



A Meta-Methodological Architecture for Decision-Relevant Mountain Vulnerability Assessment

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ABSTRACT

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Mountain vulnerability assessment has shifted from indicator-based and spatial approaches toward hybrid frameworks combining GIS, remote sensing, machine learning, MCDA, and statistical-participatory methods. Yet methodological diversity alone does not guarantee that the resulting documents are coherent, robust, or useful for decision-making. To examine the state of methodology in mountain vulnerability research, we conducted a review-based methodological assessment. Following the PRISMA 2020 protocol, we selected 96 articles and carefully analyzed their methodological landscape within a meta-method framework. Data processing, classification, and statistical analysis were performed using Python in the Google Colab environment, based on a reproducible computational flowchart. We examined the documents across several dimensions: methodological groups, methodological architecture, process robustness, output types, and their linkage to decision-making. Results showed that composite architecture dominated vulnerability assessment (83.3%, $n=80$). Uncertainty, however, received limited attention, appearing in only 10.4% of studies. Validation was reported in 57.3% of the reviewed papers. Overall, 57.3% of the studies presented a complete method–output–decision chain. Monte Carlo permutation tests followed by Benjamini–Hochberg correction indicated a significant association between methodological architecture and chain completeness (Cramér's $V = 0.441$; $pFDR = 0.0003$). Temporal shifts in methodological architecture were also evident. Synthesizing the findings within the meta-method framework confirmed an eight stage process: problem framing, vulnerability conceptualization, data architecture, method architecture, aggregation and modeling, validation and robustness, output translation, and decision linkage. The final results suggest that a methodological gap does not actually exist in this field. Rather, the core issue lies in methodological shortcomings, specifically, weaknesses in addressing uncertainty and in connecting to decision-making. As a result, methodological outputs are only partially transformed into decision functions.

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Introduction

Mountain vulnerability assessment has grown into a methodologically diverse field. Early work leaned heavily on indicators and spatial analysis. More recent studies combine GIS, remote sensing, statistical models, machine learning, multi-criteria decision analysis, scenario techniques, and participatory approaches. This expansion has increased analytical capacity. But it has not necessarily produced assessments that are equally robust or useful for decision-making. A study may bring together several advanced techniques and still leave important parts of the analytical process weakly specified. Validation may be missing. Uncertainty may go untested. Outputs may stop at vulnerability maps, indices, or classifications without being translated into a clear decision function. Moreover, methodological complexity can sometimes obscure how individual analytical choices influence the final assessment, making comparisons across studies difficult and limiting the reproducibility of reported findings. These concerns highlight the need to examine not only which methods are used, but also how they are structured, connected, evaluated, and ultimately interpreted. This study examines mountain vulnerability assessment at the level of methodological architecture. We do not ask which single method performs best. Instead, we address three questions. How have methodological families and their combinations changed over time? How are validation, sensitivity analysis, and uncertainty analysis treated? Can an empirically grounded meta-methodological architecture be derived from the literature? Particular attention is given to the connection between method, analytical output, and decision use.

Methods

A systematic scoping review and meta-methodological synthesis was conducted following the PRISMA 2020 protocol. Searches covered 2008–2026 and used Semantic Scholar and OpenAlex. Records were screened for mountain context, vulnerability focus, assessment orientation, methodological evidence, and eligibility for full-text analysis. After deduplication, title and abstract screening, full-text assessment, retrieval, and bibliographic verification, 96 studies formed the final analytical corpus. The studies were coded for several dimensions: vulnerability conceptualization, data architecture, methodological family, method sequence, indicator selection, normalization, weighting, aggregation, modelling, validation, sensitivity analysis, uncertainty analysis, output type, and decision relevance. Methods were grouped into major families. These included index-based approaches, GIS and remote sensing, statistical methods, machine learning, MCDA/AHP, scenario-based analysis, and survey or participatory approaches. Method architecture was then classified according to whether studies used a single family, two-family combinations, or multi-method combinations. Data processing and statistical analysis were performed in Python within Google Colab using a reproducible computational workflow. Associations between categorical variables were examined with Pearson's chi-square statistic and Cramér's V. Because some contingency-table cells had small expected frequencies, statistical significance was estimated using 20,000 Monte Carlo permutations. Benjamini–Hochberg false discovery rate correction was applied to multiple comparisons. The method–output–decision relationship was also coded as a methodological chain, here termed M–O–D.

