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Assessment of urbanization impact on cultural heritage based on a risk-based cumulative impact assessment method

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Abstract

Urbanization is inevitable in both developing and developed countries. However, this growth and transformation of the urban area can pose a significant threat to urban cultural heritage, which is a sensitive component of the urban environment. As cities modernize and change, a risk of irreparable loss of cultural heritage exists. Therefore, taking steps to protect and preserve these sites for posterity is crucial. To better protect urban cultural heritage, decision-makers must rapidly assess the impact of urbanization on cultural heritage while maintaining a balance between cultural heritage preservation and urban growth. This study developed a risk-based cumulative impact assessment (CIA) method that integrates a set of quantifiable indicators to address these issues. This method generates standardized assessment results based on game theory and set pair analysis theory. In contrast to other CIA methods, this risk-based approach effectively manages scientific complexity and uncertainties, thus enhancing the quality of the assessment results. This method was applied to 21 classical gardens in Suzhou, China. The results show that Suzhou classical gardens are impacted by urbanization. This study confirmed that adopting a risk-based CIA method that considers the impact of adverse urbanization on cultural heritage sites is an efficient approach. Successful implementation of the proposed method can provide decision-making support for different types of cultural heritage in other areas.

Keywords Urban cultural heritage, Urbanization, Cumulative impact assessment, Risk-based approach, Set pair analysis theory

Introduction

In the current context of rapid economic and social development, urbanization is occurring at a never-before-seen rate, and the surroundings of urban settings are changing as a result of the speedy and usually unchecked development. However, urban features are constantly changing causing challenges in the conservation of urban cultural heritage.

It is universally acknowledged that urbanization is the primary factor contributing to the decline in value and integrity of cultural heritage particularly in historical areas where preparation is still lacking [1–3]. As an integral component of the urban area, cultural heritage may be threatened by urbanization process. This may result in the loss or distortion of material properties that have cultural heritage value, thus preventing sustainable development and conservation. Notably, in recent years, many investigations and reports have demonstrated increasing levels of threats from urbanization on urban cultural heritage sites, such as building and development projects [3–5], transportation infrastructure [6], and environmental pollution [7].

Urban cultural heritage is an essential component of urban areas and can reflect the historical development

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of cities. Maintaining the connection between the past and the future is greatly dependent on the preservation and sustainable development of cultural heritage. Therefore, supporting the sustainable development of urban cultural heritage and addressing the threats faced by it requires a suitable and applicable assessment tool. In this context, the Heritage Impact Assessment (HIA) was introduced to identify and analyze the possible adverse effects of anthropogenic activities on cultural heritage sites [3]. However, the use of an assessment tool cannot be limited to only supporting the management of urban cultural heritage, but it must also have utility as a method to help protect the critical values embodied in cultural heritage. The HIA has been successfully applied and improved upon in several studies [3, 4, 8–10]. However, this approach has a drawback because the current HIA method only considers the impact of a single development project and fails to account for the combined and cumulative impacts of multiple projects. Urbanization impact on urban cultural heritage is a complex problem that requires evaluation of cumulative impacts, which can be derived from different projects. To address this issue, further research is required to investigate cumulative impact assessment (CIA) techniques that are applicable to cultural heritage sites.

CIA has long been acknowledged as a crucial component of impact assessments [11]. It is defined as a comprehensive evaluation of the combined effects of human actions and natural processes on the evaluation subject across space and time [12–14]. The assessment of cumulative impacts has been used in Canada and the United States for many years, where its procedures are incorporated into the Environmental Impact Assessment and Strategic Environmental Assessment procedures [15, 16]. CIA has been explored by researchers in many fields of science, including oceanography and marine area protection [13, 17–20], toxicology and ecotoxicology [21, 22], human health risk assessment [23], forestry [24, 25], fish and wildlife management [26–28], freshwater and watershed management [29, 30] and environmental justice [31, 32]. Compared to the HIA, CIA is more comprehensive because it considers all the potential environmental factors across time. However, no previous study has considered the application of a CIA to cultural heritage.

Characteristics of an urban environment, in particular its vast openness, high interconnection of economic and social factors, and large variability and uncertainty, generate additional complexities and challenges for CIA. However, a thorough and open framework is frequently absent from the operationalization and integration of CIA into decision-making processes. A risk-based CIA framework that divides the CIA method into risk identification, risk analysis, and risk evaluation can better analyze such complexities [13]. Moreover, cumulative impacts are defined as the combined effects of impacts and growth over time, including past, present, and foreseeable future pressures [33]. Currently, existing studies lack a prediction of possible future risks. Therefore, the risk-based CIA method is a promising approach for aligning the cumulative impact assessment with the future risks [34]. It also helps develop preventive measures, adaptive surveillance, and impact reduction measures during the urbanization projects [35].

