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An integrative hazard-ecology-perception framework for cultural landscape planning

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ABSTRACT

Cultural landscapes are increasingly vulnerable to the compounded effects of potential risks, ecological degradation, and imbalanced heritage value perceptions under intensifying climate change and global urbanization pressures. However, there is a lack of framework that systematically integrates geographical hazards, ecological sensitivity, and both expert and public heritage value perceptions to guide differentiated conservation and development of cultural landscapes. This study proposes a Hazard-Ecology-Perception Landscape Planning (HEPLP) framework to provide a spatially explicit decision-support tool that unifies hazard, ecology, and perception dimensions for cultural landscape planning. HEPLP is evaluated in a case study of Chengde Mountain Resort. A GIS-based methodology is employed to characterize geographical hazards and ecological sensitivity by combining concept of entropy and Analytic Hierarchy Process. Expert scoring and large language model content analysis are used to map heritage value perceptions. Risk-based analysis and three-dimensional clustering revealed nine distinct clusters in cultural landscape, providing spatially grounded evidence for targeted conservation and development strategies. This includes many scenes where previously implemented landscape planning strategies have been designated for complete conservation, as well as clusters where trade-offs between ecological sensitivity and heritage value perception are carefully balanced. Unlike previous frameworks that focused on single or dual dimensions, HEPLP offers an integrative tool for sustainable cultural landscape conservation and development under environmental and social challenges.

1. Introduction

Cultural landscapes are increasingly exposed to both natural and anthropogenic threats under the dual pressures of accelerating extreme climate change and global urbanization (Cook et al., 2019; Coombes and Viles, 2021; Sesana et al., 2019). The aggravated effects of frequent geographical hazards and the degradation of ecological sensitivity has significantly undermined various heritage value perceptions that define the heritage significance of cultural landscapes (Bosher et al., 2020).

Heritage value perception is not a neutral description of landscape quality but actively shapes which places are conserved, how land-use priorities are set, and which interventions are considered suitable (Yang and Shen, 2025). Indeed, heritage value perception often prioritizes expert perspectives over public perception, which can lead to professional conservation efforts that are disconnected from local-environmental realities, daily habitat, tourism experience, insufficient public engagement, and overly singular value recognition (Avrami et al., 2019). When expert perceptions prioritize certain cultural landscape features, authenticity and integrity, they may become positioned along the ecologically sensitive configurations or the edges of geographical hazards. Conversely, when areas that sustain robust ecosystem services are undervalued in both expert and public perceptions, they are more easily overlooked, which in turn weakens the ecological restoration capacity that supports the broader cultural landscape (Romanazzi et al., 2023).

The physical structures and ecological evolution of cultural landscapes worldwide suffered from geographical hazards like landslides, collapses, floods, and wildfires (Julià and Ferreira, 2021). Previous studies (Connolly, 2019) also fail to account for ecological sensitivity of cultural landscapes, which is often intertwined with the distinct regional characteristics shaped by historical land-use practices, thereby compromising conservation efforts. Meanwhile, urban encroachment, industrial land conversion, and poorly planned infrastructure irreversibly reduce the resilience and adaptive capacity of cultural landscapes to withstand environmental disturbances (Coombes and Viles, 2021). These spatial transformations also erode local identity symbols and

collective social memory, which are rooted in everyday lived spaces and sustain shared social meanings, making them central to how communities perceive heritage value (Tang et al., 2025). As community perception weakens, the social participation and capacity to monitor emerging geographical hazards, recognize ecological sensitivity, and support sustainable conservation and development is reduced, which in turn exacerbates vulnerabilities across all three dimensions (Li et al., 2025).

Instead of relying solely on the aesthetic appeal or economic potential of cultural landscapes, the conservation and development must integrate scientific approaches to characterize them in three dimensions: hazard, ecology, and perception. It is important to note that conservation and development should be grounded in the Outstanding Universal Value framework set by UNESCO (UNESCO, 2010), while emphasizing integrative and holistic cultural-natural balance, which provides a principle that advocates for the continuity, resilience, and long-term sustainability of cultural landscapes beyond overly tourism-driven interests (Min, 2025).

Landscape planning adopts landscape as an integrative approach to systematically coordinate spatial and temporal dimensions across multiple scales, elucidating the interactive mechanisms among geographical structures, ecological attributes, and human cultural dynamics (Arts et al., 2017; Reed et al., 2020; Lian et al., 2024). As a methodological approach, landscape planning offers high spatiotemporal interpretability, providing a systematic toolkit for the mapping, characterization, and assessment of cultural landscapes (Arts et al., 2017). As a process, it encodes geomorphological evolution, ecosystem dynamics, and the progression of social perceptions within landscape forms. As a carrier, it materializes socially constructed elements such as cultural memory, place identity, and disaster experiences, which collectively shape heritage value perception, influencing how communities interpret signals and meanings from geographical hazards and ecological sensitivity (Li et al., 2025). As a mediating interface, the landscape harmonizes ecological processes and human behaviors, serving as a junction of risk governance and cultural transmission (Freeman et al., 2015; Reed et al., 2020). Within the Hazard-Ecology-Perception Landscape Planning (HEPLP) framework, landscape planning therefore provides the organizing logic that brings these three dimensions together. Geographical hazard assessment produces landscape's physical layers of potential risks, while ecological analysis identifies landscape patterns of sensitivity, and expert and public heritage value perceptions are mapped as landscape intangible surfaces. It enables the identification of discrepancies between perceived heritage values and the vulnerabilities of environmental systems, and it reveals how the heritage values of sustainable but overlooked cultural landscapes are often marginalized in both expert and public perceptions, thereby supporting the reconstruction of the social foundations of cultural landscapes (Sánchez et al., 2020; Tappeiner et al., 2020).

Grounded in its interdisciplinary functionality of landscape, landscape planning provides practical pathways for translating substantive theories into implementable strategies for conservation and development of cultural landscape (Lian et al., 2024; Sánchez et al., 2020). In HEPLP, landscape planning integrates these inputs in a common spatial reference, enabling them to be overlaid, clustered, and interpreted as coherent landscape units. Functionally, this integration allows HEPLP to practically diagnose various issues such as where high heritage value coincides with high hazard or high ecological sensitivity, where undervalued areas provide critical ecological contribution, and where planning priorities need to be adjusted. Finally, HEPLP applies landscape planning to convert the three dimensional inputs into cluster-targeted planning units and zoning specific recommendations for implementing conservation and development. This study refers to the application of landscape planning in cultural landscapes as cultural landscape planning.

However, few existing theoretical frameworks have yet integrated the interactions and coordinated analysis of geographical hazards, ecological sensitivity, and heritage value perception into cultural landscape planning (Fig. 1). These aspects have largely been investigated in individual dimensions.

Hazard-centered frameworks such as the Indicator-Based Risk Assessment quantify cascading chain effects among indicators (Nguyen et al., 2022; Ravankhah et al., 2021). The Multi-Hazard Risk Prioritization Framework integrates multiple hazards through overlapping correlation spatial matrices at different priority levels (Sevieri et al., 2020; Julià and Ferreira, 2021; Lombardo et al., 2020). But in both approaches, hazards are mainly treated as physical exposure and expected damage, with limited attention to how ecological sensitivity constrains feasible interventions or how heritage values shape the outcomes of strategic planning.

Ecological related research rooted in landscape ecology emphasizes the interaction between spatial configurations and ecological processes, offering a foundation for assessing sustainability in cultural landscapes (Tappeiner et al., 2020). Extending this perspective, Nature-Based Solutions embed ecology within spatial design to align multifunctional systems(Coombes and Viles, 2021), while Urban Political Ecology exposes power-driven environmental injustices and more equitable ecological governance (Connolly, 2019). However, they usually assume that strengthened ecological functioning will automatically support heritage values and they rarely examine explicit trade-offs between hazard risks, ecological thresholds, and the zones' heritage value that significantly perceived by experts and public.

Perception-oriented frameworks, including the Historic Urban Landscape and Cultural Landscape Gene Theory, emphasize how cultural perceptions shape historical layers and evolutionary patterns (Hu et al., 2021; Ferreira et al., 2023; Rey-Pérez and Pereira Roders, 2020). Complementing this, Environmental Psychology examines spatial behavior, experience, and emotion, underscoring psychological structures that influence heritage value perception (Hussein et al., 2020). These approaches clarify how heritage values are formed, but hazards and ecological processes often remain background assumptions rather than integral analytical components. Additionally, empirical applications still rely mainly on expert judgment, with few attempts to systematically integrate both expert and public perspectives at the landscape scale.

Beyond single-dimensional analyses above, several studies introduce two intersecting theoretical perspectives. For example, the Landscape Vulnerability Model combines external environmental stressors with internal ecosystem disturbances, including soil, vegetation, and hydrological processes, together with potential hazard exposure, to generate a unified and functionally coupled index of vulnerability (Chen et al., 2023; Cook et al., 2019; Sesana et al., 2019). But heritage is usually represented only indirectly through biophysical metrics, so distinct values in what various stakeholders perceive are not explicitly captured. A Customized Disaster Risk Management framework has been proposed to align responses to climate change with the diverse perceptions of heritage values across regions (Bosher et al., 2020). Nevertheless, it offers limited operational guidance on how to integrate inside and continuously long-term socio-ecological interaction into spatially explicit zoning decisions. This approach reshapes stakeholder governance mechanisms, enhances the adaptive capacity of unconventional hazard buffer zones, and embeds participatory strategies that are rooted in community practices (Bosher et al., 2020; Durrant et al., 2023). The Cultural Ecosystem Services framework highlights how ecological processes support the formation of cultural identity and shared visions embedded within cultural landscapes (Csurgó and Smith, 2021). In addition, Social-Ecological Systems framework emphasizes the dynamic coupling between ecological disturbances and socio-cultural structures, focusing on feedback-driven mechanisms (Heslinga et al., 2017). However, these influential frameworks mostly capture perception values but remain descriptive and ecosystem-function centric lacking the integration with hazards.

