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Dan Xie

xiedan@hebut.edu.cn

Hebei University of Technology

Zhuojun Dong

Hebei University of Technology

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Climate risk assessment for preventive conservation of the Jin Great Wall in Xilingol

Dan Xie ^{1,*}, Zhuojun Dong ²

¹ School of Architecture and Art Design, Hebei University of Technology, No.29 Guangrong Road, Hongqiao District, Tianjin 300401, China; xiedan@hebut.edu.cn

² School of Architecture and Art Design, Hebei University of Technology, No.29 Guangrong Road, Hongqiao District, Tianjin 300401, China; zhuojun22@outlook.com

* Correspondence: xiedan@hebut.edu.cn; Tel.: (+86)15102232429

Abstract: Climate change exposes the earthen heritage to interactive hydromorphic, aeolic and freeze–thaw erosion processes. Here we studied a GIS-based framework to assess the climate risk of the Jin Great Wall on the bank of Xilingol League in Inner Mongolia. The framework incorporates indicators of climate hazards, eco-environment exposure and vulnerabilities of the heritage fabric. The indicator weights were derived by analytic hierarchy process and aggregated by a weighted linear model. The risk map characterizes very clear spatial distinction and it shows that risk in general decreases from the southwest to the northeast direction. Risk highspots are located mainly in the western and northern parts of Xilingol, and a great part of mapped route passes through areas with moderate or high risk. The framework enables a regional screening of earthen linear heritage and shows clearly which parts are of priorities for monitoring and preventive conservation.

Keywords: preventive conservation; climate risk; geographic information system; analytic hierarchy process; Jin Great Wall

1. Introduction

Climate change and other environmental change are exacerbating environmental pressures on heritage culture. Extreme precipitation, floods and compound hydrological hazards are increasing or damaging in many places, and changes in humidity and repeated freezing–thawing impacts heritage fabric and the fabric of its heritage preservation environment. These pressures have resulted in a movement away from repair after damage to preventive conservation based on identification of heritage conservation risks, long-term monitoring and active adaptation. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stresses that climate risk is manifested as dynamic interplay between hazards, exposure and vulnerability ^[1]. Heritage conservation has adopted this perspective when managing climate risk in heritage conservation, bringing disaster resilience, climate adaptation and environmental care to the common arena of monitoring and assessment.

Regional extent of this research is uneven. Fatorić and Seekamp found that studies on climate-change impacts on cultural heritage were concentrated in Europe and relatively under-represented other regions, on balance ^[2]. Climate-related deterioration is, however, a practical concern for cultural heritage around the world and needs risk-management response tailored to the specific region. In China, heritage policy and conservation practice have also gradually evolved from emergency repair

to preventive conservation ^[3]. Field survey, condition survey and environmental monitoring have been applied to assess the vulnerability of the major sites to extreme environmental conditions. Risk-management principles were adopted rather early in the context of some cave-temple sites like Mogao Grottoes, where monitoring, early warning and prevention intervention were packaged in an integrated conservation system ^[4,5].

Recognizing interacting hazards is another element that is altering the scale at which heritage risk is assessed. Single-hazard methods cannot model settings in which climate variability, ecological change and human disturbance interact. Multi-hazard and integrated risk assessment are important research directions for heritage studies. Aktürk and Hauser observed that climate change and disaster risk are still typically dealt with separately although strengthening heritage-site resilience requires an analytical approach able to account for both ^[6]. Ravankhah and colleagues combined climate model projections, a GIS-based spatial modelling approach, and a hazard-analysis matrix to assess vulnerability and risk for the historic centre of Rethymno in Greece ^[7]. Studies of heritage-risk assessment have progressed beyond simplistic mapping of fixed standalone hazards to spatially explicit, multidimensional analysis.

Jin Great Wall is an important element of the Great Wall heritage system of China. Parts of its earthen fabric survive in exposed semi-arid environments in which drought, dust storms, heavy downpours, strong winds, and seasonal freezing can all occur together. Wind blown sediment, large temperature ranges, soil loss and changes in land cover affect different sections in different ways, producing the need for varying levels of conservation effort, spatially differentiated conservation. This study develops a climate-risk and environmental-vulnerability model for the Jin Great Wall in Xilingol League. Climate, ecological and heritage-condition indicators were standardised, reclassified and weighted in ArcGIS to identify key risk drivers, map inter-regional variation and classify vulnerability. The study goes on to consider how the mapped pattern might inform monitoring and preventive conservation, but acknowledges the limits of a regional screening model.

2. Results

2.1 Study Subject and Area

More than 7000 km of the Jin Great Wall remains, with recorded length more than 4000 km in Inner Mongolia. All the Northeastern route, Linhuang route, Northwestern route and Southwestern route exist in the autonomous region and form a broadly connected defensive route system (Fig. 1). Its route passes through a climatic semi-arid transition area, including forest steppe, typical steppe and desert steppe. This area offers a marked gradient in climate with regard to precipitation, wind erosion, land degradation and a favourable setting for investigating effects of past climate processes on rammed-earth heritage. Inner Mongolia has also long been the priority region for national-level surveys of the Great Wall and has a very comprehensive history, archaeological and geographical survey data.