Results

Methodological combination was the dominant pattern. Of the 96 studies, 53.1% used multi-method architectures and 30.2% combined two methodological families. Only 9.4% relied on a single methodological family. Taken together, 83.3% of the corpus used a combined architecture. This indicates that the field has moved toward methodological recombination rather than the simple replacement of older methods by newer ones. The change was also temporal. Publication period was significantly associated with method architecture after Monte

Carlo testing and FDR correction (Cramér's $V = 0.279$; $pFDR = 0.0143$). Its association with the dominant methodological family was not statistically significant after correction (Cramér's $V = 0.328$; $pFDR = 0.0820$). Thus, the more evident change concerns how methods are assembled within assessments.

Methodological robustness analysis provides an alternative viewpoint on the data. According to the statistics provided above, 57.3% of studies demonstrate validation. In case sensitivity analysis is considered, the percentage goes down to 14.6%. Importantly, 10.4% of studies were distinguished by uncertainty analysis. One more important point relates to the relationship between vulnerability outputs and decision-making that was revealed in 69.8% of cases. When the chain was expanded to include explicit vulnerability conceptualization, identifiable method architecture, identifiable output, validation, uncertainty analysis, and decision linkage, only 6.2% satisfied all six components.

The statistical results support this distinction. Method architecture was associated with the completeness of the M–O–D chain (Cramér's $V = 0.441$; $pFDR = 0.0003$). The dominant method family was also associated with chain completeness (Cramér's $V = 0.417$; $pFDR = 0.0054$). By contrast, robustness architecture alone showed no significant association with M–O–D completeness after FDR correction (Cramér's $V = 0.209$; $pFDR = 0.1817$). Methodological plurality, in other words, cannot by itself be treated as evidence of methodological integration. The review of the literature from a robustness perspective shows that the concept of “uncertainty” is used in many ways. Some of the papers performed simulation and global sensitivity analysis. In other papers, model or scenario uncertainty was analyzed using either an ensemble analysis, diagnostics, or the comparison of models' performance. There were also three papers in which uncertainty was viewed as a part of the research, a suggestion, or methodological issue, but not as an element of the evaluation process. Some variability was also seen in validation techniques. Among 55 papers that used some type of validation technique, 26 used predictive or statistical validation, such as cross-validation, AUC/ROC, and other performance measures. Nine papers compared their model outputs with field data or other data. In three papers, the validation was performed by experts or stakeholders, and in 17 papers, no information on validation methods was provided. This variability is important, since they reflect different aspects of evaluation process. The first one is discriminatory ability, while the second one refers to performance versus observation.

Conclusions

The synthesis produced an eight-stage meta-methodological architecture: problem framing, vulnerability conceptualization, data architecture, method architecture, aggregation and modelling, validation and robustness assessment, output translation, and decision linkage. These stages describe functions that need to be connected, not a prescribed sequence of techniques. The main methodological problem identified in the literature is therefore not a shortage of assessment methods. The field already contains a wide range of analytical tools and increasingly combines them. The weaker point lies elsewhere. Uncertainty is rarely examined explicitly. Validation remains incomplete. Analytical outputs do not always reach a clear decision function. For mountain vulnerability assessment, the practical question is consequently less about adding another method and more about maintaining a defensible analytical chain from the definition of vulnerability to the use of results in planning, management, or policy.

باشد. این مدل پتانسیل این را دارد که به یک چک لیست تبدیل شود که دیدگاهی پیش رو در فرآیند ارزیابی وجود دارد را بهتر هدایت کند (Utassee et al., 2016; Kee et al., 2025).