Taken together, this body of work is rich but fragmented. Existing
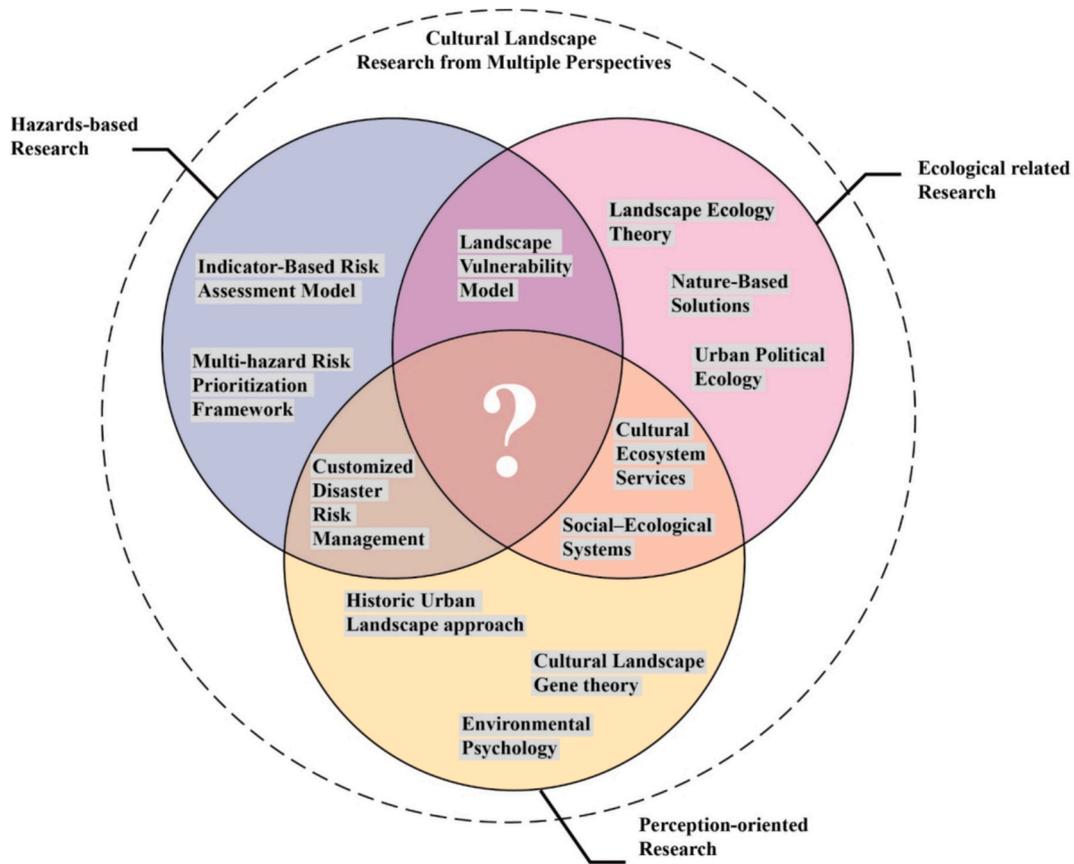
Fig. 1. A critical overview of relevant theoretical frontiers: multidiscipline, overlap, and research gap.

studies only partially overlap across hazard, ecology, and perception perspectives and rarely provide an integrative framework that simultaneously links them together, to support differentiated conservation and development strategies inside the entire cultural landscape. This fragmentation limits both theoretical understanding and practical capacity in landscape planning to anticipate how trade-offs between risk reduction, ecological thresholds, and heritage values shape long-term resilience and sustainability.

This paper investigates how cultural landscapes can be systematically characterized under the combined pressures of geographical
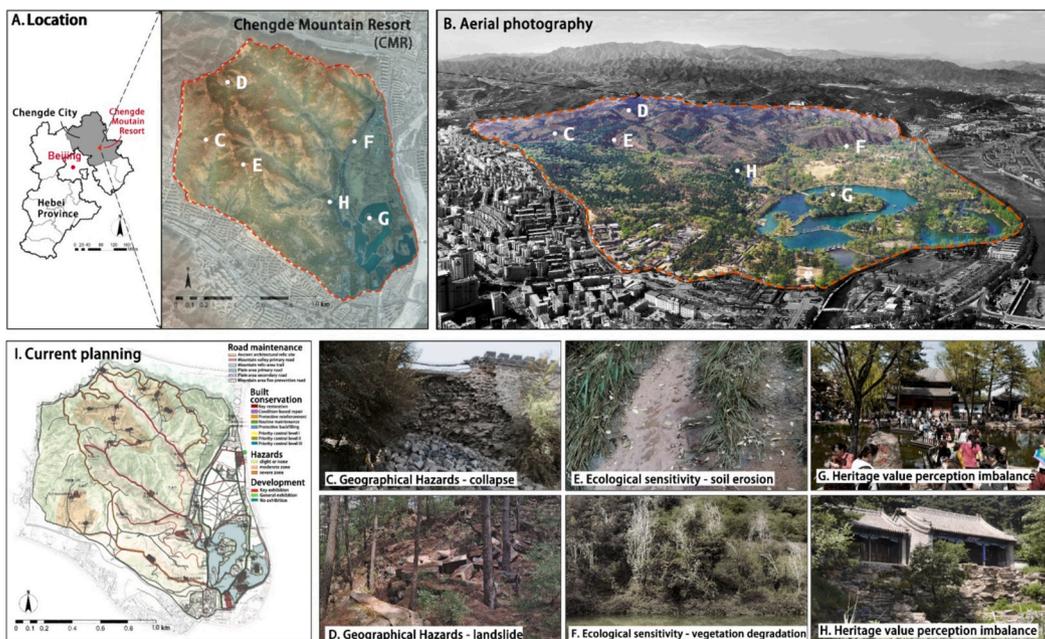
Fig. 2. Location and aerial photography (A-B). Multi-Dimensional challenges in CMR: geographical hazards (C–D), ecological sensitivity (E-F), and heritage value perception imbalance (G-H).Current planning(I).

hazards, ecological sensitivity, and heritage value perception. and how such charaterization can improve cultural landscape planning. To address this, HEPLP is developed with a GIS-based method that integrates entropy and Analytic Hierarchy Process for hazard and ecological analysis, together with expert scoring and public content analysis for value perception. Therefore, risk-based analysis and three-dimensional clustering are used to delineate planning units and identify clusters with distinct combinations of hazard, ecology, and perception. The main contribution of this study is to unify expert and public heritage value perceptions with geographical hazard and ecological assessments in an intergeated system to derive cluster-targeted balanced conservation and development strategies. In this way, HEPLP advances the cultural landscape planning from isolated descriptive analyses toward an integrative and predictive framework.

2. Method

2.1. Study area

This study analyzes the Chengde Mountain Resort (CMR), which is a typical cultural landscape case for other universal applications (UNESCO, 1994). Built in 1703 in Hebei province, China (Fig. 2. A-B), the CMR has an area of 5.64 km^2, comprising 144 smaller **scenes** that reflect the historic scenic spots like other cultural landscapes, including fantastic views, buildings, courtyards, rockeries, waterscapes, and vegetation. In total, 144 representative scenes are used (named and numbered by the design emperors) in this study.

CMR was inscribed on the UNESCO World Heritage List in 1994. It embodies a distinctive spatial expression of the understanding of landscape order. Integrating political, religious, ecological, and aesthetic values (UNESCO, 1994), CMR represents a concentrated manifestation of the philosophical concept of harmony between humans and nature. Its heritage significance is not only tied to national historical memory and identity but also offers the international community a unique perspective on oriental culture (UNESCO, 1994).

CMR faces challenges related to geographical hazards, the degradation of ecological sensitivity, and imbalances in heritage value perception, which critically undermine the authenticity, integrity,and sustainability of the CMR (Jun, 2020; Pan et al., 2024; Shi et al., 2025). CMR is located in the transitional fault belt of the North China Plain, an area historically prone to seismic fault activity and characterized by complex geological conditions (Shi et al., 2025). The intersections between mountainous terrain and historic structures are particularly susceptible to landslides and collapses (Fig. 2. C–D). CMR also experienced ecological degradation due to climate change and anthropogenic disturbances, including soil erosion, vegetation decline, and siltation and shrinkage of water systems (Pan et al., 2024)(Fig. 2.*E*-F). Public attention is predominantly concentrated on the core imperial architecture, while more remote areas which are rich in ecological, religious, and historical significance are largely neglected(Fig. 2.G-H) This imbalance in perception narrows public understanding of the cultural landscape's full value and results in an unequal allocation of conservation resources (Jun, 2020).

However, current planning presents three main limitations (Fig. 2. I). First, it does not cover all scenes but instead focuses primarily on those with intact conservation. Second, while hazards and ecological conditions are addressed, the approach remains at an area-based planning level and lacks detailed conservation and development strategies for individual scenes. Third, it does not consider the balance of public perception. Scenes that are highly attractive are often prioritized for development, resulting in a concentration of tourism hotspots.

2.2. Data collection

Our research data consist of three components: (1) geographical hazards data, used for risk assessment and determination of

conservation levels; (2) ecological sensitivity data, applied to ecological zoning analysis of CMR; and (3) heritage value perception data, used to evaluate both expert and public perceptions of different scenes. Details are listed in Table 1.

2.3. Justification for the selection of the indicators

This Table 2 functions as a structured reference for the indicator system used in the HEPLP framework at the CMR. It clarifies how geographical hazard, ecological sensitivity, and heritage value perception indicators are selected and categorized, and explains the role each variable plays. By linking indicators to their specific functions, the table ensures coherence in integrating multi-source evidence for scene-level assessment and planning decisions.

2.4. HEPLP framework

Fig. 3 shows the stepwise workflow of the HEPLP framework through three stages. Step 1 identifies hazard risks using Information Quantity Model (IQM) and Analytic Hierarchy Process (AHP), generating six risk levels where scenes at Risk I are marked with white circles and set for complete conservation. For the remaining scenes, Step 2 conducts analysis on ecology and perception, combining Entropy Weight Method (EWM) and AHP with 50% equal weighting to calculate ecological sensitivity and merging expert scoring with public evaluations derived from LLM analysis. Step 3 integrates a three-dimensional clustering defined by ecological sensitivity, expert perception, and public perception. The natural breaks method is used to distinguish high (H) and low (L) levels for each dimension, and the results are matched to form eight composite clusters (HHH,HHL,HLH,HLL,LHH,LHL,LLH,LLL), revealing explicit trade-offs between ecological sensitivity and heritage value perception. Colored arrows trace the flow of information across steps, while gradient bars illustrate the transition from hazard exclusion to ecology-perception coupling and finally to spatial planning outputs for balanced conservation and development.

2.5. Data analysis

2.5.1. Geographical hazards analysis

A circle with a radius of 50 m is selected as the basic environmental unit, and statistical analysis is conducted on the data within the unit. A radius of 50 m is selected as the basic environmental unit because this scale effectively captures the local topographic and environmental conditions surrounding each scene that directly influence potential geographical hazards. The 50 m spatial extent aligns with the typical physical size of individual scenes in the CMR and matches the spatial resolution of the DEM and land cover datasets, allowing local variations to be represented while avoiding excessive sensitivity to single-pixel noise or over-smoothing of overlapping features. This radius therefore provides a balanced scale between preserving fine-grained spatial detail and ensuring stable analytical outcomes. It is also a commonly adopted unit in geohazard sensitivity studies (García-Grajales et al., 2023; Shi and Zhang, 2022), which enhances the spatial discriminability and methodological reliability of the HEPLP framework.