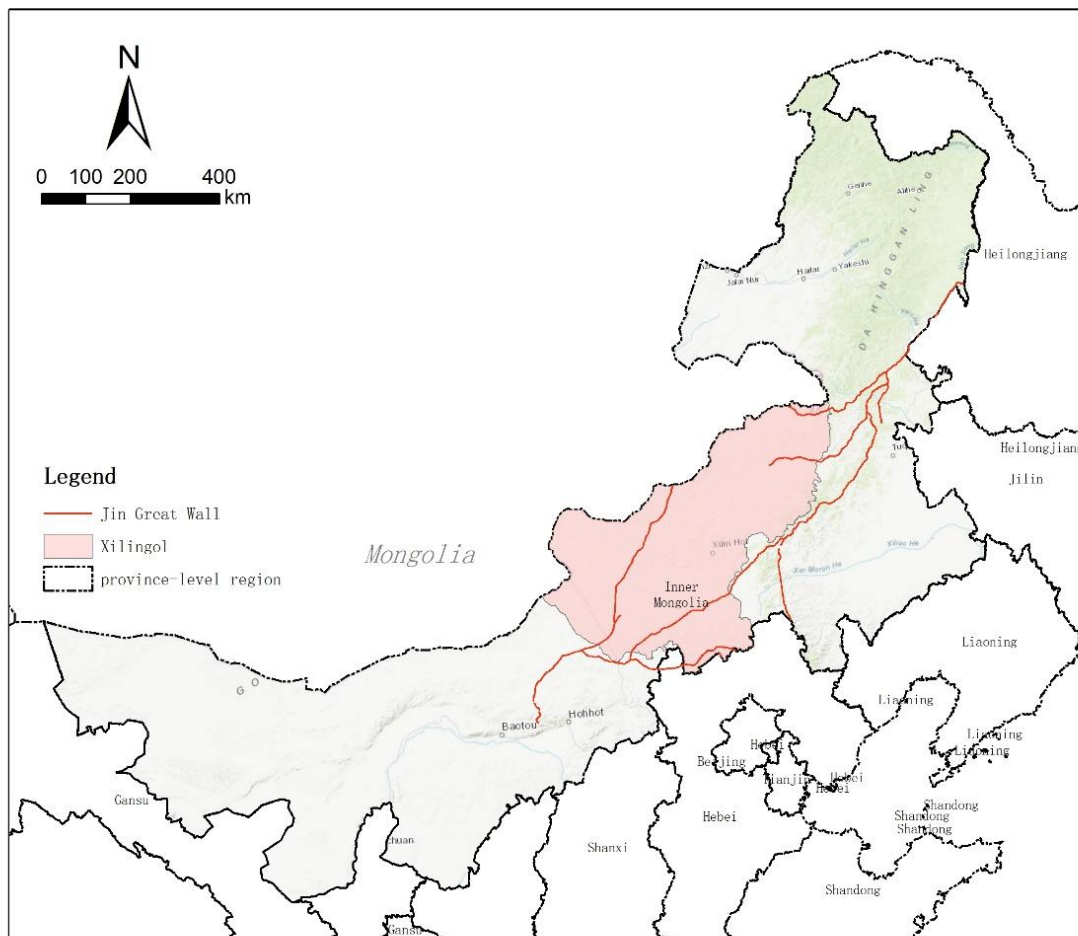


Figure 1 Distribution of the Jin Great Wall in Inner Mongolia and the location of Xilingol League.

Line-density maps were produced using the ArcGIS Line Density tool, for the mapped ditch-and-wall alignments within the neighbourhood of each raster cell. The line density output raster (Fig. 2) shows where the linear remains are most dense and gives the spatial setting for choosing Xilingol League as the core study area.

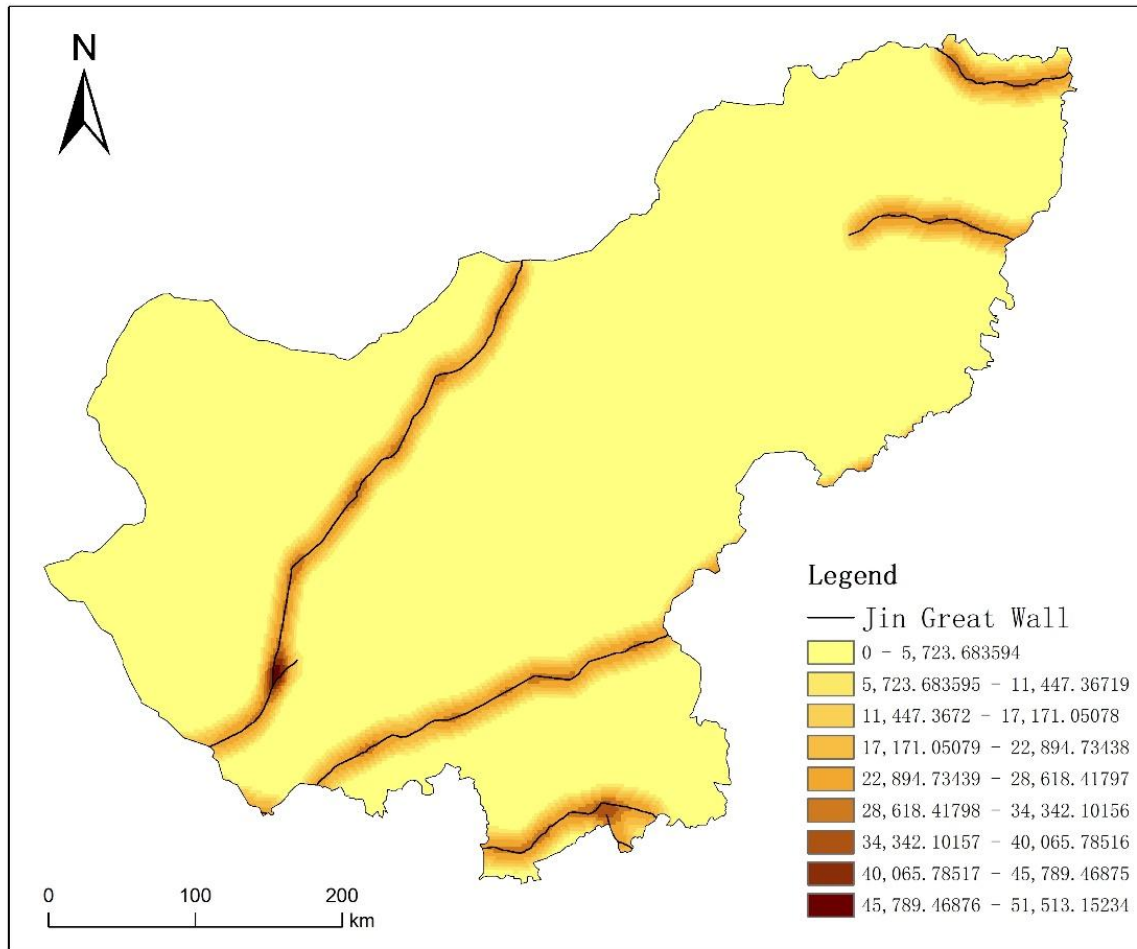


Figure 2 Line-density raster of the Jin Great Wall ditch-and-wall alignments in Xilingol.