این مطالعه اگر چه نکات مشخصی را برجسته کرد اما از محدودیت‌هایی هم برخوردار است. اول این که اگر چه مطالعه ۹۶ مطالعه را بررسی کرد اما با سوگیری مقالات منتشر شده از یک سو و از سوی دیگر مقالات قابل ارزیابی رودرو است. لذا نمی‌توان ادعا کرد نمونه کاملی از تمامی مطالعات بالقوه مرتبط با آسیب‌پذیری کوهستانی به شمار می‌آید. سوگیری بعدی که وجود دارد به انتشار مقالات در کشورهای شمال باز می‌گردد که به طور متعارف بسیار بیشتر از کشورهای جنوب است که خود یک موضوع قابل تامل است. درنهایت باید اشاره کرده که جداول توافقی پراکنده، مورد استفاده در تحلیل مونت کارلو تفسیر زیرگروه‌ها را با دقت بالا محدود خواهد ساخت. به عبارت دیگر توصیه می‌شود که یک آزمایش بر اساس چارچوب شناختی که در بالا بحث شد انجام شود و نتایج آن گزارش شود. در مورد دیگری که در آن امکان استفاده از این چارچوب در مناطق کوهستانی با انواع مختلف دسترسی به داده‌ها و رژیم‌های خطر مورد بررسی قرار گرفته است. این پیشنهاد مطابق با آن تغییر کرده و پس از تایید به پروتکل تابیدشده تبدیل خواهد شد. لازم به ذکر است که چون فرایند کدگذاری دوگانه برای تمام مواد کدگذاری شده انجام نشده است، ممکن است سوگیری طبقه‌بندی در میان متغیرهای تفسیری ایجاد شود. اما این مشکل از طریق راهنمایی‌های از پیش تعریف شده و ارجاعات متنی حل شده است.

نتیجه‌گیری

هدف از این مطالعات عبارت بود از ارزیابی مبتنی روش‌های ارزیابی آسیب‌پذیری مناطق کوهستانی مبتنی بر چارچوب بر فراروش تعدد ۹۶ مطالعه مستقل در این تحقیق در بازه زمانی ۲۰۰۸ تا ۲۰۲۶ استفاده شد. نتایج بیانگر آن بود که ارزیابی آسیب‌پذیری در مناطق کوهستانی از تحلیل‌های تک روشی فراتر رفته است. اما تنوع‌گرایی روش‌شناختی قادر به ارزیابی معماری کامل این مطالعات نبوده است. لذا یک چرخه ناقص از زنجیره روش خروجی و تصمیم‌گیری شکل گرفته است. اگر چه که در این فرایند روش‌های ترکیبی در حال حاضر غالب است اما درمقابل عدم‌قطعیت حاکم بر دستاوردها موضوعی چالش‌برانگیز در این حوزه است. از سوی دیگر انتقال نتایج به دست آمده به فرآیند تصمیم‌گیری از الگوی ناقصی برخوردار است. در بهترین حالت قوی‌ترین نتیجه ساختاری به دست آمده موید ارتباطی متوسط بین معماری روش و کامل‌بودن زنجیره M-O-D است که خود جای بررسی عمیق‌تری دارد.

افزودن بر این‌ها، به نظر نمی‌رسد توسعه ابزارهای تحلیلی جدید، اگر به صورت هم‌زمان به انسجام معماری ارزیابی توجه نشود، به‌تنهایی برای رفع این شکاف کفایت نخواهد کرد. تمرکز بر تکمیل زنجیره از چارچوب‌بندی مسئله و مفهوم‌سازی آسیب‌پذیری، از طریق معماری داده و روش، مدل‌سازی استوار، ترجمه خروجی و پیوند با تصمیم در قالب یک چارچوب هشت‌مرحله‌ای پیشنهادی گزینه‌ای تعیین‌کننده برای رفع این مشکل ساختاری است. لذا همین موضوع نیز می‌تواند بنیاد مطالعات بعدی برای بهبود ساختاری مبتنی بر داده‌های تجربی فراهم سازد.

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