OPEN ACCESS
PAPER

Mongolian Journal of Geography and Geoecology - MJGG

Received: 09 May 2025; Accepted: 05 June 2025; Published online: 1 September 2025
https://doi.org/10.5564/mjgg.v62i46.4129

Knowledge-based geoecological mapping for sustainable land management in Khuvsgul region

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CITATION
Boldbaatar N, Bayartungalag B, Khaliuna S, Amarsaikhan D (2025) Knowledge-Based Geoecological Mapping for Sustainable Land Management in Khuvsgul Region. *Mongolian Journal of Geograhy and Geoecology,* 62(46), 1–6.
https://doi.org/10.5564/mjgg.v62i46.4129

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ABSTRACT

Geoecological mapping plays a critical role in advancing sustainable land management by enabling the integration of geological, geomorphological, and ecological dynamics. This study elaborated a geoecological map by incorporating detailed geomorphological and ecological information using a knowledge-based mapping approach. The methodology combines rule-based logic, expert interpretation, and the integration of various spatial datasets. Geological relationships, including stratigraphic sequences, lithological associations, and fault structures were encoded within a rule-based framework to ensure spatial and conceptual coherence. Expert knowledge, we derived from pre-existing geological and geomorphological data and supported by conceptual models, guided manual digitization and semi-automated interpretation processes. Multi-source datasets, including satellite imagery, digital elevation models (DEMs), and seismological layers, were integrated using domain-specific reasoning strategies. Geoecological units were delineated by considering the combined cumulative effects of three primary driving forces: (1) endogenic factors, stemming from deep-seated geodynamic processes such as tectonics and seismic activity; (2) exogenic factors, related to surface processes such as weathering, erosion, and mass movement; and (3) technogenic factors, resulting from human-induced changes including land use alterations, infrastructure development, and resource exploitation. The final geoecological map offers a robust analytical framework for understanding landscape evolution, assessing environmental vulnerability, and supporting evidence-based decision-making in land-use planning and natural resource management.

KEYWORDS

Geoecological mapping, Land management, Landscape evolution

1. INTRODUCTION

Geoecological mapping has become an essential interdisciplinary tool for understanding landscape complexity and supporting sustainable land management. It facilitates the spatial integration of geological, geomorphological, and ecological data, thereby enabling the analysis of natural processes and anthropogenic impacts across multiple scales [1], [2]. These integrated frameworks are increasingly important in the face of environmental degradation and the demand for evidence-based land-use planning.

Historically, geoecological mappings were grounded in expert field interpretation and manual cartographic techniques, often limited by data resolution and availability [3]. With advancements in remote sensing, geographic information systems (GIS), and the proliferation of high-resolution digital data such as satellite imagery, DEMs, and geophysical layers the mapping process has become significantly more robust and data-rich [4], [5]. Among contemporary methodologies, knowledge-based approaches have gained prominence due to their ability to embed rule-based logic and expert reasoning into systematic spatial analysis [6], [7], [8]. These methods enhance the internal consistency of geoecological maps by explicitly encoding relationships such as stratigraphy, lithology, and structural geology into reproducible mapping frameworks.

In this study, we developed a geoecological map using a knowledge-based mapping approach that integrates rule-based logic, expert interpretation, and a suite of heterogeneous spatial datasets. Geological relationships including stratigraphic sequences, lithological associations, and fault structures were encoded within a structured rule-based system to ensure spatial and conceptual consistency. Expert knowledge, derived from existing geological and geomorphological data and guided by conceptual models, supported both manual digitization and semi-automated interpretation.

Multiple data sources including high-resolution satellite imagery, DEMs, and seismological datasets were assimilated using domain-specific reasoning strategies to refine interpretive accuracy. Geoecological units were delineated based on the combined influence of three dominant driving forces: (1) endogenic factors related to tectonic and seismic processes, (2) exogenic surface processes such as weathering, erosion, and mass movement, and (3) technogenic drivers including land use change, infrastructure development, and resource exploitation [9], [10]. The geoecological map provides a comprehensive analytical framework for interpreting landscape structure and function. It contributes to improved environmental vulnerability assessments and supports evidence based planning and management of land and natural resources in complex terrain settings.

2. RESEARCH METHODS

This study was conducted in the Khuvsgul region of northern Mongolia, an ecologically and geologically diverse area characterized by mountainous terrain, tectonic activity, and varied land cover types.We used knowledge based geoecological mapping methodology that integrates geological, geomorphological, and ecological data using a rule based framework, expert interpretation, and multi-source spatial analysis. The methodology consisted of four main stages: (1) data acquisition and preprocessing, (2) rule based system development, (3) expert guided interpretation and delineation, and (4) integration of driving forces.