Xilingol was selected taking into account the extent and recognisability of the remains, and available documentation to support. Almost 1,080 km of Jin-period ditch-and-wall remains cross East Ujimqin Banner, West Ujimqin Banner, Xilinhot, Abag Banner, Sonid Left Banner, Sonid Right Banner, Zhenglan Banner, Duolun County and Taibus Banner. The route passes along the junction of Lingnan line and the main line, has a direct link towards the east to Holingol, Jarud Banner, and goes towards the west to Ulanqab. Its unbroken distribution favours spatial analyses at a regional scale.

Some Xilingol sections still preserve wall profiles, about 1.5–2.5 m in height, well detected ditches and accompanying frontier forts, watch platforms and other structures. Rescued excavation at the outskirts of Quansheng village in Sonid Right Banner had built by compaction of red clay, white clay and gravel, single-ditch-single-wall and double-ditch-double-wall forms in similar periods. Historical research and archaeological study in the region include Wang Guowei's XilinGuoriguling starting with his 1927 research of a Jin boundary trench, then latest field surveys and some particular studies of frontier fortifications of Jin. Counting the boundary trench in the Great Wall resource survey of the whole nation at the year of 2007 broadened the register of the site archive and GIS available for the current research.

Located in Xilingol, the related places of Jin Great Wall include the western branch of the lingnan line, the Monan line, the main line and the southern branch of the main line, with a totaled mapped

length of 1,079.902 km. Watchable walls are left along 513.035 km of it and 566.867 km of it is vanished. In the survey records, its route has 248 segments and has been surveyed 861 watch platform, 58 frontier forts, two gate forts and 37 guardhouse sites, and its construction often adopts one ditch / one wall, one ditch / two wall and two ditch / two wall styles in rammed mud walls or stone walls, long eroding weathering are greatly reduced the number of segments into discontinuous earth ridges or stone line and its preservation varies greatly along the route.

Work in the Great Wall National Cultural Park and in the Fourth National Survey of Cultural Relics has bolstered and updated the evidence. Real-time kinematic surveying, UAV photogrammetry and high-resolution images were used to record location, condition and surrounding situation. These information allowed a gradual transition from the resource inventory to graded monitoring, risk identification and differentiated protection.

2.2 Spatial patterns of individual risk indicators

The indicator maps exhibit a clear w–e contrast across Xilingol. Precipitation risk, freeze-thaw damage, light vegetation, soil erosion, wind erosion and desertification add up to a relative concentration of the environmental stress in the w and n sides of the study area. Figure 3 has eight mapped 1st level indicators. For precipitation, Jenks natural breaks divided the observed values into five groups: 152.8–232.4, 232.4–283.4, 283.4–332.9, 332.9–388.5 and 388.5–535.6 mm. The rest of the continuous layers were also converted into five ordinal risk classes before weighted overlay.