The study is based on the IQM, and its theoretical foundation is information theory (Ash, 1966). We adopt IQM because its entropy formulation allows indicator contributions to adjust automatically according to their internal variability and information content, thereby reducing subjective weighting and enhancing objectivity and discriminative power (Lin et al., 2021; Zhang et al., 2023). At the same time, IQM is robust under heterogeneous multi-indicator conditions, and its quantile-based integration avoids extreme-value effects, harmonizes differing scales, and provides interpretable factor contributions, which facilitates the derivation of planning-relevant risk classes (Lin et al., 2021). The equation of IQM follows:

Table 1

The three categories of data.[*]

Data category	Data type	Data format	Data source
Geographical hazards data	Landslide and rockfall occurrence points	Vector points	- Official Plan for the Overall Conservation of the Ancient Ruins of the CMR from Chengde Cultural Heritage Bureau (CCHB) -The Mapping and investigation team from the Cultural Heritage Conservation Center (CHCC) of Beijing Tsinghua Urban Planning & Design Institute (THUPDI) -Faults Map of Hebei from the China Geological Survey (CGS)
	Lithology Groundwater Level Gully Development Water Erosion Geomorphic Unit	Raster data	
	Distance to faults		
Shared data (used in both hazard and ecological sensitivity analyses)	Coniferous and broadleaf mixed forest (land use) Coniferous Forest (land use) Broadleaf Forest (land use) Grassland (land use)		-CMR vegetation database (Total station field digital coding with RTK for each single tree) from Chengde Cultural Heritage Bureau (CCHB)
Ecological sensitivity data	Water body (land use) Slope (topography) Construction Land (land use) Distance from Roads (Anthropogenic factors) Distance between Scenes (Anthropogenic factors) Elevation (topography)	Vector polygon to raster data	- Official Plan for the Overall Conservation of the Ancient Ruins of the CMR from Chengde Cultural Heritage Bureau (CCHB) -The Mapping and investigation team from the Cultural Heritage Conservation Center (CHCC) of Beijing Tsinghua Urban Planning & Design Institute (THUPDI) -CMR close-range photogrammetry database from Chengde Cultural Heritage Bureau (CCHB). -High-quality cloud points generated from M300rtk with a DG4 pro-penta-lens camera. Scoring from five senior experts (professor-level engineers with 30 years of experience) from the Chengde Mountain Resort's conservation and planning departments participated in the consultation. CMR-themed search and retrieve content obtained under restricted access from Dianping, Ctrip, Fliggy, Baidu Maps, and Agoda. All comments were parsed to identify pre-defined scene names. Time range is January 2015 to January 2025.
	Slope Direction (topography)	Raster data	
Heritage value perception data	Expert scoring of heritage value	Number table	
	User-generated content	59, 852 comments	

[*] Several types of data are employed in both hazard assessment and ecological sensitivity analysis, but with distinct conceptual roles: in the hazard model they act as conditioning indicators for geological hazard events, while in ecological analysis they represent the different levels of sensitivity and adaptive capacity of ecosystems.

$$I = \sum_i^n I(X_i, D) = \sum_i^n \ln \frac{S_i/A_i}{S/A}, \tag{1}$$

where $I(X_i, D)$ represents the information provided by factor X_i on geological hazard in the study area. S_i is the number of geohazard scenes in factor X_i, and A_i denotes the number of indicators X_i, S is the total number of hazard scenes, and A is the total scenes of the study area.

In addition, to fully utilize expert knowledge, the AHP was applied to evaluate the risks of geographical hazards. An indicator system was established based on expert assessments, and a corresponding weighting matrix was formulated (Supp. Data A). The Jaccard Index was employed to quantify the degree of overlap between IQM and AHP. It is defined as the ratio of the intersection to the union of two sets, ranging from 0 (no overlap) to 1 (complete overlap). This allows us to evaluate the consistency and divergence between two datasets.

2.5.2. Ecological sensitivity analysis

This study employed the EWM as an analysis method. EWM is selected because it translates the internal variation of each indicator into a measurable information contribution, assigning higher weights to ecological indicators with strong discriminative weight while downweighting those with limited influence. This enhances the objectivity and effectiveness of the sensitivity assessment. In a multi-source and heterogeneous ecological indicator system, EWM does not rely on subjective judgments and performs reliably with modest sample sizes, ensuring comparability across indicators with different units within a unified analytical framework (Zhe et al., 2021; Sun et al., 2025). Based on information entropy theory, it determines the weight of each indicator (positive and negative) by calculating the degree of dispersion in the data, effectively reflecting the amount of information each variable contributes to the system (Supp. Data B). In comparison, EWM is designed to determine objective indicator weights for ecological sensitivity, whereas IQM quantifies the relationship between hazard occurrences and conditioning factors. The main equations of EWM follow:

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^n \left(\frac{x'_{ij}}{\sum_{i=1}^n x'_{ij}} \cdot \ln\left(\frac{x'_{ij}}{\sum_{i=1}^n x'_{ij}} \right) \right) \tag{2}$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^m (1 - e_j)} \tag{3}$$

where x'_{ij} is the normalized value of the original data for the i-th sample under the j-th indicator, used to eliminate the influence of differing units or dimensions. n represents total number of samples (i.e., the number of evaluated objects), and m means total number of indicators. ln is natural logarithm function used for calculating information entropy, and e_j represents the information entropy of the j-th indicator, which measures the uncertainty in the distribution of this indicator across all scenes. w_j is the final weight of the j-th indicator, representing its relative importance in the overall evaluation.

Furthermore, we conducted weight calculations using the AHP (Supp. Data B) and developed the associated judgment matrix. Finally, we integrated the two methods by averaging their respective weights to obtain the final weights.

2.5.3. Heritage value perception

We invited five experts from the cultural relics management team of the CMR, each with over 30 years of experience and holding the title of professor-level senior engineer. Two of them are affiliated with the

Table 2

Indicator system and functional justification for the HEPLP assessment at the CMR.

Indicator category	Indicators	Justification
Geographical hazards indicators	Landslide and rockfall occurrence points	It helps identify high-risk areas and assess the impact of topography, geology, and climate conditions on hazard occurrence in the history of CMR.
	Lithology	CMR has various special lithologies since crustal movement, which exhibit different levels of weathering resistance and stability.
	Groundwater Level	CMR has fluctuations in groundwater levels related to historic waterscape which also affects soil and rock stability, while high groundwater levels reduce soil shear strength.
	Gully Development	Gully development happened in CMR reflecting the long-term concentration of surface runoff.
	Water Erosion	Water erosion in CMR weakens the stability of surface materials, leading not only to soil loss but also potentially triggering landslides and debris flows.
	Geomorphic Unit	CMR has many geomorphic units which are associated with distinct geological hazards, as landslides tend to occur in mountainous terrain, whereas valleys are more prone to soil erosion.
	Distance to faults	Rock masses near fault zones are more fractured and have higher permeability, making them more susceptible to landslides.
Shared indicators (used in both hazard and ecological sensitivity analyses)	Coniferous and broadleaf mixed forest (land use)	One of the main vegetation species in the CMR, its dense canopy and mixed structure stabilize soils and slopes, support habitat diversity, and reflect historically maintained vegetation mosaics that enhance landscape continuity.
	Coniferous Forest (land use)	One of the main vegetation species in the CMR, its evergreen canopy, winter cover reduces erosion and maintains year round microclimate buffering but sensitive to disturbance that can expose soil and alter hydrology.
	Broadleaf Forest (land use)	One of the main vegetation species in the CMR, its seasonal canopy, higher litter input supports soil formation and moisture regulation, the changes of it can affect visual character of heritage woodland settings.
	Grassland (land use)	A rare large-scale grassland in oriental historic gardens within the CMR, it enhances water retention and provides open visual corridors.

Table 2 (*continued*)

| Indicator category	Indicators	Justification
	Water body (land use)	It controls local microclimate and moisture, supports riparian habitats, and is often a key heritage attribute of CMR as its degradation can propagate to adjacent scenes.
	Slope (topography)	Many scenes in CMR located on steeper slopes which increase susceptibility to erosion and mass movement, threatening vegetation cover and the stability of heritage features.
	Construction Land (land use)	It increases runoff, fragments habitats, elevates disturbance intensity, and can erode the ecological setting that buffers CMR's heritage attributes
Ecological sensitivity indicators	Distance from Roads (Anthropogenic factors)	It reflects access pressure and edge effects. It serves as a proxy for trampling, pollution, noise, invasive species introduction, and management accessibility, as proximity to roads often accelerates ecological degradation of CMR.
	Distance between Scenes (Anthropogenic factors)	It captures the ecological fragmentation and linkage among CMR's scene-based heritage units, as cultural landscape integrity depends on the continuity of ecological corridors and inter-scene relationships rather than isolated patches.
	Elevation (topography)	It reflects temperature and precipitation gradients of CMR, shaping vegetation patterns, freeze thaw and moisture regimes, and long-term ecosystem stability across the site.
	Slope Direction (topography)	It determines CMR's exposure to solar radiation and prevailing winds, directly shaping microclimatic conditions and explaining intra-site heterogeneity.
Heritage value perception indicators	Expert scoring of heritage value	It captures the CMR scenes' heritage significance in terms of historically grounded attributes such as historic design principles, garden artistry, sacred symbolism, and authenticity and integrity, providing a standardized baseline for comparing value across the serial landscape units.
	User-generated content	It captures how visitors actually recognize and experience CMR scenes through recurring narratives about scenery, atmosphere, comfort, crowding, accessibility, and perceived safety, offering a socially grounded and dynamically updated evidence layer for scene-level value perception.
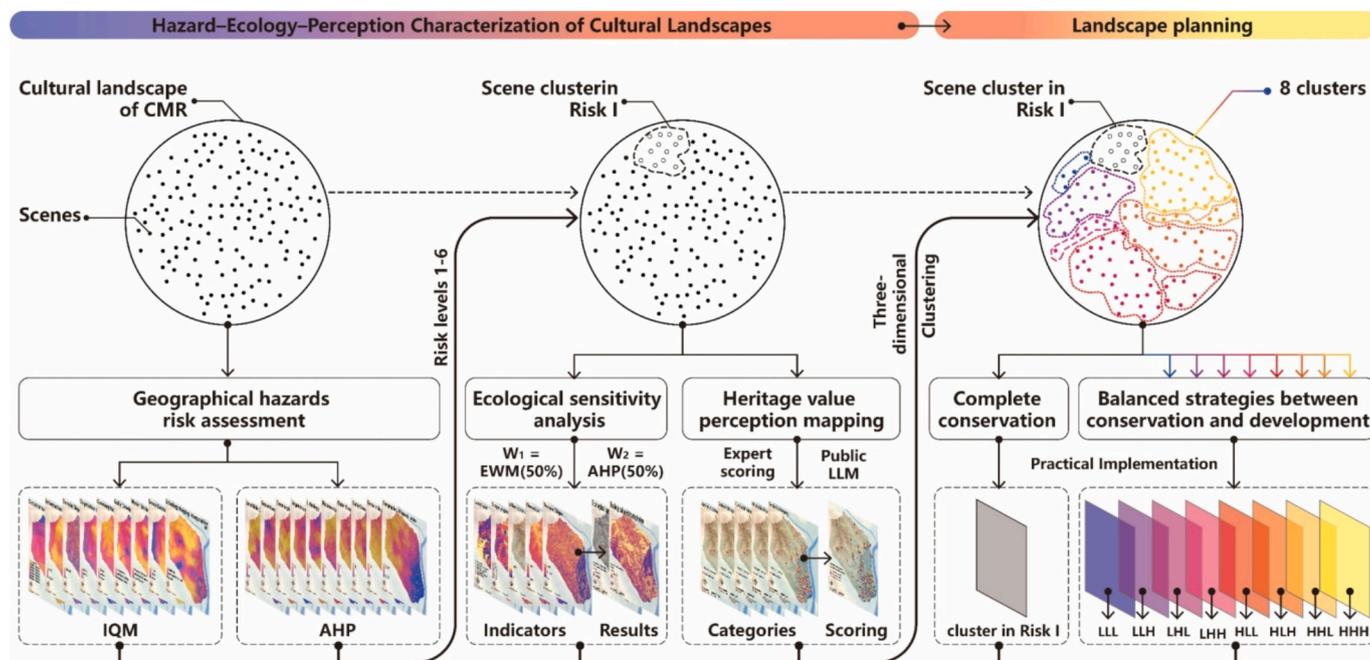
Fig. 3. HEPLP Framework: from Hazard–Ecology–Perception characterization to landscape planning.