Given the distinctive characteristics and unparalleled value of urban cultural heritage sites, this study aimed to present a risk-based CIA framework that incorporates a set of indexes to assess the impact of urbanization on urban cultural heritage. The proposed method is designed to provide scientific, quantitative, and standardized methods for assessing the impact of urbanization on cultural heritage sites based on objective and quantitative data.

Method: a risk-based approach to cumulative impact assessments

Overview of the method and design

Cumulative impacts are related to the complexity of human endeavors and initiatives that result in numerous pressures that build up and impact cultural heritage sites [36]. To address this complexity, the CIA was formulated in a risk-based setting.

Risk is the consequence of the interaction between the impacts of an event or hazard and the associated probability that it will occur [37]. The consequences are negative impacts caused by social, political, economic, and environmental factors. In risk analysis, the impacts are often expressed in terms of exposure and vulnerability. Exposure is the totality of objects present in hazardous areas that are subject to potential losses. Vulnerability refers to the characteristics, environments, systems, or resources that make an individual susceptible to the negative impact of a hazard [38]. Hence, the CIA method should reveal the probability of cumulative impact, exposure of cumulative impact, and vulnerability of cumulative impact on cultural heritage.

$$Cumulative\ impact = f(CP, CE, CV) \tag{1}$$

where CP is the cumulative impact probability, CE is the cumulative impact exposure and CI is the cumulative impact vulnerability.

This study presents a risk-based CIA framework that integrates a set of indicators to assess urbanization's impact on cultural heritage sites (Fig. 1). This framework is embedded in the International Organization for Standardization (ISO) risk management process, which