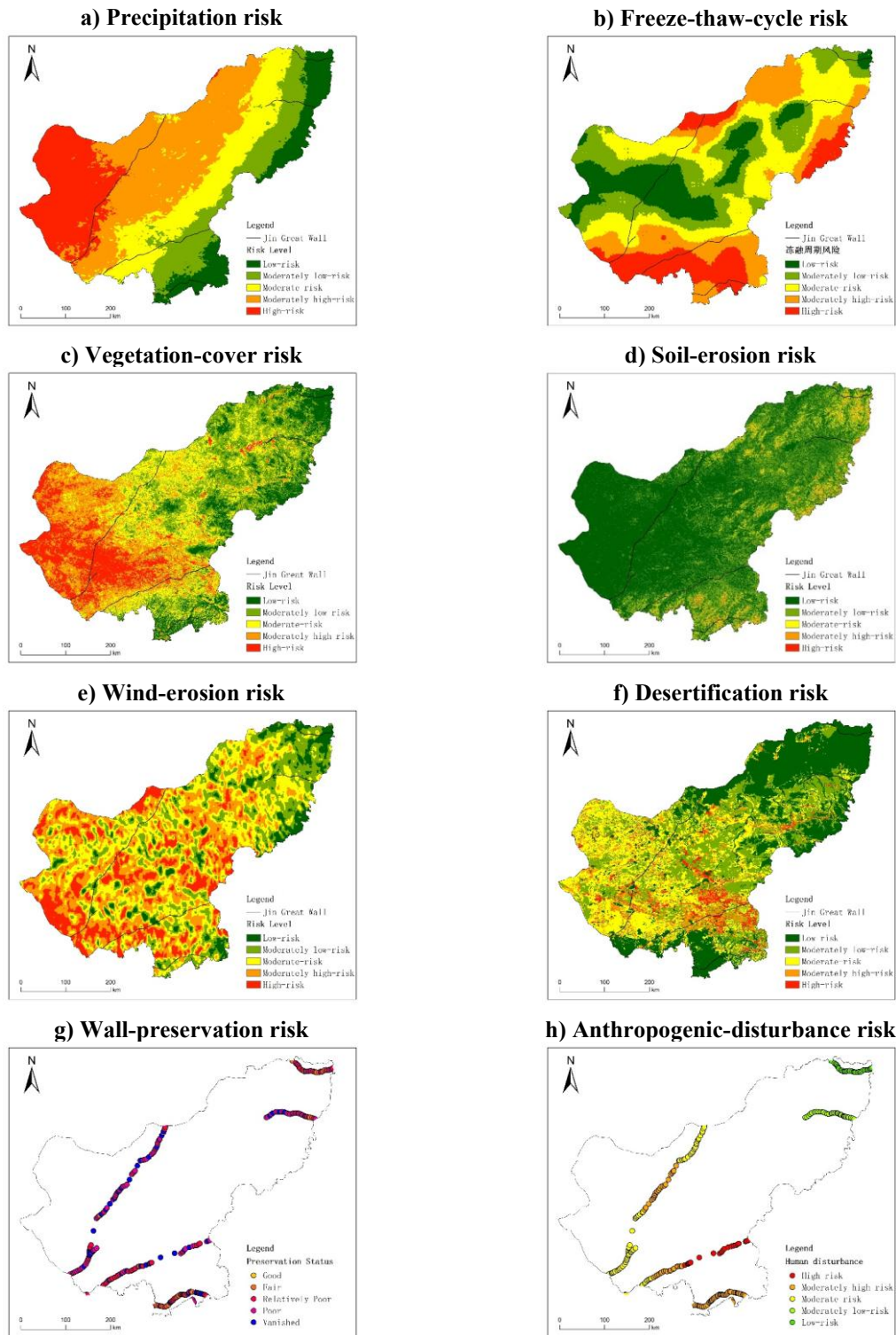


Figure 3 Indicator-level risk maps for the Jin Great Wall in Xilingol. The risk-class wording embedded in the source maps is retained.

Western and north-western Xilingol, such as Sonid Left Banner and the Erenhot area, has the longest-lasting clusters of high risk. Sparse vegetation offers a poor level of protection for the soil surface, and can also increase its susceptibility to wind erosion. Where the pressure of grazing has led to a decrease in the cover of vegetation, exposed ground can also be affected more strongly by freeze–thaw action. Eastern and southern Xilingol generally has more desirable moisture and temperature

conditions and denser vegetation, and is, therefore, of less ecological risk. However, this pattern is not fixed: variability of climate and land use will both affect the degree and spatial distribution of degradation.

2.3 Composite climate-risk zoning

Following reclassification, the standardised indicator layers were then multiplied by their weights and concatenated with each other in Raster Calculator. The combination result was divided into five classes with the corresponding levels of terminology used in the source maps: Low-risk, Moderately low-risk, Moderate-risk, Moderately high-risk and High-risk (Fig. 4). This pattern is spatially differentiated and in general decreases from the southwest to the northeast.

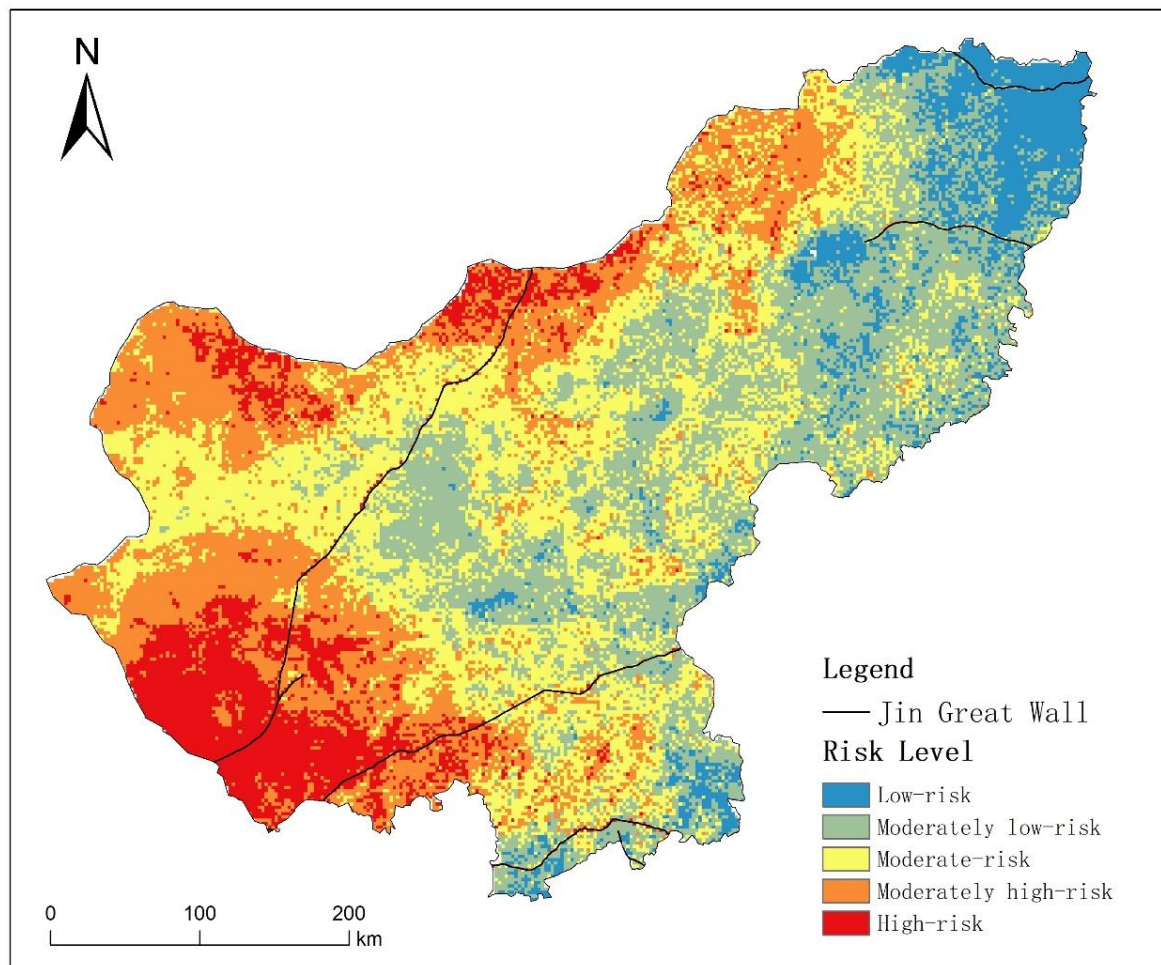


Figure 4 Composite climate-risk zoning and the Jin Great Wall route in Xilingol.