heritage conservation and research department, and three are from the cultural landscape planning department. Each expert independently evaluated the five different heritage value categories using the Heritage Value Assessment Matrix (Supp. Data C) (CHCC&CMACH., 2023; Silva and Roders, 2012; UNESCO, 1994). The scoring follows a standardized 1–5 scale, where 1 represents "Very Low" and 5 represents "Very High." Experts completed the assessments individually using an Excel-based scoring matrix, drawing on their professional knowledge, extensive research experience, and their understanding of the physical and cultural characteristics of each scene in CMR.To spatialize expert perception, we used the scene as the basic spatial unit. Each scene has a unique Scene ID and a corresponding polygon boundary in the CMR scene map. For each scene and each value category, we aggregated the five expert scores by taking the arithmetic mean, producing one expert score per category per scene. We then joined the aggregated scores to the scene polygon layer using the Scene ID. Maps of expert perception were generated by symbolizing the scene polygons based on the aggregated scores, and the same procedure was applied to the integrated expert perception index derived from Principal Component Analysis (PCA).

Public perception data were collected from multiple Chinese social media and travel platforms using a structured keyword strategy. The retrieval keywords consisted of two groups, general names referring to the Chengde Mountain Resort as a whole and specific names corresponding to each scene, in both Chinese and English including Pin Yin (Supp. Data C). To geolocate text based comments onto spatial units, we assigned each comment to a scene level unit using a rule based matching procedure. First, comments obtained from platform pages that are explicitly associated with a named scene or POI were directly assigned to the corresponding scene. Second, for comments retrieved through keyword search, we matched the text to the official scene name list. When a comment contained one unique scene name, it was assigned to that scene. Comments that only mentioned general site level or that mentioned multiple scenes without a dominant reference were treated as non-assignable at the scene level and were excluded from the scene based scoring to avoid ambiguous spatial attribution. After assignment, comments were cleaned by removing duplicates, advertisements, and irrelevant content.

In this study, we adopted the few-shot learning approach for Large Language Model (LLMs) as proposed by Luo et al. (2025) to enhance

performance in the AI model-based analysis of user-generated content. Their comparative study assessed the performance of multiple LLMs (*GLM, ERNIE, Moonshot*) in analyzing Chinese user-generated content for cultural perception, while *Moonshot-v1* demonstrated superior performance than other similar models in both micro- and macro-averaged precision. Specifically, we utilized the *Moonshot-v1-128k* version to analyze 59,852 comments from various social media, incorporating structured prompt engineering inputs that included (1) task instructions, (2) definitions of heritage value categories, (3) background information on CMR, and (4) expert scoring examples for 144 scenes (Table 3).

Finally, to conduct a comprehensive analysis, we performed PCA on the scores of five categories (historical, cultural, scientific, social, and artistic), resulting in integrated scores for both expert evaluations and public evaluations. PCA was used to reduce dimensionality and capture the main variance across value dimensions, ensuring that the combined perception index reflects the dominant patterns shared among categories.

2.5.4. HEPLP comprehensive analysis

The HEPLP comprehensive analysis integrates multidimensional data, encompassing geographical hazards, ecological sensitivity, and heritage value perception data. It defines cluster of complete conservation based on scenes identified as having the highest geographical hazard risks (Risk level I), establishing a foundational spatial boundary for controllable conservation. Building upon this, the approach clusters the scenes by normalizing the ecological sensitivity, experts' scoring, and publics scoring to eliminate dimensional inconsistencies. After normalization, each of the three indicators was reclassified into "high" and "low" using the natural breaks method implemented in ArcGIS. This is a one-dimensional, threshold-based classification method that determines breakpoints by locating density valleys and by minimizing within-class variance while maximizing between-class variance for a given indicator distribution, rather than functioning as a multivariate clustering algorithm.

To ensure robustness of clustering, we conducted a sensitivity analysis of the classification boundaries by slightly adjusting the breakpoint values. A micro-adjustment of ± 0.02 was applied, corresponding to a 4.3% to 5.1% change in the original breakpoints. Given that the indicators were normalized to a [0,1] scale, this represents a 2% shift in

Table 3

The four prompt engineering process of LLM.

Prompt Component	Description	Data Source / Reference	Function
Task Instructions	The model was instructed to identify five distinct categories of heritage value—historical, cultural, scientific, social, and artistic—reflected in social media comments related to the CMR. Each category was to be rated on a scale from 1 (lowest) to 5 (highest) according to its significance.	This task instruction was adapted from existing research (Luo et al., 2025) and aligns with an expert discussion framework.	Providing clear task instructions can significantly improve the effectiveness of few-shot learning by ensuring the model adheres to a uniform evaluation criterion.
Definition of 5 categories	The heritage value perception spans five categories: historical (political and ethnic integration), cultural (traditional diversity and synthesis), scientific (site selection and construction techniques), social (education, tourism, religion, and civic life), and artistic (aesthetic landscape and spatial design). (Supp. Data C)	(Silva and Roders, 2012) (UNESCO, 1994) (CHCC&CMACH., 2023)	These definitions served as label explanations or output templates in the few-shot examples, assisting the model in accurately identifying and evaluating each category. This, in turn, supports targeted comment analysis and enables precise classification and scoring.
Background: Introduction to CMR	We indexed 2520 academic articles from the CNKI platform published over the past 30 years related to CMR. Following the basic PRISMA methodology and using abstracts, keywords, and titles, we screened and selected 290 articles with direct relevance. After conducting a literature review, a 3000-character background document was generated.	CNKI	This section clearly establishes CMR as the study subject and, grounded in academic literature, enhances the scientific rigor, credibility, and validity of the overall task.
Expert Scoring Examples for Scenes	Relevant documentation for 144 scenes was evaluated by five senior experts across five heritage value categories. Of these, 115 scenes (80%) were used for model context construction, and 29 scenes (20%) for testing. The LLM predictions showed strong alignment with expert scores, achieving a Pearson correlation of 0.771, recall of 0.976, and precision of 0.825.	Collection of historical archives / Expert scoring	This process built a representative labeled dataset that enabled the model to learn diverse and accurate scoring patterns, serving as a reliable reference for the evaluation task. The reserved test set ensured an objective assessment of the model's performance.

unit terms, providing a moderate and reasonable analysis that does not fundamentally alter the classification system, but is sufficient to test its sensitivity. To further strengthen the robustness assessment, additional tests (± 0.01 and ± 0.05 of breakpoint) were also conducted, capturing both fine-grained and more extensive perturbations. Finally, the Coefficient of Variation (CV) is calculated to quantify the stability of each category combination during the breakpoint adjustment process.

These distinct clusters enable the formulation of differentiated intervention and guidance strategies. Finally, the method emphasizes the role of local multi-stakeholder participation, fostering collaborative planning, governance, and institutional innovation under the tripartite coupling of hazard, ecology, and perception.

3. Results

3.1. Risk level identification of geographical hazards

The index data of eight factors were evaluated using the IQM. The generated information quantity index and its ranking are shown in

Table 4 and Fig. 4 to which are used to assess the risks for geological hazards in CMR (Supp. Data A). The results are divided into six levels using the natural-break method (Table 5). In terms of AHP analysis based on the composite scores and weights (Supp. Data A), six different risk levels of geographical hazards are identified using the natural breaks method (Table 5).

The spatial distribution of geographical hazards reveals a clear northwest-southeast gradient, with higher risks concentrated in the northwestern sector of the CMR. This pattern is consistent with the frequent gully development and steeper terrain in this area (Fig. 4. C, E, G), which elevate the likelihood of landslides and collapses. In contrast, the southeastern sector exhibits relatively lower hazard levels despite having comparable vegetation coverage, likely due to gentler slopes and more stable lithological conditions (Fig. 4. A, F, G). It is interesting to note that certain hazard indicators show partial inconsistency: for example, because of human-driven forest exploitation, water erosion hotspots are not fully correlated with areas of high groundwater levels (Fig. 4. B, D), as the latter are predominantly located in the southwest. Vegetation coverage is generally denser in both the north and the south

Table 4

Index system of geological hazards assessment based on IQM.