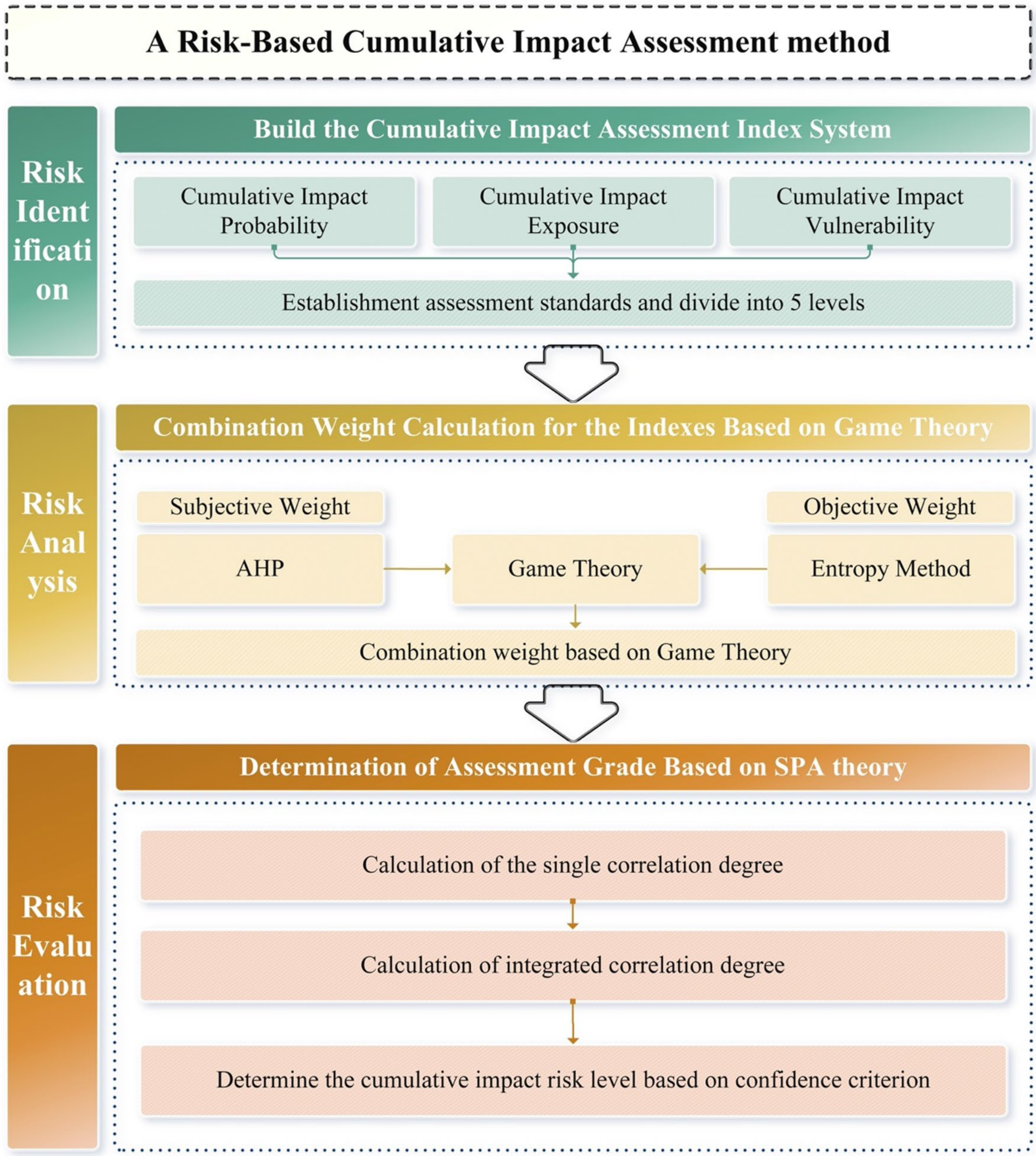

Fig. 1 Flowchart of the risk-based CIA method employed in this study

includes three parts: risk identification, risk analysis, and risk evaluation.

First, risk identification is the process of identifying and assessing risk sources and their potential impacts. Creating cause-and-effect links or risk pathways to describe the vulnerability of cultural heritage to the effects of urbanization is a crucial challenge in risk identification [11]. In this step, an index system including cumulative impact probability, cumulative impact exposure, and cumulative impact vulnerability is constructed, and the evaluation criteria of each index are determined by Jenks classification.

Second, risk analysis comprises comprehending the nature of risk and determining the weight share between risk sources [39]. In this stage, the analytic hierarchy process (AHP) and entropy weight (EW) methods are used to calculate the subjective and objective weights of each index, and game theory is used to determine the combined weight.

Third, risk evaluation identifies specified risk criteria and determines the risk level. The decision concerning risk treatment is aided by risk evaluation, which also necessitates a performance review of new measures [40]. This step introduced set pair analysis (SPA) theory to determine the cumulative impact risk level.

Risk identification

Cumulative impact assessment index system

A cumulative impact assessment index system was constructed using the risk-based CIA framework (Table 1). Cumulative impact probability refers to the probability of future urbanization having an impact on the cultural heritage site. Cumulative impact vulnerability refers to the current impact of urbanization on the cultural heritage site and its vulnerability.

The cumulative impact probability indices are measured as follows:

A) Population density (D1) has helped examine population growth as it indicates how cultural heritage sites are prone to urban growth. The distance from cultural heritage sites to densely populated areas has been found to be proportional to the possibility of interference from human activities [41]. The index refer to the population density of the subdistrict where the heritage sites are located.
B) The new construction land area (D2) is used to examine future construction projects around the cultural heritage sites. Construction projects can generate mechanical shock, pollute the environment, and damage heritage sites. This index is measured by the ratio of the new construction land area within the buffer zone to the buffer zone area.
C) The percentage of surrounding commercial land use (D3) is used to measure the possibility of interference from human activities. The higher the proportion of commercial land around the heritage site, the more human activities and the more intensive the potential urban construction activity. This index is measured by the ratio of the commercial land use area within the buffer zone to the buffer zone area.

The cumulative impact exposure indices are measured as follows:

A) The area of cultural heritage (D4) is an index that reflects a heritage site's level of exposure to the impact of urbanization. The larger the area of the cultural heritage site, the higher the exposure.
B) The percentage of open space (D5) is an index that reflects a heritage site's level of exposure to the impact of urbanization. Open spaces are exposed to urban environments and are more sensitive to the visual impact and noise caused by urban construction.
C) Accessibility (D6) is used to measure the accessibility of cultural heritage sites through transportation networks. Mechanical shock and pollutants from heavy traffic on streets often exceed this limit, posing a risk to the cultural heritage site. Noise can also degrade the tranquility of the site [41]. This index can be calculated using the ArcGIS software based on the origin destination (OD) cost matrix analysis tool.
D) Distance from the subway station (D7) is an index used to measure the distance between a cultural heritage site and subway stations. Typically, more commercial and urban construction activities occur around metro stations.
E) The distance from subway tracks (D8) is an index used to measure the distance between cultural heritage sites and subway tracks. Both the construction

Table 1 Cumulative impact assessment index system of urban cultural heritage

Goal layer (A)	Criteria layer (B)	Index (D)	Index attribute
Risk of cumulative impact	Cumulative probability	Population density (D1)	Positive
		Area of new construction land (D2)	Positive
		Percentage of surrounding commercial land (D3)	Positive
	Cumulative exposure	Area of the cultural heritage (D4)	Positive
		Percentage of open space (D5)	Positive
		Accessibility (D6)	Positive
		Distance from subway station (D7)	Negative
		Distance from subway tracks (D8)	Negative
	Cumulative vulnerability	Harmony index of neighboring building form (D9)	Negative
		Heritage site history (D10)	Positive
		Heritage protection level (D11)	Positive

and operation of the metro system affect cultural heritage sites [42].