High-risk areas account for 23.30% of the study area. They extend from south-western Sonid Right Banner to western Sonid Left Banner and form an additional belt along the northern border of Sonid Left Banner. Moderately high-risk areas account for 27.20% and occur mainly in western and west-central Xilingol. The Moderate-risk class occupies the largest contiguous area. Low-risk areas account for 12.07% and are located mainly in East Ujimqin Banner and along the south-eastern corridor through Zhenglan Banner, Duolun County and Taibus Banner, where moisture, thermal conditions and vegetation are comparatively favourable.

Overlaying the Jin Great Wall routes on the composite zoning map reveals considerable differences in exposure between the lines and sections. The south-western sections of the main line and the Monan line mainly run through the High-risk and Moderately high-risk zones. Risk starts to decrease closer to Xilinhot, but the northern route runs across the high-risk belt in northern Sonid Left Banner. Along the southern branch of the main line, risk generally decreases west-to-east, whereas much of the western branch of the Lingnan line is located within the Low-risk zone. A preliminary space estimation estimates that half of the mapped Jin Great Wall route falls in Moderately high-risk or High-risk zones. These sections are influenced by each other by freeze-thaw action, wind erosion and aridity and need to be prioritized for field monitoring and preventive conservation in the near future.

3. Discussion

Thus, there is a high risk concentration in western and northern Xilingol because of the regional climate gradient, surface conditions and human occupation conditions. The study region has a typical mid-temperate and semi-arid continental monsoon climate. It is true that the precipitation decreases and evaporation increases from east to west; the corridor between Sonid Left Banner and Erenhot have an annual precipitation that is less than 250 mm, yet have more than 80 strong-wind days, whose limited rainfall preserves the ground surface dry; more frequent strong winds remove fine materials and soil erodibility increases. IPCC identifies semi-arid regions as being vulnerable to climate change, as these regions feature pronounced warming and substantial precipitation variability^[1]. Greater climate change variability could then enhance drought and wind-erosion pressure in this part of the study region.

For the route-level overlay, we can also see that the Jin Great Wall cannot be treated as something that all its segments are under the same environmental setting. The main line and south-western Monan line repeated going through High-risk and Moderately high-risk regions, the northern line passes through a second High-risk belt, and the southern branch has a clear west–east gradient. The western branch of the Lingnan line is comparatively less affected. Around half of the mapped route lies in the two highest risk classes, which tells us that there is significant spatial heterogeneity across this linear heritage system. Conservation interventions for this system should focus on climate adaptation and ecological restoration and intervention on nearby human activities, with balance in interventions adjusted to the dominant pressures affecting each section.

Our assessment gives a practical means of allocating scarce conservation resources. The Erenhot-Sonid Left Banner corridor would benefit from wall-stability surveys and denser coverage of monitoring. In the transition from Sonid Right Banner to Abag Banner, scheduled preventive maintenance and routine inspection would be appropriate. Lower-risk areas in the south-east still need baseline monitoring, but community involvement can be useful in detecting disturbance due to grazing, roads and other routine activities. This levelled response can direct scarce funds and technical resources towards sections where environmental pressures and low wall-stability are concordant, as opposed to distributing effort unequally without regard to risk.

Several limitations limit our interpretations. The anthropogenic component does not yet include grazing intensity, the road density or the tourism-development pressure. Field observations indicate that livestock trampling and loss of vegetation near some sections of the western side increase the disturbance of surfaces and wall erosion, but continuous quantitative information was not available. The indicator system also does not yet include density, moisture content, compressive strength or other properties of the rammed earth, even though these affect resistance to wind erosion, water erosion, freeze-thaw deterioration and so on. Field sampling, non-destructive testing and laboratory test experiments would make future vulnerability estimates to be more responsive to the real condition of the fabric.

Finally, there is the scale problem. County administrative units are convenient for integration of data and match the existing management responsibility. But they hide different local situations among slopes, landforms and land-use types at the same banner or county. The boundaries of administrative units also do not match environmental risk boundaries. Our maps are therefore suitable for regional screening and priority setting, and not suitable for diagnosis of individual wall sections or specifying construction interventions. Before the outputs are used for practical planning and project application, the input data should be improved, the model should be tested against observed deterioration and the extent of each risk class should be clarified.

Despite these limitations, our study also shows that risks along the Jin Great Wall are not generated by a single hazard. Climate, ecological situation, preservation state and local land use work together and the relative importance of them change along different sections. Sections seriously affected by the freeze-thaw action require seasonal monitoring; sections affected by wind erosion and vegetation degradation require complementary treatment of heritage fabrics and surrounding environment. Together with field investigation and long-term monitoring, the framework can assist with risk zoning, monitoring point location and conservation investment allocation for the Jin Great Wall, and can even give a comparative method for other extensive earthen and linear heritage systems in the north China.