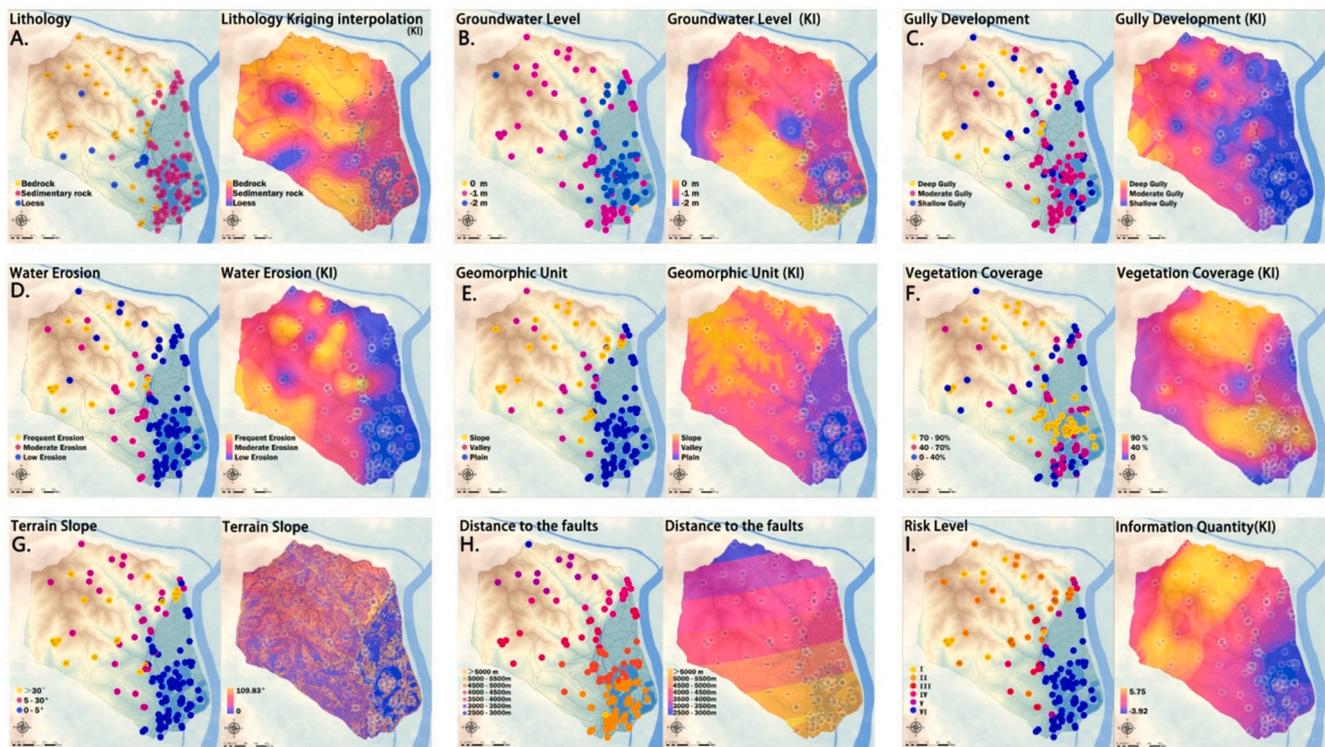| Index	Segmentation standards	Information quantity	Order	Index	Segmentation standards	Information quantity	Order
Lithology	Bedrock	0.63	9	Vegetation Coverage (%)	<40%	0.17	11
	Sedimentary Rock	−0.36	20		40–70%	−0.06	14
	Loess	0.12	12		>70%	−0.08	15
Groundwater Level(m)	< −1 m	−0.18	16	Terrain Slope (°)	<5	−0.79	22
	0 ~ −1 m	0.12	12		5–30	0.6	10
	0 m (Surface)	0.72	8		>30	0.77	7
Gully Development	Shallow Gully	−0.26	18	Distance to the faults(m)	>5000 m	N/A	N/A
	Moderate Gully	−0.38	21		5000-5500 m	−0.83	23
	Deep Gully	1.25	3		4500-5000 m	−1.19	24
Water Erosion	Low Erosion	−0.23	17		4000-4500 m	0.07	13
	Moderate Erosion	−0.27	19		3500-4000 m	0.98	5
	Frequent Erosion	1.15	4		3000-3500 m	1.3	2
Geomorphic Unit	Plain	−0.83	23		2500-3000 m	1.41	1
	Valley	0.6	10				
	Slope	0.78	6				

Fig. 4. (A-I). The visualization of each Geographical hazards' indicators of 144 scenes with R-50m units in CMR.

Table 5
Six geographical hazard risk levels based on IQM and AHP.

Risk level	Definition	Number of scenes (IQM)	Number of scenes (AHP)
I	Extremely High Risk	13	16
II	High Risk	24	16
III	Moderately High Risk	10	15
IV	Moderate Risk	14	19
V	Moderately Low Risk	15	22
VI	Low Risk	62	56

Table 6
A combined weighting approach using EWM and AHP.

Indicator	EWM	AHP	Combined	Order
Water Body	0.129	0.283	0.206	1
Broadleaf Forest	0.188	0.15	0.168	2
Mixed Forest (Coniferous and Broadleaf)	0.089	0.184	0.137	3
Coniferous Forest	0.142	0.108	0.125	4
Slope	0.185	0.045	0.115	5
Grassland	0.13	0.064	0.097	6
Elevation	0.083	0.036	0.06	7
Distance from Roads	0.002	0.083	0.042	8
Slope Direction	0.035	0.014	0.025	9
Distance Between Scenes	0.008	0.023	0.015	10
Construction Land	0.01	0.01	0.01	11

(Fig. 4. F), yet hazard risks are higher in the north, underscoring the slope and geomorphic conditions as more controlling factors (Fig. 4. E, G). These findings demonstrate the necessity of using multi-source geospatial indicators to capture compound hazards, rather than relying on a single dataset, which emphasizes the multidimensionality of heritage landscape risks.

To further validate and compare the classification outcomes, we conducted a Jaccard Index intersection analysis between the AHP results and those derived from the IQM. The Jaccard Index between the two datasets was calculated to be 70.5%, indicating a relatively high degree of similarity. This comparative approach enabled us to identify a consistent set of extremely high-risk areas (Risk Level I) with 12 scenes for complete conservation. Thus, they are excluded from the subsequent overlay-based clustering procedure in *Section 3.4*.

3.2. Integrated weight for ecological sensitivity

The final average weight of the EWM and AHP Weight Analysis is shown in following table (Table 6). The final average weight of the EWM and AHP analyses is shown in Table 5. Water bodies (0.206), broadleaf forests (0.168), and mixed forests (0.137) exhibit the highest combined weights, indicating their dominant influence on ecological sensitivity and their key role in maintaining hydrological and vegetation stability

within the resort. In contrast, construction land (0.01), distance between scenes (0.015), and slope direction (0.025) contribute comparatively, reflecting their limited ecological relevance at the landscape scale.

For each scene (Fig. 5), we calculated the mean ecological sensitivity index within the same unit and used this average value to assign corresponding levels of ecological sensitivity index (Supp. Data B). Fig. 5. A shows a clear gradient of ecological sensitivity, with higher values in the northwestern mountains dominated by steep slopes and forests, and construction land is relatively sparse. On the contrary, lower values appear in the southern and eastern plains with concentrated construction land, gentle terrain, and grassland. Usually erosion-prone slopes and fragmented forests are the most sensitive elements, but at the scene-unit scale (Fig. 5. B): some eastern river-adjacent scenes show high sensitivity despite moderate slopes, and certain northern scenes record low values due to homogeneous vegetation and proximity to construction land. These spatial variations underscore the importance of integrating multiple indicators in ecological sensitivity assessment rather than relying on any single indicator.
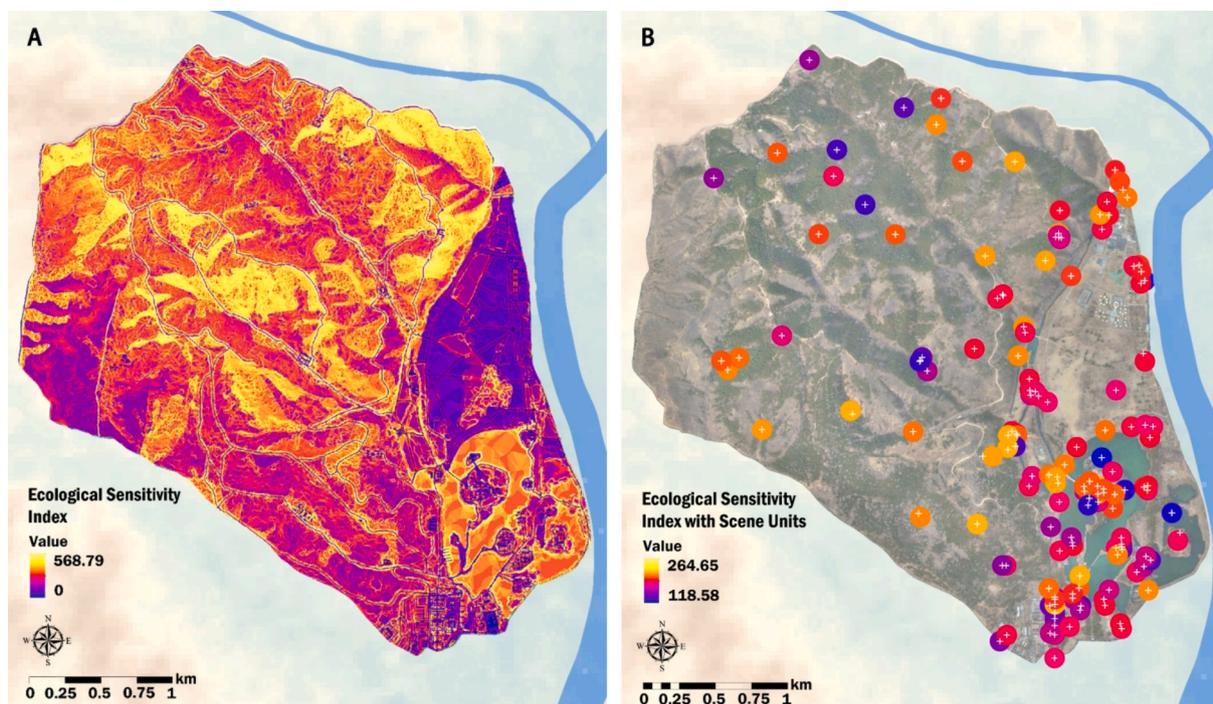
Fig. 5. A Map of Ecological Sensitivity Index. B. Map of Index with Scene Units. ArcGIS Pro 3.4.3 is used to conduct a weighted overlay analysis to derive the ecological sensitivity index across different regions.

3.3. Experts' and public's heritage value perception mapping

To synthesize the experts' scoring, we first calculated the average scores from five independent experts across five heritage value categories and subsequently conducted a PCA. The first principal component accounted for 89.76% of the total variance and shows uniformly high and positive loadings across all five value dimensions (0.44–0.47) (Table 7; Supp. Data C). The remaining four components each explained less than 4 % of the variance (3.35%, 2.55%, 2.46% and 1.88%). All five heritage value categories loaded positively and with similar magnitudes on PC1, indicating a high degree of internal consistency in the expert assessments. In parallel, we performed PCA on the public heritage value scoring derived through few-shot prompting using an LLM, in which the PC1 explained 92.34% of the variance, with the remaining four components contributing less than 5% (4.12%, 2.82%, 0.61% and 0.11%), indicating a strongly one dimensional structure (Table 7; Supp. Data C). These two sets of PCA-derived scores were then integrated into a spatial mapping analysis that reflects both expert-informed and publicly perceived heritage significance (Fig. 6). Fig. 6 shows heritage value scores of 144 scenes, where expert ratings remain consistent while public perceptions are more polarized, concentrating on core areas and

overlooking peripheral sites.

It is noted that the heritage value scoring is spatially imbalanced, particularly in the northwestern area where fewer sample points increase uncertainty. To mitigate this, we integrated both experts' and public's evaluations by standardizing their scales through PCA and spatial interpolation, which balanced the weight of underrepresented scenes and reduced bias arising from uneven comment density and expert subjectivity in decision-making.

3.4. Three-dimensional comprehensive analysis

As mentioned in Section 3.1, we excluded the scenes located in Risk Level I of geographical hazards. For the remaining scenes, we conducted a three-dimensional comprehensive analysis using the high and low classes defined by the natural breaks thresholds (0.468 for ecological sensitivity, 0.548 for expert scoring, and 0.390 for public perception) and applied pairwise clustering, resulting in a total of eight distinct clusters (Fig. 7. A, Supp. Data D).

Fig. 7. A shows the three-dimensional clustering of ecological sensitivity, expert scoring, and public scoring. The divergence along the public scoring axis is clearly greater than along the other two

Table 7
PCA results for expert and public heritage value scoring.