The cumulative impact vulnerability indexes are measured as follows:

A) Harmony index of neighboring building forms (D9) is used to indicate the degree of harmony reflected in the relationship between human-made facilities, buildings, infrastructure, and heritage sites. High harmony rarely reduces landscape integrity [43]. This indicator is obtained from the ratio of the area of incongruous building forms within the construction control area to the total construction control area.
B) Heritage site history (D10)—that is, the antiquity of a cultural heritage site—is used as a proxy for heritage value. The longer the heritage site's history, the higher its value and vulnerability to disasters.
C) The heritage protection level (D11) reflects the value of the heritage site, the higher the protection level, the higher the value. Five classes of heritage protection levels exist, namely heritage on the World Heritage List, national-level protected heritage, provincial-level protected heritage, city-level protected heritage, and non-protected heritage units, which are assigned the values of 9, 7, 5, 3, and 1, respectively.

Grading standard of assessment indexes

The risk standards connected to the indices were divided into five classes per the Jenks classification (Table 2). It is a data categorization method that is designed to optimize the arrangement of a set of values into natural classes. This approach clusters data into groups that minimize the within-group variance and maximize the between-group variance [44, 45]. Natural groupings, inherent in the data, serve as the foundation for natural breaks. The best group of similar values and those that emphasize class distinctions are used to determine class breaks [46].

Risk analysis

Combination weight calculation

Determining the appropriate weights for the cumulative impact assessment index system is an essential step in the CIA method. There are two weighting methods, the subjective and the objective, both with advantages and drawbacks [47]. The use of the subjective weighting method can reveal experts' subjective opinions and experiences. A widely utilized subjective method is the AHP [48, 49]. Objective weights based on mathematical theory can avoid subjectivity. The objective weight method—named EW—has been applied in several studies [50, 51]. However, because the objective weight approach can only analyze the value change between indices, the information relevance between indices cannot be assessed. Therefore, game theory was applied in this study to combine the advantages of each of the two weighting methods.

Subjective weight based on the AHP

The AHP is a decision-making strategy that uses a systematic method to evaluate and integrate the effects of many factors [52]. By creating a pairwise comparison judgment matrix between the parameters, this well-known decision-analysis technique enables an analyst to generate weights. Ten experts were invited to participate in this study and complete a questionnaire to construct the judgment matrix.

Objective weight based on EW

Based on the degree of dispersion of each index value, EW may objectively calculate the index weight [53]. Four main steps exist in the entropy method calculation

Table 2 Grading standard of cumulative impact assessment indexes

Indexes	Lowest level	Lower level	Medium level	Higher level	Highest level
D1	0–5628	5628–11500	11500–14709	14709–16615	16615–17000
D2	0–31.533	31.533–43.409	43.409–50.422	50.422–52.084	52.084–56.547
D3	0–0.05	0.05–0.12	0.12–0.16	0.16–0.27	0.27–0.61
D4	758–2416	2416–4709	4709–9323	9323–20491	20491–63958
D5	0.50–0.60	0.60–0.70	0.70–0.80	0.80–0.88	0.88–0.94
D6	0.11–2.61	2.61–3.77	3.77–4.68	4.68–5.81	5.81–8.10
D7	1200–812	812–601	601–427	427–253	253–181
D8	1000–694	694–505	505–265	265–104	104–0
D9	1–0.98	0.98–0.96	0.96–0.89	0.89–0.83	0.83–0
D10	238–502	502–1279	1279–1662	1662–1856	1856–1935
D11	0–2	2–4	4–6	6–8	8–10

process: (1) building a judgment matrix, (2) determining the entropy of each index, (3) calculating the difference coefficient of each index, and (4) obtaining the weight of each index.