4. Methods

4.1 Data sources and preprocessing

Administrative-boundary data for Inner Mongolia were obtained from the National Geomatics Center of China. A 30 m digital elevation model (DEM) was acquired from the International Scientific Data Service Platform of the Computer Network Information Center, Chinese Academy of Sciences. Climate data for Xilingol covered a ten-year period [exact start and end years to be supplied] and were obtained from the National Earth System Science Data Center. Freeze-thaw cycles were calculated from reanalysis data [the ERA5 or ERA5-Land product, temporal resolution and cycle-counting rule are to be supplied] ^[8]. Vegetation metrics were derived from Landsat imagery obtained through the Geospatial Data Cloud. Land-use data were resampled from a 1 km x 1 km raster in ArcGIS. Soil erosion was estimated with the Revised Universal Soil Loss Equation (RUSLE), and desertification data were derived from the 1:100,000 Map of Deserts in China.

The spatial datasets were projected to a common coordinate system, clipped to the study area, aligned and resampled to a consistent working grid. Continuous variables were reclassified as ordinal risk scores, while categorical variables were scored using published thresholds or expert judgement. Figure 5 presents six representative input layers: river density, decadal mean annual precipitation, freeze-thaw cycles, vegetation cover, soil erosion and desertification type.

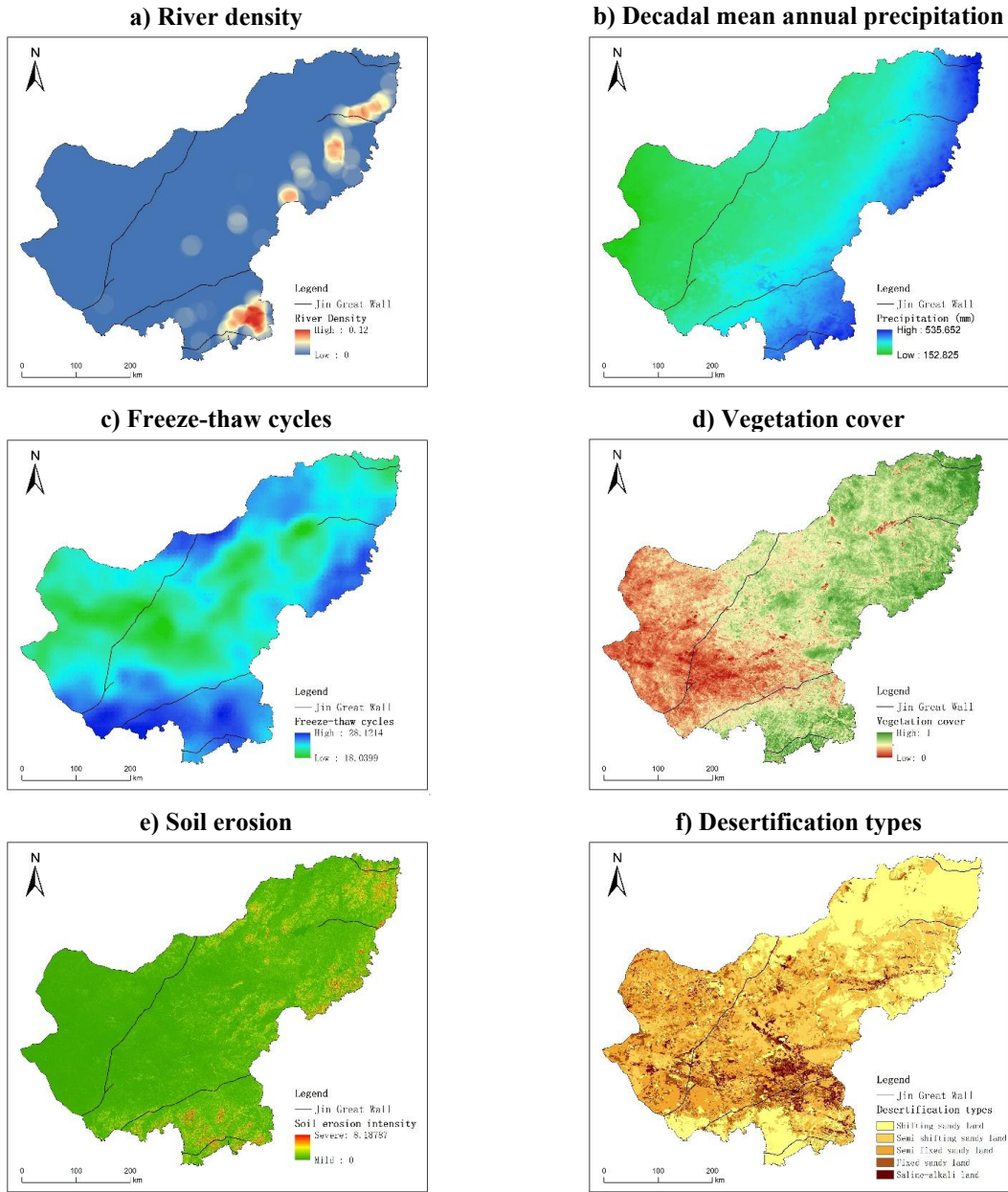


Figure 5 Representative spatial input layers used in the assessment.

4.2 Risk framework and indicator selection

The indicator system follows the climate-risk concepts developed in the IPCC Fifth and Sixth Assessment Reports ^[1,9]. Risk was treated as a function of interactions among hazard (H), exposure (E) and vulnerability (V), expressed conceptually as $R = f(H, E, V)$. For the Jin Great Wall, these dimensions were operationalised as climate hazard, eco-environmental exposure and vulnerability of the heritage fabric. The hierarchy contains nine first-level indicators and 17 second-level indicators.

