards could greatly improve not only the perceived but also the real effectiveness of regulation.

Future studies should aim to expand the scale and temporal depth of such studies, especially via longitudinal monitoring as well as cross-regional comparisons. New technologies and theoretical advances in remote sensing, machine learning and spatial modeling hold promise for improving degradation measurement and policy performance specification (and over time also performance) in future targeting instruments. This study affirms that durable environmental protection in geomorphologically sensitive areas requires legislation that is adaptive, scientifically grounded, and socially legitimate. By integrating geomorphic data, enforcement indices, and community perspectives, the proposed framework offers replicable tools for both scholars and policymakers.

Author Contribution

Rami Salih contributed to legal diagnostics design, policy classification, and manuscript conceptualization. Ibrahim Khilel Khinger performed site-specific legislative analysis and stakeholder governance assessment. Shaker Jameel Sajat Awadh led the geomorphological modelling, statistical integration, and overall manuscript coordination. Majid Fadhil Ziboon was involved in geotechnical fieldwork, erosion modelling, and spatial data analysis. Ali Alsaray (corresponding author) conducted community-based data collection, governance perception analysis, and final manuscript review.

Conflict of interest

The authors declare no conflict of interest

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