Combination weight based on game theory

Game theory is an essential subfield of operations research that focuses on the interaction between competing alternatives and the rational behavior of various decision-makers, including their decision equilibrium when their actions affect each other. In the game, all parties make decisions to minimize their losses or maximize their interests; this requires all parties to find a balanced combination to maximize common interests. Consequently, it is possible to make an individual yet collaborative decision that optimizes all stakeholders' projected returns [47]. The procedure is as follows:

1) The basic combination of weights is carried out by collecting and using results from different weighting methods $W = \{w_1, w_2, \ldots, w_m\}$, where wm is the weight vector of weights for m indices, and W is obtained by the linear combination coefficient ai as follows:

$$W = \sum_{i=1}^{m} a_i w_i^T (a_k > 0) \quad (2)$$

2) By optimizing the weight coefficient ak, the most satisfactory W can be found, which could minimize the deviation between W and wk.

$$min\| \sum_{j=1}^{m} a_j w_j^T - w_i^T \| i = 1, 2, \ldots, m \quad (3)$$

According to the differentiation properties of the matrix, the condition for the optimal first-order derivative in Eq. (3) is as follows:

$$\sum_{j=1}^{m} a_j \times w_i \times w_j^T = w_i \times w_i^T i = 1, 2, \ldots, m \quad (4)$$

Then, to facilitate analysis, the matrix form of Eq. (4) is expressed as follows:

$$\begin{pmatrix} w_1 \times w_1^T w_1 \times w_2^T \ldots w_1 \times w_m^T \\ w_2 \times w_1^T w_2 \times w_2^T \ldots w_2 \times w_m^T \\ \ldots\ldots\ldots \\ w_m \times w_1^T w_m \times w_2^T \ldots w_m \times w_m^T \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ \ldots \\ a_m \end{pmatrix} = \begin{pmatrix} w_1 \times w_1^T \\ w_2 \times w_2^T \\ \ldots \\ w_m \times w_m^T \end{pmatrix} \quad (5)$$

3) To obtain a*, the weight coefficient is calculated and normalized as follows:

$$a_k^* = \frac{a_k}{\sum_{k=1}^{m} a_k} \quad (6)$$

4) Finally, the most satisfied combination weight can be reached as follows:

$$w^* = \sum_{k=1}^{m} a_k^* w_k^T \quad (7)$$

Risk evaluation

Set pair analysis theory

In 1989, Zhao created the SPA theory as an innovative system analysis approach that aims to explore the certainty and uncertainty of a particular system [54]. SPA theory is used to study the connection between certainty and uncertainty by treating two sets with certainty and uncertainty as a set pair and describing the sameness, difference, and opposition of the set pair in terms of the degree of connection [55].

Calculation of single correlation degree

Suppose the set of evaluation factors, *A*, and the set of evaluation criteria, *B*, constitute the set pair *M*, which is analyzed to obtain *N* characteristics; the set pair is described by the degree of association *u*:

$$\mu_{AB} = \frac{S}{N} + \frac{F}{N} i + \frac{P}{N} j = a + bi + cj \quad (8)$$

where *S/N* denotes the homogeneity of the set pair; *F/N* denotes the degree of difference of the set pair; *P/N* denotes the opposition degree of the set pair, denoted as *a*, *b*, *c*; $a+b+c=1$; *i* denotes the difference degree coefficient, taking values between [−1,1]; and *j* is the opposition degree coefficient, generally assumed to be -1.

Depending on the study object, the degree of connection can be diversified. The expression for the *k* degree of connection is as follows:

$$\mu = a + b_1 i_1 + b_2 i_2 + \cdots + b_{k-2} i_{k-2} + cj \quad (9)$$

When studying the risk level of the cumulative impact, the risk is divided into five levels, whose single-indicator correlation can be expressed as follows:

$$\mu = a + b_1 i_1 + b_2 i_2 + b_2 i_3 + cj \quad (10)$$

The indexes were divided into positive and negative indicators depending on their characteristics, and their correlation degrees were calculated as follows:

Positive index correlation degree calculation:

$$\mu_m = \begin{cases} 1+0i_1+0i_2+\cdots+0i_{k-2}+0j\,(x_m\le S_1) \\ \frac{S_1+S_2-2x_m}{S_2-S_1}+\frac{2x_m-2S_1}{S_2-S_1}i_1+0i_2+\cdots+0i_{k-2}+0j\,(S_1;x_m\le\frac{S_1+S_2}{2}) \\ 0+\frac{S_2+S_3-2x_m}{S_3-S_1}i_1+\frac{2x_m-S_1-S_2}{S_3-S_1}i_2+\cdots+0i_{k-2}+0j\,(\frac{S_1+S_2}{2}];x_m\le\frac{S_2+S_3}{2}) \\ 0+0i_1+\cdots+\frac{2S_{k-1}-2x_m}{S_{k-1}-S_{k-2}}i_{k-2}+\frac{2x_m-S_{k-1}-S_{k-2}}{S_{k-1}-S_{k-2}}j\,(\frac{S_{k-2}+S_{k-1}}{2};x_m\le S_{k-1}) \\ 0+0i_1+0i_2+\cdots+0i_{k-2}+1j\,(x_m\ge S_{k-1)}) \end{cases} \tag{11}$$