Precipitation. Rainfall affects the stability of rammed-earth sites through surface wash and infiltration. Microscopic and mineralogical studies indicate that infiltration reduces matric suction, moves near-surface soil from an unsaturated towards a saturated state and lowers strength, allowing material to detach along weak planes ^[10]. Raindrop impact and capillary transport can mobilise fine particles and clog pores, further disrupting the surface structure ^[11]. Wetting and drying can also

interact with wind erosion in the progressive deterioration of earthen fabric ^[12]. Xilingol receives approximately 200-350 mm of precipitation annually, with substantial interannual variability and a pronounced summer concentration. Short-duration heavy rainfall can produce gullies around the remains, and increased soil moisture can intensify subsequent freeze-thaw damage. The assessment therefore included mean annual precipitation, extreme-precipitation frequency, the spatial distribution of decadal mean annual precipitation and river density.

Freeze-thaw action. Pore water expands by approximately 9% when it freezes, generating frost-heave pressure and microcracking. Soil strength then falls during thaw, and repeated cycles promote a loosened surface layer and detachment of crusts ^[13]. Winters in Xilingol are long and cold, with a mean annual temperature of approximately 0-3 °C, extreme minima below -40 °C and maximum frost depths of 295-346 cm. Freeze-thaw action is therefore an important mechanism of deterioration for exposed earthen remains ^[14]. Annual freeze-thaw frequency and maximum frost depth were included as indicators.

Wind erosion. Wind erosion is a major external process affecting earthen heritage in semi-arid environments. The Revised Wind Erosion Equation (RWEQ) integrates climatic forcing, soil erodibility, surface roughness and vegetation cover ^[15]. Application of the model to the Inner Mongolian Plateau shows a marked decline in modelled wind-erosion intensity from west to east ^[16]. Xilingol experiences approximately 60-80 strong-wind days each year, 40-50% of them in spring. Mean wind speeds are approximately 4-5 m s⁻¹, with maxima of 25-34 m s⁻¹. Wind-blown sediment abrades exposed walls, removes fine particles and progressively weakens their profiles; experimental work on coupled deterioration also shows that the presence of abrasive particles can greatly increase soil loss relative to wind alone ^[12]. The RWEQ-derived wind-erosion modulus and annual number of strong-wind days were used as indicators.

Vegetation cover. Vegetation limits wind and water erosion by sheltering the soil surface. Across arid and semi-arid north-western China, the Normalized Difference Vegetation Index (NDVI) is negatively associated with wind-erosion sensitivity ^[17]. Xilingol crosses meadow steppe, typical steppe and desert steppe, and its east-west gradient in vegetation cover affects the resistance of the wall's environmental setting to erosion. Fractional vegetation cover derived from Landsat imagery and the trend in vegetation degradation were included in the assessment ^[18].

Soil erosion. Soil loss can expose wall foundations and contribute to local collapse. RUSLE estimates water-driven soil loss from rainfall erosivity, soil erodibility, slope length and steepness, cover management and conservation practice ^[19]. The model has been applied in the Chinese Loess Plateau and related catchments ^[20,21]. Wind erosion dominates much of Xilingol, but water erosion is also important; approximately 93,000 km², or 46% of the league, is reported to be affected by soil and water loss ^[22]. The RUSLE-derived soil-erosion modulus and the proportion of land affected by erosion were included.

Desertification. Desertification changes the surface around the remains, removes fine material and increases the susceptibility of the wall to wind erosion. Remote-sensing analysis identifies Xilingol as one of the parts of Inner Mongolia most extensively affected by land desertification ^[18]. Regional research also reports a positive association between desertification indices and wind-erosion intensity

[23]. Desertification severity class and the spatial distribution of desertification types were used to characterise this component of eco-environmental exposure.

Preservation of the heritage fabric. Present condition indicates the capacity of a wall segment to withstand further environmental stress. The 2007 national Great Wall survey standard defines five preservation classes from the proportion of fabric retained: good (at least three quarters), fair (one quarter to three quarters), relatively poor (less than one quarter), poor (surface traces only) and vanished (no visible remains at ground level) [24]. The wall-preservation indicator assigns greater vulnerability to sections in poorer condition.

Anthropogenic disturbance. Grazing, agricultural reclamation, ditch infilling, road construction and settlement expansion can affect the Jin Great Wall directly or indirectly. Li et al. represented human activity near the Ming Great Wall using distance to farmland, construction land and roads [25]. Nicu used road networks and settlements as vulnerability indicators in an AHP-GIS assessment and created 250 m road buffers to examine their relationship with cultural-heritage vulnerability [26]. Distance to the nearest road was the available disturbance indicator in the present assessment.

Heritage value. Sections differ in construction form and statutory protection status. Under comparable hazard intensity, damage to a highly valued section entails a greater loss of heritage significance. A multi-hazard assessment of 781 Great Wall remains in Miyun District placed 7.42% in very-high-risk areas and identified cracking or collapse threats among more than half of the high-risk remains [27]. Following that framework, statutory protection level was treated as an independent indicator within vulnerability of the heritage fabric. Protection status was joined directly to mapped wall segments rather than interpolated as a continuous regional raster, so no separate regional heritage-value map is presented in Fig. 3.

4.3 Indicator weighting with the analytic hierarchy process

The analytic hierarchy process (AHP) was used to derive indicator weights [28]. The hierarchy comprised three dimensions, nine first-level indicators and 17 second-level indicators. Pairwise comparisons used values from 1 to 4 and their reciprocals: 1 indicated equal importance, 2 slightly greater importance, 3 greater importance and 4 markedly greater importance. The restricted scale was used to reduce excessive amplification of differences in expert judgement. For a reciprocal comparison matrix $A = (a_{ij})_{n \times n}$, the geometric mean of each row and the normalised local weight were calculated as

$$M_i = (\prod_{j=1}^n a_{ij})^{1/n},$$

$$w_i = M_i / \sum_{i=1}^n M_i.$$

Consistency was evaluated from

$$\lambda_{max} = (1/n) \sum_{i=1}^n [(Aw)_i / w_i], \quad CI = (\lambda_{max} - n) / (n - 1), \quad \text{and} \quad CR = CI / RI.$$

The random index RI was set to 0.58 for $n = 3$ and 0.90 for $n = 4$. A comparison matrix was accepted when $CR < 0.10$. Table 1 gives the dimension-level matrix. First-level global weights were obtained by multiplying each dimension weight by the local weight of the indicator within that dimension. Second-level weights were calculated as the product of the first-level global weight and the corresponding local second-level weight (Table 2).