2.1. Data acquisition and preprocessing

A range of spatial datasets was collected to represent the geophysical and ecological characteristics of the study area. This included multispectral satellite imagery from Sentinel-2 and Landsat 8, which were used to assess land cover, vegetation indices, and spectral signatures associated with surface processes [11], [12]. DEMs, such as those derived from the Shuttle Radar Topography Mission (SRTM), were employed for terrain analysis at resolutions of 30 m [13]. Geological and geomorphological maps were sourced from Geological survey of Mongolia and regional archives to provide stratigraphic, lithological, and structural context [14]. Seismological datasets capturing fault distributions and historical seismicity were incorporated to assess endogenic activity [15]. Land use/land cover (LULC) data were obtained from sources including the Google earth engine database [16]. All datasets underwent preprocessing, including geometric rectification, radiometric calibration, coordinate transformation, and terrain attribute derivation (e.g., slope, aspect, hillshed), to ensure spatial consistency and analytical compatibility [17].

2.2. Rule based system development

A rule-based model was developed to integrate thematic layers and define geoecological unit boundaries in a consistent and theoretically grounded manner. The rules captured spatial relationships between lithological units, stratigraphic sequences, and terrain features. Deterministic rules were applied to well-defined phenomena, such as fault traces and lithological contacts, while fuzzy logic was used for areas of transitional characteristics, such as gradual slope changes and geomorphological zones [18]. Terrain thresholds (e.g., slope > 15°) and topographic indices (e.g., topographic wetness index) were used to parameterize landform identification [19]. Implementation was conducted within a GIS environment using ArcGIS ModelBuilder and Python scripting, enabling automated and reproducible classification workflows.

2.3. Expert guided interpretation and delineation

To enhance interpretive accuracy, the semi-automated classification results were refined through expert analysis. Manual digitization was conducted via heads up GIS techniques, supported by conceptual models of landscape evolution and local geological knowledge. This step was particularly critical for resolving ambiguities in complex terrain and transitional zones where automated classifications alone were insufficient. The combination of expert judgment and rule based logic enabled the creation of spatially coherent and ecologically meaningful geoecological units.

2.4. Integration of driving forces

The delineation of geoecological units was based on the cumulative influence of three major categories of driving forces. Endogenic factors included tectonic uplift, lithospheric deformation, and seismic activity, identified through geological structures and seismic datasets [20]. Exogenic factors such as weathering, erosion, fluvial activity, and aeolian processes, inferred from terrain morphology and surface dynamics derived from DEMs and remote sensing imagery [21]. Technogenic influences comprised anthropogenic modifications to the landscape, including agriculture, urban development, mining, and infrastructure expansion, assessed through LULC change detection and impact analysis [22]. These three drivers were evaluated collectively to produce an integrative classification of geoecological zones that reflects the dynamic interplay of natural and human-induced processes. The final geoecological map was subjected to a rigorous validation process. First, spatial overlay analyses were conducted against pre-existing geological and ecological maps to assess topological accuracy [14], [23]. Second, field verification campaigns were carried out at selected representative sites to evaluate the physical correspondence of delineated units. Third, expert panel reviews provided qualitative assessments of thematic and conceptual coherence.

3. RESULT AND DISCUSSION

The geoecological characterization of the Lake Khuvsgul region reveals substantial spatial heterogeneity driven by the interplay of lithology, topography, climate, vegetation, and tectonic dynamics. The classification into ten geoecological zones with nine lithological characteristics reflects environmental regimes shaped by both natural processes and anthropogenic pressures [24].

Lithological diversity is a key determinant of ecological and geomorphological conditions across the region. The northern highlands are predominantly underlain by Precambrian metamorphic complexes and Paleozoic granitic intrusions, which are associated with shallow, acidic soils and coniferous taiga vegetation [25], [26]. In contrast, the southern and central depressions are composed of Mesozoic sedimentary rocks and unconsolidated alluvial deposits that support more fertile soils and steppe grasslands [27]. These lithological variations influence soil-forming processes, hydrological pathways, and vegetation community structure [28].

Geoecological conditions vary across elevation gradients and moisture regimes. The humid high mountain taiga zones exhibit permafrost-affected soils and alpine tundra ecosystems dominated by *Larix sibirica*, *Betula*, and *Vaccinium* species. These zones demonstrate high ecological integrity but are vulnerable to climate-induced permafrost degradation and associated shifts in vegetation [29]. In contrast, semi-arid intermontane depressions and steppe zones are more susceptible to erosion, land degradation, and grazing pressure, particularly in anthropogenically modified areas near settlements and roads [30]. These areas frequently exhibit signs of vegetation thinning, soil compaction, and altered hydrological regimes. Tectonic features further modulate geoecological dynamics. Major fault systems traverse the region and are associated with numerous seismic events recorded between 1964 and 2023 [31]. These tectonically active zones influence terrain formation, groundwater movement, and potential geohazards. The inclusion of recent epicentral data highlights the relevance of seismic risk assessment in environmental planning [33].