Negative index correlation degree calculation:

$$\mu_m = \begin{cases} 1+0i_1+0i_2+\cdots+0i_{k-2}+0j\,(x_m\ge S_1) \\ \frac{2x_m-S_1-S_2}{S_1-S_3}i_1+\frac{2S_1-2x_m}{S_1-S_2}i_1+0i_2+\cdots+0i_{k-2}+0j\,(\frac{S_1+S_2}{2}\le x_m\quad lt;S_1) \\ 0+\frac{2x_m-S_2-S_3}{S_1-S_3}i_1+\frac{S_1+S_2-2x_m}{S_1-S_3}i_2+\cdots+0i_{k-2}+0j\,(\frac{S_2+S_3}{2}\le x_m\quad lt;\frac{S_1+S_2}{2}) \\ 0+0i_1+\cdots+\frac{2x_m-2S_{k-1}}{S_{k-2}-S_{k-1}}i_{k-2}+\frac{S_{k-1}+S_{k-2}-2x_m}{S_{k-2}-S_{k-1}}j\,(S_{k-1}\le x_m\quad lt;\frac{S_{k-1}+S_{k-2}}{2} \\ 0+0i_1+0i_2+\cdots+0i_{k-2}+1j\,(x_m\quad lt;S_{k-1}) \end{cases} \tag{12}$$

where S1 to Sk are the upper thresholds for the respective risk levels and xm is the actual value of the evaluation indexes.

Calculation of the integrated correlation degree

After calculating the single-index correlation degree of each index by Eqs. 11 and 12, the integrated correlation degree of the set pair H (A, B) can be calculated as follows:

$$\mu_{AB} = \sum_{m=1}^{n} w_m \mu_m \tag{13}$$

where w_m is the weight of the index and μ_{AB} is the integrated correlation degree of the risk index on the corresponding risk level.

Determining the risk level of the cumulative impact

Because the value of the coefficient of variation varies, this study introduced a confidence criterion to determine the risk level of the evaluation unit to avoid a discussion of the coefficient of variation and reduce the complexity of the calculation process [56]. In this study, the cumulative impact risk was classified into five risk levels: low-risk, lower-risk, medium-risk, higher-risk, and high-risk, labeled as I, II, III, IV, and V, respectively.

$$f_1 = \sum_{m=1}^{n} w_m a_m \tag{14}$$

$$f_2 = \sum_{m=1}^{n} w_m b_{1m} \tag{15}$$

$$f_3 = \sum_{m=1}^{n} w_m b_{2m} \tag{16}$$

$$f_4 = \sum_{m=1}^{n} w_m b_{3m} \tag{17}$$

$$f_5 = \sum_{m=1}^{n} w_m c_m \tag{18}$$

In this study, where λ is the confidence degree, which is generally taken between [0.5–0.7]. In this study, λ was taken as 0.6. If $f_1 > \lambda$, the risk of the cumulative impact of the heritage site was level I. If $f_1 + f_2 > \lambda$, it was level II. If $f_1 + f_2 + f_3 > \lambda$, the risk was level III; and so on. The risk level of each heritage site can thus be calculated.

Study area and data sources

Study area

Suzhou is located in the Jiangsu Province of China and has a history of over 2500 years [57]. It is the prefecture-level city in China with the highest economic development and one of the first 24 historical and cultural cities in China. As one of the most important cultural heritages of Suzhou, Suzhou Classical Gardens have a long history that extends back to the Spring and Autumn Period in the sixth century BC. Suzhou Classical Gardens are gardens built in ancient times or inherited from the typical local gardening techniques in Suzhou, China. They contain various landscape elements and complex spaces, are the essence of Chinese gardening art and valuable world cultural heritage sites [58]. Nine of the Suzhou Classical Gardens are on the World Heritage List designated by UNESCO. However, the urbanization process of Suzhou has threatened the protection of the classical gardens. The urbanization outbreak in Suzhou is strongly linked to the Chinese strategy for reform and opening up in 1978. Rapid economic development has promoted the process

Fig. 2 Photographs that depict the urban environment of Gusu District; **a**, **b**: Photograph of the contemporary style buildings; **c**: Photograph of the Suzhou classical style buildings

of urbanization. Additionally, their recognition as World Heritage Sites by UNESCO in 1997 has caused a wave of tourists to the city of Suzhou. Suzhou has had to reshape and develop its urban infrastructure to meet the requirements of the tourism industry. Therefore, it is necessary to assess the impact of urbanization on the Suzhou Classical Gardens.