PCA results				Five heritage value perception				
Category	Component	Eigenvalue	Variance (%)	Historical	Cultural	Scientific	Social	Artistic
	*PC1	*4.490	*89.76	*0.458	*0.469	*0.447	*0.452	*0.439
	PC2	0.170	3.350	0.687	−0.571	0.041	−0.318	0.516
experts' scoring	PC3	0.130	2.550	−0.112	0.183	−0.903	0.341	0.314
	PC4	0.120	2.460	0.204	0.731	−0.154	−0.702	0.057
	PC5	0.090	1.880	0.584	−0.162	0.173	0.468	−0.646
	*PC1	*4.620	*92.34	*0.461	*0.478	*0.417	*0.450	*0.425
	PC2	0.110	4.120	0.094	0.287	0.615	−0.388	−0.616
publics' scoring	PC3	0.040	2.820	0.679	0.276	−0.603	−0.201	−0.243
	PC4	0.030	0.610	0.131	−0.300	−0.001	0.740	−0.587
	PC5	0.01	0.11	0.548	−0.723	0.29	−0.24	0.189

* PC1, which explains 89.76% (experts) and 92.34% (public) of the variance, was selected as the composite heritage value index.

0.468 and 0.493, the interval forms a density valley in the empirical distribution. Expert scoring exhibits a similarly segmented distribution, leading the natural breaks method to select 0.548 as a meaningful breakpoint. This threshold divides a low group of 54 scenes with a mean value of 0.39 and a high group of 78 scenes with mean value of 0.73, revealing a strong contrast in expert evaluation patterns. Density valley is 0.548 to 0.560, meaning that any cut point within this gap produces exactly the same clustering. Public perception exhibits a pronounced bimodal structure. The natural breaks method therefore identifies 0.39 as a structural breakpoint. This threshold separates a low group of 26 scenes with a mean value of approximately 0.015 from a high group of 106 scenes with a mean value of approximately 0.82, indicating a distinct divide between scenes with minimal public perception and those receiving substantial public perception.

As mentioned in *Section 2.5.4,* we acknowledge that any threshold based classification will assign values that are numerically close to the breakpoint (for example 0.463 and 0.468 in ecological sensitivity) to different classes by construction. To evaluate how sensitive our results are to this issue, sensitivity analysis of the classification boundaries by slightly adjusting the breakpoint values as follows: Table 8 shows that under ±0.01, all clusters yield extremely low CV values (ranging from 0.014 to 0.043), indicating minor variation in group sizes. With ±0.02 adjustments, the CVs range from 0.058 to 0.151, providing a moderate but stable window to test robustness. Even under the larger ±0.05 adjustments, the system remained structurally consistent, with no evidence of category collapse or abnormal inflation (CVs between 0.09 and 0.174). These findings confirm that the clustering framework is not overly sensitive to threshold selection, and that ±0.02 serves as a representative and meaningful perturbation scale for robustness evaluation.

4. Discussion

4.1. Risk-based complete conservation practices

All scenes falling within Risk Level I of the geographical hazard
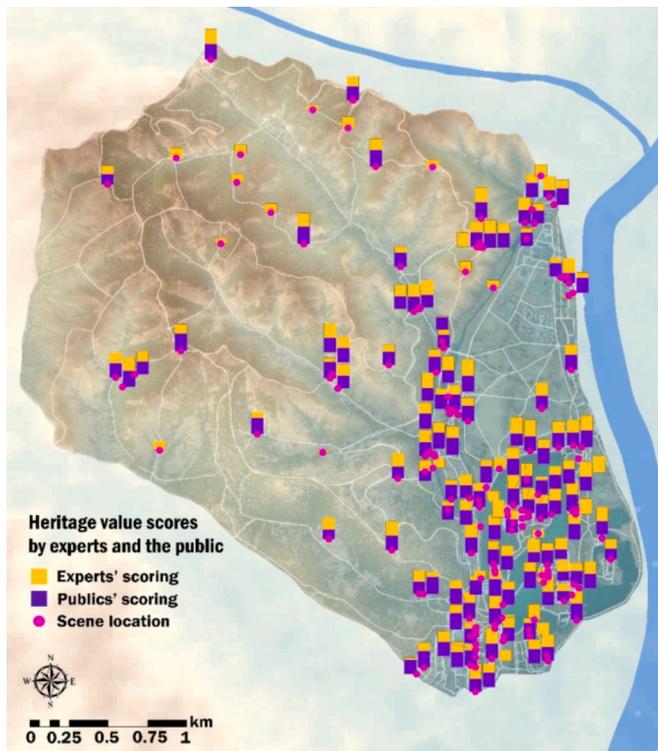

Fig. 6. The visualization of heritage value scoring.

dimensions, indicating higher variability in public perceptions. In Fig. 7. B, ecological sensitivity shows a clear bimodal pattern and the natural breaks method therefore identifies 0.468 as a structural breakpoint. This threshold separates a low group of 60 scenes with a mean value of 0.30 from a high group of 72 scenes with a mean value of 0.65, indicating a pronounced structural separation. Since no observations fall between
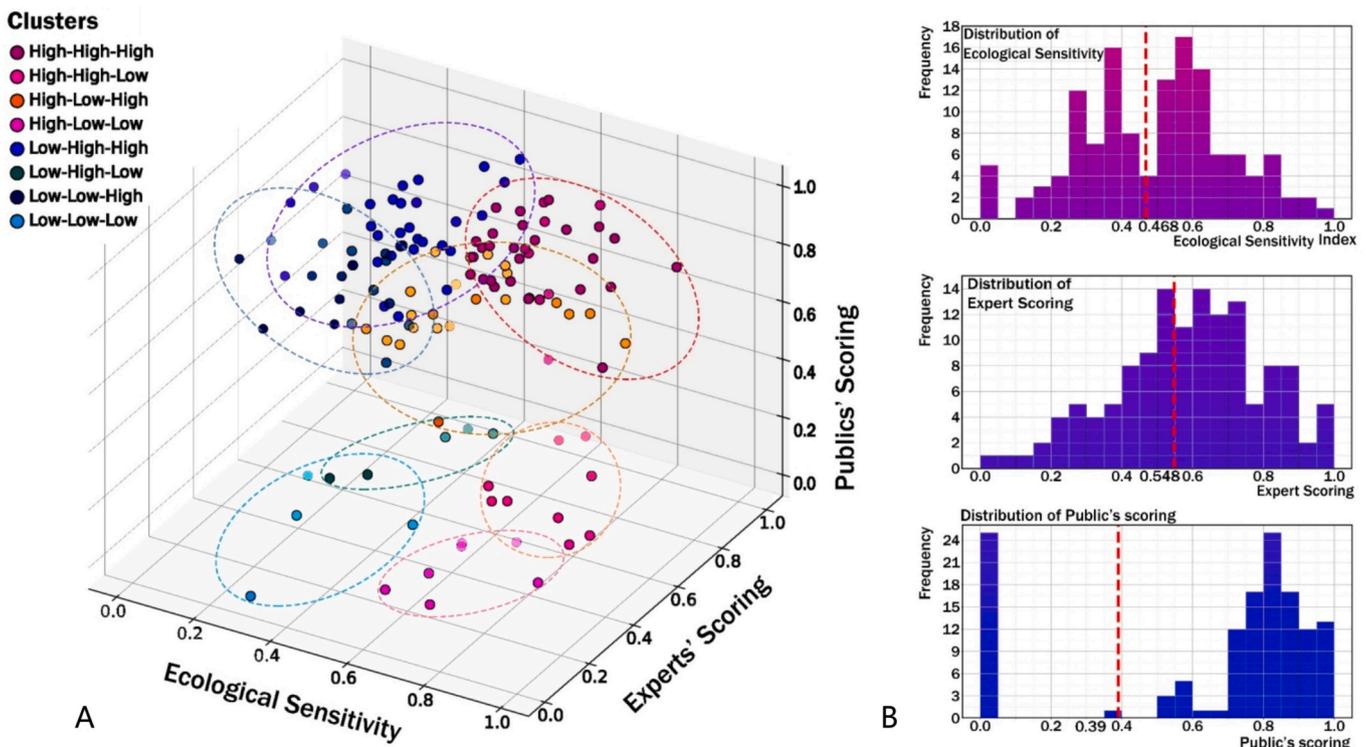

Fig. 7. A Three-dimensional clustering and eight clusters; **B.** Distributions of ecological sensitivity (top), expert scoring (middle), and public scoring(bottom).

Table 8
Robustness test of clustring results under breakpoint perturbations.

Order	Clusters	±0.01			±0.02			±0.05		
		Mean	Std	CV	Mean	Std	CV	Mean	Std	CV
1	High-High-High	34.33	0.481	**0.014	34.44	1.998	**0.058	35	3.150	**0.09
2	High-High-Low	9.67	0.280	**0.029	9.56	0.707	**0.074	9.67	0.948	**0.098
3	High-Low-High	21.67	0.477	**0.022	21.56	1.660	**0.077	20.67	3.597	*0.174
4	High-Low-Low	7.33	0.249	**0.034	7.44	0.707	**0.095	7.33	0.946	*0.129
5	Low-High-High	30.67	0.951	**0.031	30.67	4.079	*0.133	30.33	5.065	*0.167
6	Low-High-Low	4.67	0.173	**0.037	4.89	0.484	**0.099	5	0.815	*0.163
7	Low-Low-High	19.67	0.472	**0.024	19.67	2.970	*0.151	20.33	3.334	*0.164
8	Low-Low-Low	4	0.172	**0.043	3.78	0.556	*0.147	3.67	0.576	*0.157

*Values marked with ** denote very low variation (CV < 0.10), and * denotes moderate variation (CV < 0.2).

assessment were designated for complete conservation cluster, as shown by the white circles in Fig. 8. The extremely high risk in this group of scenes results from the combined effects of landform, lithology and hydrological processes rather than any single factor.

Most scenes are located approximately 2500–4000 m from the main fault within a highly fractured influence zone and are frequently superimposed on steep terrain slopes and valley geomorphic units, where rock masses are densely jointed and structurally weak, making sliding along preferential weak planes more likely. The development of deep gullies further undermines slope toe support. At the same time, shallow groundwater responds rapidly to rainfall, causing sharp increases in pore water pressure which, under substrates dominated by fractured bedrock or thick loess, substantially reduces soil shear strength and facilitates the initiation of landslides (Lin et al., 2021; Lombardo et al., 2020). Although vegetation coverage is relatively high in some scenes, ecological buffering within such a fractured landform system is insufficient to compensate for the long term structural instability, highlighting the vulnerability of heritage landscapes to geological hazards (Cook et al., 2019; Sesana et al., 2019). Consequently, the space that can be safely used for construction or visitor activities is extremely limited, and even minor changes in drainage or loading conditions may trigger latent instability.

This designation reflects a threshold-based and spatially explicit rationale aligned with UNESCO's relevant operational guidelines (UNESCO, 2010), which state that areas exposed to the highest levels of risk (Fig. 9.A), exceed the limits of manageable intervention and must be excluded from any short-term development. The proposed model formalizes this logic by providing a quantifiable basis for zoning severely vulnerable areas as minimal intervention zones, forming the foundation for bottom-line conservation strategies.