Table 1 Pairwise comparison matrix and normalised dimension weights.

Dimension	Climate hazard	Eco-environmental exposure	Vulnerability of heritage fabric	Geometric mean M_i	Normalised weight w_i
Climate hazard	1	2	3	1.817	0.540
Eco-environmental exposure	1/2	1	2	1.000	0.297
Vulnerability of heritage fabric	1/3	1/2	1	0.550	0.163

Table 2 Indicator weights for climate-risk assessment of the Jin Great Wall in Xilingol.

Dimension	First-level indicator	Weight	Second-level indicator	Weight
Climate hazard	Precipitation risk	0.209	Mean annual precipitation	0.051
			Frequency of extreme precipitation events	0.092
			Spatial distribution of decadal mean annual precipitation	0.046
	Freeze-thaw-cycle risk	0.239	River density	0.021
			Annual number of freeze-thaw cycles	0.160
			Maximum frost depth	0.080
	Wind-erosion risk	0.091	Wind-erosion modulus	0.061
			Number of strong-wind days	0.030
Eco-environmental exposure	Soil-erosion risk	0.160	Soil-erosion modulus	0.107
			Proportion of land affected by soil erosion	0.053
	Vegetation-cover risk	0.088	Fractional vegetation cover	0.059
			Vegetation degradation trend	0.029
	Desertification risk	0.049	Desertification severity class	0.032
			Distribution of desertification types	0.016
Vulnerability of heritage fabric	Wall-preservation risk	0.088	Wall preservation status	0.088
	Heritage-value risk	0.027	Statutory protection level	0.027
	Anthropogenic-disturbance risk	0.049	Distance to the nearest road	0.049

4.4 Risk classification

Qualitative indicators were assigned ordinal scores by expert judgement, whereas quantitative indicators were classified using thresholds reported in relevant studies. Line Density, kernel density estimation and buffer analysis were applied where appropriate to the relevant spatial variables. The resulting layers were divided into five classes - Low-risk, Moderately low-risk, Moderate-risk, Moderately high-risk and High-risk - and assigned scores from 1 to 5 (Table 3). Jenks natural breaks were used for continuous distributions when fixed literature thresholds were unsuitable.

Table 3 Five-class risk-scoring criteria for the Jin Great Wall assessment.

Indicator	Low-risk (1)	Moderately low-risk (2)	Moderate-risk (3)	Moderately high-risk (4)	High-risk (5)
Mean annual precipitation (mm)	>350	300-350	250-300	200-250	<200

Indicator	Low-risk (1)	Moderately low-risk (2)	Moderate-risk (3)	Moderately high-risk (4)	High-risk (5)
Freeze-thaw cycles (cycles yr ⁻¹)	<30	30-50	50-70	70-90	>90
Wind-erosion modulus (t km ⁻² yr ⁻¹)	<500	500-1500	1500-2500	2500-4000	>4000
SPI	>-0.5	-1.0 to -0.5	-1.5 to -1.0	-2.0 to -1.5	<-2.0
Elevation (m)	1200-1500	1000-1200	800-1000	1500-1800	<800 or >1800
Slope (°)	<5	5-15	15-25	25-35	>35
NDVI	>0.5	0.4-0.5	0.3-0.4	0.2-0.3	<0.2
Soil-erosion modulus	<500	500-1000	1000-2500	2500-5000	>5000
Preservation status	Good	Fair	Relatively poor	Poor	Vanished

4.5 Spatial integration and composite evaluation

All indicator layers were standardised to values from 0 to 1 and integrated through a weighted linear combination model. The Fortification Vulnerability Index (FVI) was calculated as

$$FVI = \sum_{i=1}^n W_i X_i,$$

where $n = 17$, W_i is the AHP-derived weight of indicator i with $\sum W_i = 1$, and X_i is the standardised value of that indicator. Larger FVI values indicate greater vulnerability and a higher risk class. The composite raster was reclassified into five zones using natural breaks. The mapped Jin Great Wall routes were then overlaid on the zoning to identify sections exposed to Moderately high-risk and High-risk conditions.

Declarations

(1) Data Availability

Data can be provided upon request from the corresponding author.

(2) Code Availability

Not applicable.

(3) Acknowledgements

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(4) Author Contributions

Conceptualization, DanXie. and Zhuojun Dong.; investigation, DanXie. and Zhuojun Dong.; data curation, DanXie. and Zhuojun Dong.; writing-original draft preparation, Zhuojun Dong.; writing—review and editing, DanXie. and Zhuojun Dong.; funding acquisition, DanXie. All authors have read and agreed to the published version of the manuscript.

(5) Competing Interests

The authors declare no conflict of interest.

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Figure legends

- Figure 1 | Distribution of the Jin Great Wall in Inner Mongolia and the location of Xilingol League.
- Figure 2 | Line-density raster of the Jin Great Wall ditch-and-wall alignments in Xilingol.
- Figure 3 | Indicator-level risk maps for the Jin Great Wall in Xilingol. The risk-class wording embedded in the source maps is retained.
- Figure 4 | Composite climate-risk zoning and the Jin Great Wall route in Xilingol.
- Figure 5 | Representative spatial input layers used in the assessment.

Table legends

- Table 1 | Pairwise comparison matrix and normalised dimension weights.
- Table 2 | Indicator weights for climate-risk assessment of the Jin Great Wall in Xilingol.
- Table 3 | Five-class risk-scoring criteria for the Jin Great Wall assessment.