Gusu District belongs to Suzhou City and is located in the central part of the city (Fig. 2). With more than 4000 years since the first written records were published, Gusu District is the oldest central city of Suzhou and has the first National Historical and Cultural City Reserve in China. According to the statistics on the official website of the Suzhou City Landscape and Greening Administration, more than half of Suzhou Classical Gardens are located in the Gusu District.

This study focused on 21 Suzhou Classical Gardens in Gusu District (Fig. 3), analyzing the impact of rapid population growth and economic expansion in recent years. The name and protection level of the 21 Suzhou classical gardens can be seen in Table 3. The aim was to provide theoretical support for cultural heritage protection in Suzhou and a reference for analyzing urbanization effects on cultural heritage sites in other cities.

Data sources

The data used in this study included urban planning, heritage statistics, social and economic data, and street map data.

1) Urban planning data: The Suzhou Gusu District National Land Spatial Planning Recent Implementation Plan was obtained from the Suzhou Gusu District People's Government Official Website (http://zrzy.jiangsu.gov.cn/sz/ghcgy/index_2.htm).
2) Heritage statistical data: Statistical data on Suzhou Classical Gardens were obtained from the official website of the Suzhou City Landscape and Greening Administration (http://ylj.suzhou.gov.cn/szsylj/ylml/nav_list.shtml).
3) Social and economic data: A statistical report on the national economic and social development of Suzhou's subordinate districts and counties in 2022 was used.
4) Street map data: We collected road data from the Open Street Map (https://www.openstreetmap.org/). Street map data were used to calculate garden accessibility.