For instance, targeted measures have been implemented at the CMR to mitigate geographical hazards recently. Selecting key vegetation within core zones has been supported and reinforced to enhance soil stability and reduce the risk of surface erosion (Fig. 9.B). In addition, reversible structural bracing has been applied to heritage walls adjacent to unstable slopes to prevent collapse due to terrain movement (Fig. 9. C). Finally, protective shelters have been constructed over areas prone to rockfall to shield vulnerable remains from further damage (Fig. 9.D).

The Risk Level I cluster serves as a pre-emptive control mechanism, acting as an intelligent switch: when geographical hazard intensity surpasses a defined threshold, the model automatically initiates a complete conservation protocol, prohibiting inappropriate development, infrastructure construction, and tourism activity. It safeguards the ecological and cultural integrity of the site. Moreover, this risk-based mechanism is structurally compatible with broader territorial governance systems. It can be seamlessly embedded into national and regional landscape planning frameworks, providing a scientifically robust and administratively actionable tool for excluding the most risk heritage sites from land use or transformation. Its application is particularly relevant for cultural landscapes located in high-risk seismic belts, cyclone-exposed coastal zones, or geologically unstable mountain environments.

4.2. Strategic practices based on integrated ecological and perception analysis

For the remaining scenes, we conducted an overlay analysis of ecological sensitivity and heritage value perception, resulting in eight distinct groups. The gradient of ecological sensitivity arises from the interaction between the cultural landscape's inherent natural structure (mountain-water system) and contemporary land use. In the CMR, water bodies function as both the scenic core and the ecologically sensitive elements, while forest cover and terrain shape how mountain scenes sensitively respond to ecological disturbance (Chen et al., 2023; Tappeiner et al., 2020). In terms of heritage value perception, experts apply institutional criteria such as authenticity and integrity, generating a relatively even spatial distribution (Silva and Roders, 2012; Avrami et al., 2019), whereas public perceptions are driven by route accessibility and visual experience, producing concentrated hotspots in the southeastern area (Hussein et al., 2020; Tang et al., 2025). When combined those three categories together reveal mechanisms behind them (Table 9).

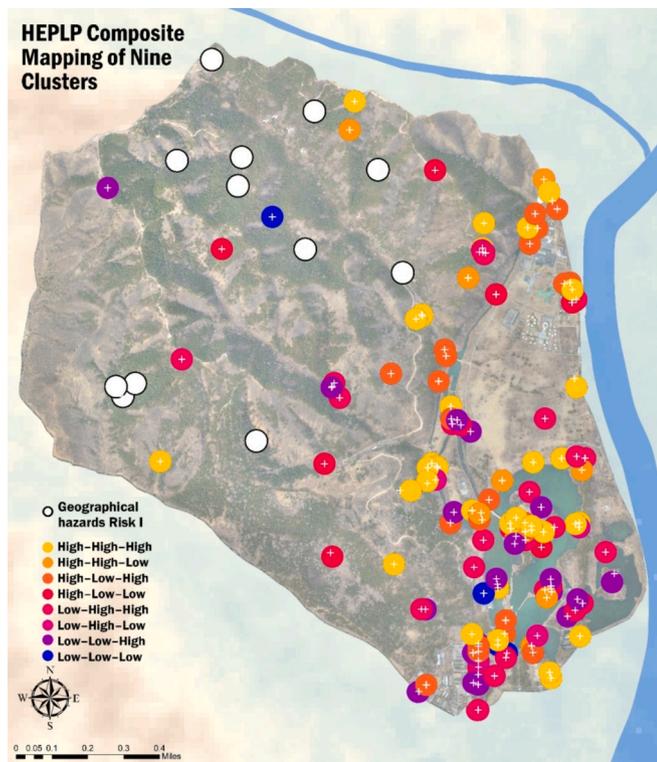Each group was assigned a tailored strategy of intervention,

Fig. 8. HEPLP composite mapping of nine clusters.

Fig. 9. Site-specific conservation interventions in Risk Level I cluster.

balancing conservation priorities with appropriate forms of sustainable development (Table 10). This approach aims to align conservation measures with both the ecological sensitivity and the perceived heritage significance of each scene, thereby ensuring context-sensitive and value-driven landscape planning.

In summary, areas with high ecological sensitivity are typically prioritized for conservation over development, as complex ecosystems are integral to cultural meaning. Their disturbances cause irreversible damage and suffer substantial restoration costs, eroding the heritage values embedded in cultural landscapes. However, these clusters may overlap with scenes of strong public heritage perception, as popular scenes attract disproportionate attention and carry symbolic or aesthetic meanings. Such overlaps create tensions between ecological conservation and social expectations. Resolving such conflicts calls for collaborative, multi-stakeholder governance anchored in a long-term vision for sustainable landscape planning.

In Cluster 1, conservation takes precedence when development with clearly defined intervention and restoration limits is permitted. Fig. 10. (A1–2) illustrates the popular tourist dock and the restoration work conducted by engineers at the same scene. However, Cluster 2 is often marginalized or overlooked, which presents more potential to utilize expert knowledge and technical expertise for restorative interventions and ongoing maintenance in areas of high heritage value as shown in (Fig. 10. B1–2). Such efforts can help unlock latent potential, rearticulate long-term significance, and ultimately enhance public recognition and appreciation (Ferreira et al., 2023). Cluster 3 reflects a paradoxical case where ecologically vulnerable scenes, though rated low in expert-assigned heritage value, are popularly recognized by the public, requiring restricted on-site access and the use of virtual exhibitions to balance ecological conservation with symbolic engagement (Wu et al., 2021) (Fig. 10. C1–2). The scenes in Cluster 4 are currently planned for the archaeological backfilling and ecological restoration, due to their high ecological sensitivity and relatively low perception of both experts and the public (Pijpers, 2024) (Fig. 10. D1–2). This long-term initiative supports the conservation of the enduring natural environment evolution that underpins the sustainability and living characteristics of the cultural landscape.

On the contrary, when ecological sensitivity is relatively low, these clusters offer considerable potential for strategic landscape planning and targeted interventions. Cluster 5 is highly appreciated from the perspective of heritage value perception. Therefore, development based on adaptive reuse becomes a priority, with the goal of revitalizing the functional role of heritage such as commercialized commemorative site leasing and culturally creative products (Wang et al., 2023) (Fig. 10. E1–2). Due to its ecological stability, Cluster 6 holds potential for expert reconstruction efforts. Physical interventions through reconstruction with specific exhibitions can help reproduce the characteristics and values of heritage, restore the cultural context, and promote public heritage education, social perception, and engagement (Lucchi, 2023) (Fig. 10.F1–2). For Cluster 7, the management strategy can focus on functional renovation centered on public popularity and everyday value. Given the absence of ecological constraints, the introduction of modern recreational facilities and cultural and religious gathering spaces can endow this area with renewed social significance (Yenin et al., 2020) (Fig. 10.G1–2). Cluster 8 serves as a buffer between conservation and development, functioning as equipment storage or a temporary activity space. While not part of core conservation, it supports overall landscape planning by easing pressure on other key clusters and improving operational flexibility (Fig. 10.H1–2).

4.3. Theoretical contribution of HEPLP

This study makes three key theoretical contributions to the field of landscape planning, especially for the heritage issue.

The first theoretical contribution of HEPLP is to conceptualize cultural landscapes as a triply coupled hazard, ecology and perception system. At its core, a multilayered relational structure is established in which environmental scientific measurements and socio-cultural perceptions are able to coexist within a shared decision grammar. This recognition offers a gentle but substantive correction to the technocratic tendencies that currently shape research on heritage resilience. Several existing frameworks have attempted to link various dimensions, but each remains partial in scope. To situate the HEPLP framework within existing theoretical landscapes, Table 11 compares it with three

Table 9
Mechanisms underlying high and low values across three categories.

Category	The mechanism behind the *High*	The mechanism behind the *Low*
Ecological sensitivity	1), These scenes are exposed to large seasonal fluctuations in water level, sediment deposition, limited self-purification capacity, and habitat fragmentation caused by concentrated visitor trampling and human construction. 2), The viewing platforms in the mountain zone, cliff temples and valley scenes are mostly located within steep gully systems, where subsurface foundations and hardened pavements intensify weathering, freeze and thaw processes and water erosion, and roads severely fragment the surrounding forest.	1), These scenes are located within political-oriented palace constructions, where courtyard vegetation and small water features dominate. 2), Plain scenes lie in grassland and sparse woodland meadow landscapes with very gentle slopes, where natural elements are concentrated and relatively continuous. 3), Lake area scenes are service spaces inside islands, far from the water body, so the ecological disturbance is low. 4), Mountainous scenes are located on fore-mountain terraces or small basins and do not serve as the primary visual focal points.
Expert heritage value perception	1), These scenes embody the historical symbols of imperial authority and major multi-ethnic religious practices. 2), They are also highly textualized in pictorial and archival records, giving them strong significance in art and literary history. 3), They represent the finest paradigm of Chinese imperial architecture and landscape craftsmanship, integrating landscape philosophy into multilayered visual corridors, spatial axes and refined timber construction systems.	1), These scenes serve primarily functional and auxiliary roles within the overall layout, such as ferry crossings for route transfer, embankment bridges linking water and land, and secondary courtyards or studios for leisure and dwelling, usually attached to the periphery of core axes and major scenic ensembles. 2), Over time, many have evolved into ruin-type spaces, where only platforms and scattered structural elements remain, which has weakened their authenticity and integrity.
Public heritage value perception	1), These scenes are located along the palace axis, the lake-area loop, key entrances or other highly accessible nodes with strong tourism exposure. 2), Their supporting facilities are well constructed, offering a visual appeal and a strong spatial openness. Combined with a comfortable microclimate and small, walkable spaces suitable for lingering, they substantially enhance tourism experience. 3), They are repeatedly featured in social media, allowing visitors to form positive associations of story richness and cultural significance.	1), These scenes are located on the periphery, along mountain slopes or away from main circulation routes. 2), Most retain only platforms or fragments, with the original buildings no longer extant and the remaining structures relatively small in scale, making their spatial organization difficult to discern. 3), Visitors are unable to understand their historical functions, as there is no clear on-site narrative and little interpretive support to facilitate experiential or contextual engagement.

Table 10
Balanced conservation and development strategic implementation of landscape planning.

Cluster No.	Ecological Sensitivity	Experts' Scoring	Publics' Scoring	Conservation and Development Strategy
1	High	High	High	Conservation is the priority, but gradual long-term development can be implemented, with visitor flows controlled during operational periods.
2	High	High	Low	Conservation is the priority, combined with various degrees of professional and technical restoration and maintenance. Long-term exhibitions are organized to enhance public awareness and perception
3	High	Low	High	Limit on-site visits, supplemented by online exhibitions to reduce the physical damage caused by on-site displays
4	High	Low	Low	Conservation should remain the long-term focus, with no consideration for short-term development, and establishing archaeological backfilling for ecological restoration.
5	Low	High	High	Development is the priority, incorporating modern interventions for adaptive reuse, focusing on exhibitions to promote the dissemination of heritage value.
6	Low	High	Low	Reconstruction can be carried out to reproduce heritage value, and specific exhibitions can enhance public heritage education, heritage value perception and social engagement.
7	Low	Low	High	Significant intervention and renovation can be undertaken, with the addition of more recreational infrastructure that integrates modern functions.
8	Low	Low	Low	Serve as a buffer zone for conservation and development, functioning as storage space for equipment or temporary activities service spaces.

potential conflicts to synergies in cultural landscape intervention, integrating heterogeneous logics of trade-off within an institutional prototype. Indeed, a GIS based multi-criteria procedure is not only a decision-support tool but the operational expression of a theoretical claim that cultural landscape significance emerges from the coupled and continuous dynamics between environmental evolution and anthropogenic practices.