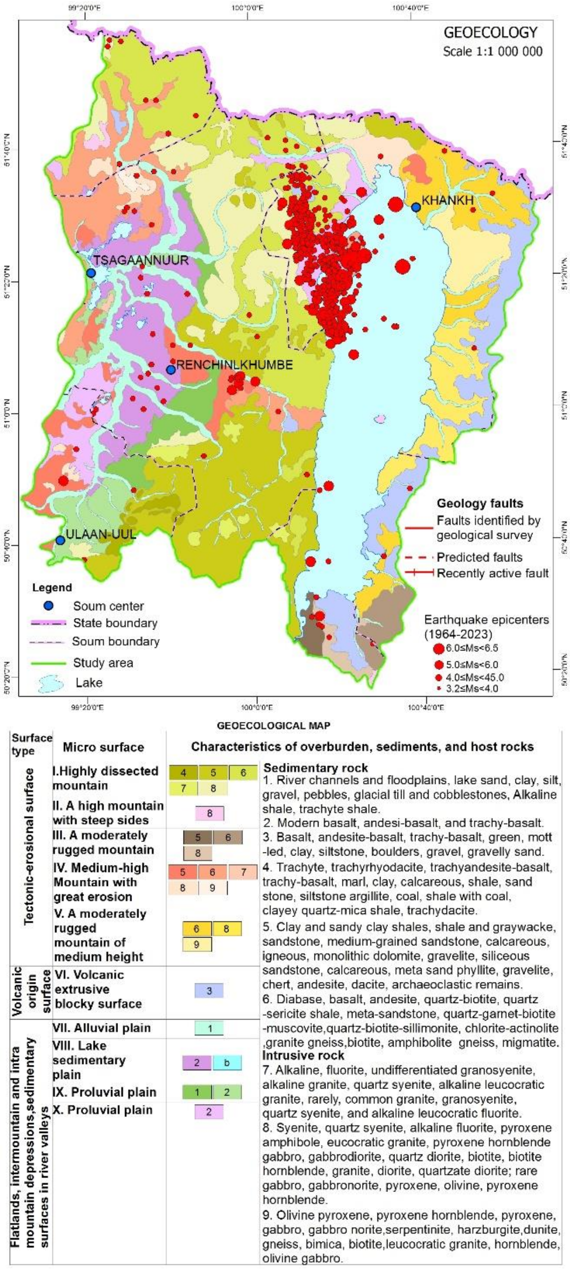

Figure 1. Geoecological map of Khuvsgul region

The integrated geoecological mapping also provides insights into landscape resilience and restoration potential. Zones dominated by intact forests and undisturbed soils offer higher buffering capacity against external disturbances, while areas with fragile soil structure and intensive land use demand targeted conservation and rehabilitation strategies. The multi-parameter approach combining lithology, vegetation, soil, and tectonics enables spatially explicit assessment essential for nature-based solutions and sustainable land management [32]. This study demonstrates that the Lake Khuvsgul region represents a mosaic of geoecological systems governed by deep geological history and ongoing surface processes. Understanding these spatial patterns and their interactions is fundamental to designing adaptive management practices in the face of climate change, land use transformation, and tectonic hazards.

4. CONCLUSION

This study presents a comprehensive geoecological characterisation of the Lake Khuvsgul region, emphasising its pronounced spatial heterogeneity arising from the interplay of lithological substrates, topographic variation, soil properties, vegetation assemblages, and tectonic processes. The delineation of ten geoecological zones, underpinned by nine distinct lithological units, reflects the region's diverse environmental regimes and the cumulative effects of both natural and anthropogenic drivers.

Lithological variability emerges as a fundamental control on soil genesis, hydrological dynamics, and vegetation structure, with marked contrasts observed between the Precambrian and Paleozoic complexes of the northern highlands and the Mesozoic and Quaternary deposits of the southern lowlands. Elevation-dependent gradients further modulate geoecological conditions, producing distinct ecological zones ranging from permafrost-influenced alpine taiga to arid steppe systems increasingly affected by land degradation and human disturbance. Tectonic structures, including active fault systems and recurrent seismicity, introduce additional complexity by influencing geomorphic development, groundwater flow, and landscape stability. These dynamics underscore the importance of integrating seismic risk considerations into regional environmental assessments.

The multi-parameter mapping approach used, incorporating lithology, vegetation, soils, climate, and tectonics, provides a robust spatial framework for evaluating ecosystem resilience, degradation risk, and restoration potential. This integrative perspective is essential for informing nature-based solutions, guiding sustainable land-use planning, and enhancing adaptive capacity in the context of climate change and socio-ecological transformation. Ultimately, the Lake Khuvsgul region exemplifies the illustrates how geological processes and ecological systems are interlinked. Advancing our understanding of such geoecological interactions is critical for the development of science based strategies aimed at conserving ecological integrity and fostering long-term landscape sustainability.

ACKNOWLEDGMENTS

This research was supported by the Mongolian Foundation for Science and Technology (DSTIPCPI - 2022/152). The authors gratefully acknowledge to the Institute of Geography and Geoecology, Mongolian Academy of Sciences for providing the resources and facilities that made this research possible. Special thanks go to anonymous reviewers for providing constructive comments that helped to improve the manuscript.

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