Third, this study systematically integrates both expert and public heritage value perceptions, extending beyond the qualitative orientation of frameworks such as the Historic Urban Landscape (Rey-Pérez and Pereira Roders, 2020; Ferreira et al., 2023), renewing the integration of knowledge systems projected at different standpoints. Through structured LLM content analysis, HEPLP uses computational methods standardizing heritage value semantic vectors and identifying the interpretive dominant perception patterns, bridging qualitative value discourses and quantitative planning models. Indeed, HEPLP treats heritage value perception as an independent semantic structure, an evidence base, and a governance object, and jointly structures it with hazard risks and ecological sensitivity for conflict diagnosis and intervention portfolio design. This goes beyond approach such as Customized disaster risk management frameworks (Bosher et al., 2020), where

representative approaches that have shaped the discourse on cultural landscape planning. HEPLP seeks to construct a network capable of effectively mediating the tension between the external constraints acting upon a cultural landscape and its internally defined value significance.

Second, HEPLP extends the conceptual reach of existing frameworks. For instance, studies on Cultural Ecosystem Services (Csurgó and Smith, 2021) show that cultural heritage, sense of place and tourism are central but are usually assessed independently from multi-hazard risk and ecological sensitivity, which limits their application in solving the site-anchored conflicts in planning. Building upon those research, HEPLP introduces a multidimensional conceptual unit method to transform

Fig. 10. Strategic conservation and development practices for each of the eight clusters.

Table 11
Comparison of HEPLP with related frameworks.

Framework	Focus	Limitations	HEPLP Contribution
Landscape Vulnerability Model (Cook et al., 2019; Sesana et al., 2019)	Integrates external stressors with internal ecosystem disturbances into a vulnerability index.	Strong on geographical-ecological assessment but neglects heritage value perceptions and governance interfaces.	Extends vulnerability analysis by embedding perception mapping and zoning conservation-development tradeoffs.
Customizable Disaster Risk Management Framework (Bosher et al., 2020; Durrant et al., 2023)	Aligns heritage value perceptions with disaster risk governance across regional contexts.	Conceptually broad, limited spatially social-ecological explicitness and operational details.	Operationalizes heritage disaster-perception linkages with multi-level ecological integration and clustering.
Cultural Ecosystem Services Framework (Csurgó and Smith, 2021); Social-Ecological Systems framework (Heslinga et al., 2017)	Highlights how ecological processes underpin cultural identity, collective interests, and shared visions.	Captures perception values but remains descriptive and ecosystem-function centric, lacking integration with hazards.	Bridges these theories by aligning geographical hazard layers, enabling conflict identification and adaptive alignments.
HEPLP	Hazard–Ecology–Perception Landscape Planning	Unifies hazard, ecology, and perception into one framework.	Provides an integrated, spatially explicit tool that supports precisely targeted strategies and resilience-oriented landscape planning.

heritage value is typically framed as contextual background or scenario description rather than an explicit decision layer. In addition, HEPLP provides a transferable workflow that translates UNESCO's holistic principles into operational outputs, including spatially explicit evidence layers, cluster based zoning, and rule based intervention catalogues that can be replicated across cultural landscape sites with local calibration of indicators and thresholds.

4.4. Policy and governance implications

The HEPLP framework carries direct policy relevance by functioning as a decision-support tool that can be embedded into different levels of existing governance systems.

From a localization perspective, the newly revised *Cultural Relics Protection Law* (2024), effective from 2025, together with its implementing regulations, defines the conservation scope and the construction control zone as the core spatial objective of heritage governance. In current practice, however, control within construction control zones is often applied through a single boundary based logic and still relies heavily on experience judgment. Within this institutional framework, HEPLP conceptualizes different clusters as governance units characterized by distinct risk and heritage value mechanisms and translates them into graded activity catalogues specifying which intervention is permitted, conditionally permitted, or strictly prohibited. By translating spatial evidence into operational interventions, HEPLP enables direct application in budgeting, inspection logs, monitoring and early warning,

and reporting procedures, and is particularly effective in transitional areas where hazards, ecology and heritage value perceptions are in tension, thus addressing technical gaps in the scientific preparation of conservation plans under the *Regulation on the Protection of Famous Historical and Cultural Cities, Towns and Villages* (2008). Meanwhile, HEPLP outputs can be integrated as GIS based overlay layers within the territorial spatial planning system. At the master planning level, they support the delineation of risk baselines and control buffers. At the detailed planning level, they translate into access conditions and development controls. In addition, these layers provide a shared spatial reference for cross checking hazard, ecology, and heritage value related special plans, thereby facilitating coordinated implementation.

At the international level, HEPLP translates the principle in *the Operational Guidelines* (UNESCO, 2025) that Outstanding Universal Value (OUV) must be continuously sustained into a spatial governance grammar, thereby providing an actionable spatial lever for state responsibility rather than leaving it at the level of general declarations. In doing so, it enables a more equitable valuation of areas that have traditionally been overlooked in heritage assessments. HEPLP offers a technicalized implementation example of the *Recommendation on the Historic Urban Landscape* (UNESCO, 2011), particularly its emphasis on social participation and integrated management of natural and cultural processes. UNESCO and its advisory bodies such as the *International Council on Monuments and Sites* (ICOMOS) *and the International Union for Conservation of Nature* (IUCN) can use HEPLP to mobilize public support as a social foundation for advancing risk-informed monitoring and heritage environmental management. As complementing the *Sendai Framework for Disaster Risk Reduction* (United Nations Office for Disaster Risk Reduction, 2015), HEPLP can be embedded into national disaster risk management and spatial planning systems to foster cross-sectoral collaboration among cultural heritage authorities, environmental agencies, and tourism departments.

In addition, from a sustainability perspective, HEPLP explicitly distinguishes between non-negotiable baseline conservation zones and negotiable transitional zones, reducing the space for experience-based bargaining under economic development pressure. In this sense, it serves as a practical complement to the *World Heritage Policy on Sustainable Development* (UNESCO, 2015) and the *World Heritage Climate Action Policy* (UNESCO, 2023), moving beyond a conceptual model to become an operational governance instrument for building the long-term resilience of cultural landscapes.

4.5. Limitation

While the HEPLP framework provides a structured integration of hazard, ecology, and perception dimensions, there remain some limitations. First concern is about the expert perception dataset. Only five experts participated in the heritage value assessment matrix, which inevitably restricts the diversity and representativeness of expert viewpoints. A small expert panel may not fully capture alternative interpretations of heritage value. Future studies could expand the expert sample broader across institutions and disciplines and incorporate structured consensus methods such as group-based evaluation workshops to enhance the robustness and generalizability of expert based assessments. In addition, the scoring of public heritage value perception is based on secondary data from social media sources, which may not fully capture the diversity of local or less digitally active voices. Future work could incorporate field-based methods such as interviews or participatory mapping to improve inclusiveness, because HEPLP may need adaptation in cultural landscapes without strong digital footprints. While the LLM-based analysis offers valuable insights, online comments are unevenly distributed and may carry bias. We mitigated this by data cleaning and balanced sampling, and cross-validated results with expert scores using kappa statistics and a confusion matrix, which confirmed substantial agreement.

Second, the clustering of ecological sensitivity and heritage value

perception, though supported by sensitivity tests, may oversimplify complex gradients. HEPLP uses threshold based high and low classification of the normalized indicators, so scenes with very similar values near a breakpoint may fall into different clusters. Our sensitivity analysis indicates that this does not alter the overall cluster structure, but values close to the thresholds should be interpreted with caution. More refined clustering approaches could improve the model's responsiveness to subtle differences across sites.

Third, the framework emphasizes spatial clustering but pays limited attention to temporal dynamics. Geographical hazards, ecological sensitivity, and heritage value perceptions all evolve over time. Integrating temporal scenarios or monitoring data would support more adaptive planning strategies.

5. Conclusion

This study introduces a HEPLP framework that systematically identifies the tensions among between geographical hazard assessment, ecological sensitivity analysis, and heritage value perception mapping, thereby improving the cultural landscape planning. The framework demonstrates how a composite spatial decision pathway informs differentiated conservation and development strategies in the case study of CMR. The study converts multisource data into cluster-targeted characterization process, identifying nine spatially explicit clusters, revealing both synergies and conflicts between external constraints and internally defined value significance. Specifically, one cluster with high-risk scenes require complete conservation, while the remaining eight clusters present nuanced trade-offs between ecological sensitivity and heritage value perception, necessitating tailored implementations of landscape planning.

Beyond its empirical application, the HEPLP framework provides a theoretical innovation by establishing a multilayered relational structure that allows environmental scientific measurements and socio-cultural perceptions to coexist within a shared planning decision system. It extends the articulation of landscape planning theory through site-anchored conceptual prototype, integrating previously fragmented elements into issue-specific interventions. Moreover, the integration of public heritage value perception by LLM with hazard and ecology, which is often overlooked in formal planning, enhances the social engagement. Through this process, knowledge systems projected from different coordinates converge, bridging qualitative value discourses and quantitative planning models to offer a more transferable and interpretive implementation. Additionally, HEPLP demonstrates direct policy relevance by translating those evidences into spatially explicit, graded governance instruments that can be embedded across local and international planning systems. It operationalizes key principles by converting abstract commitments on risk-informed management, conservation and value identification into an actionable spatial governance for environmental resilience, social engagement, and sustainable management.

Future research can extend the temporal dimension into a dynamic scenario and feedback framework, since indicators vary dramatically with seasonal cycles, extreme events, and management interventions. Accordingly, scenario simulation and rolling update mechanisms can be introduced to form a landscape planning chain of monitoring, adaptive triggers, and zoning adjustment. In parallel, mechanism testing should be continuously conducted to examine which governance measures genuinely reshape coupled relationships among geographical hazards, ecological sensitivity, and heritage value perception, thereby enhancing HEPLP as an evaluable intervention framework rather than a merely diagnostic tool. In addition, future work can accumulate a semantic repository of common cluster configurations and context specific thresholds to establish a transferable benchmarking system, for example across historic urban districts, industrial heritage, and coastal heritage.

CRediT authorship contribution statement

Jingsen Lian: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steffen Nijhuis:** Writing – review & editing, Supervision. **Xu Shan:** Writing – review & editing, Supervision. **Gregory Bracken:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2026.114681.

Data availability

Data will be made available on request.

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