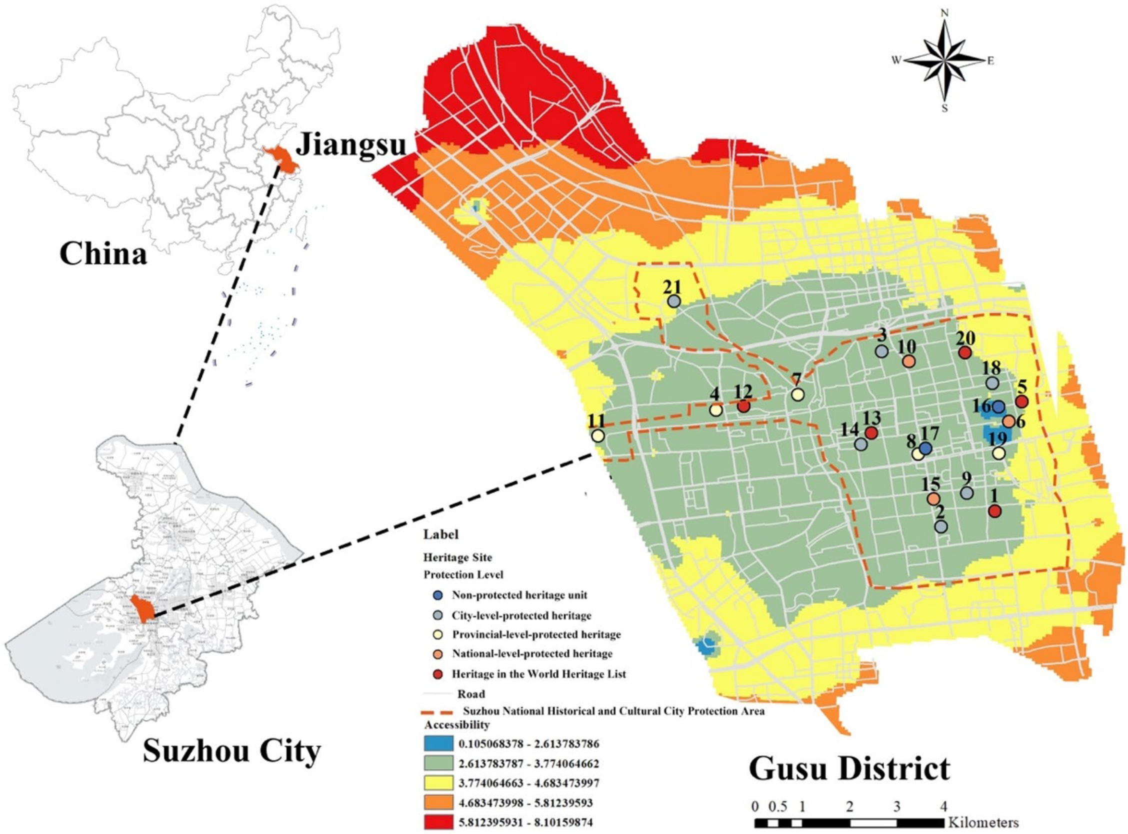

Fig. 3 Distribution of 21 Suzhou classical gardens in the Gusu District

Results

Weight analysis

The subjective weights and the objective weights of each index were obtained following the AHP and EW methods, respectively. Subsequently, the combination weights were obtained based on game theory. Table 4 lists the obtained weights. As shown in Table 3, D2, D4, and D9 were significant. This result shows that construction and commercial activities have a critical cumulative impact on the cultural heritage sites. Additionally, D6, D7, and D8 played a key role in the cumulative impact assessment. This demonstrates that transportation activities, such as subways and heavy traffic, often exceed limits and potentially damage the heritage sites. However, other indexes, such as D1, D5, D10, and D11, accounted for small weights. These results demonstrate that the cumulative impact is influenced more by the external urban environment of the heritage site, whereas indexes related to information about the heritage site itself are less important.

Cumulative impact assessment of Suzhou Classical Gardens in the Gusu District

Based on Eqs. 11 and 12, the single correlation degree of each index of Suzhou Classical Gardens can be calculated. Taking the Master of Nets Garden as an example, the single correlation degree for each index of The Master of Nets Garden is listed in Table 5. The integrated degree of correlation can be obtained using Eqs. 14, 15, 16, 17, 18 through each index's weight: $f_1=0.1378$, $f_2=0.2667$, $f_3=0.4786$, $f_4=0.0398$, $f_5=0.0771$, $f_1+f_2+f_3>0.6$. Therefore, the risk of the cumulative impact of the Master of Nets Garden can be determined as Level III.

By repeating the above process, the integrated degree of correlation and risk levels of the 21 Suzhou Classical Gardens were obtained (Table 6). The results are listed in Table 7. Fifty-seven percent of the classical gardens have cumulative impact risk levels at or below “medium” risk. Overall, five classical gardens were classified as having a cumulative impact risk level of “highest,” four as having a cumulative impact risk level of “higher,” nine as having

Table 3 Name and protection level of the 21 Suzhou Classical Gardens

Number	Garden name	Protection level
1	The master of nets garden	Heritage in the world heritage list
2	The Ke Garden	City-level-protected heritage
3	The Pu Garden	City-level-protected heritage
4	The Xi Garden	Provincial-level-protected heritage
5	The Couple's Garden	Heritage in the world heritage list
6	Quanjin Hall	National-level-protected heritage
7	Yuhan Hall	Provincial-level-protected heritage
8	The Yi Garden	Provincial-level-protected heritage
9	The Chai Garden	City-level-protected heritage
10	North Temple Tower	National-level-protected heritage
11	Hanshan Temple	Provincial-level-protected heritage
12	The Lingering Garden	Heritage in the world heritage list
13	Huanxiu Shanzhuang	Heritage in the world heritage list
14	The Sui Garden	City-level-protected heritage
15	Tianxiang Xiaozhu	National-level-protected heritage
16	The Inkwell Garden	Non-protected heritage unit
17	The Mu Garden	Non-protected heritage unit
18	The North Half Garden	City-level-protected heritage
19	Shangzhi Hall	Provincial-level-protected heritage
20	The Humble Administrator's Garden	Heritage in the world heritage list
21	The Ying Garden	City-level-protected heritage

Table 4 Weight of each index obtained by the combination weighting method

Index	Weight		
	AHP	EM	GT
D1	0.0292	0.0796	0.0549
D2	0.1532	0.1193	0.1359
D3	0.0669	0.0776	0.0724
D4	0.0742	0.2298	0.1536
D5	0.0606	0.0410	0.0506
D6	0.1213	0.0754	0.0979
D7	0.1898	0.0513	0.1192
D8	0.1478	0.0735	0.1099
D9	0.0982	0.1759	0.1378
D10	0.0214	0.0254	0.0233
D11	0.0374	0.0515	0.0445

Table 5 Single correlation degree of each index of the Master of Nets Garden

Index	Single correlation degree				
	a	b_1	b_2	b_3	c
D1	0	0.35	0.65	0	0
D2	0	0.4	0.6	0	0
D3	0	0	0	0.55	0.45
D4	0	0.32	0.68	0	0
D5	0	0	1	0	0
D6	0	0.65	0.35	0	0
D7	0	0.13	0.87	0	0
D8	0	0.52	0.48	0	0
D9	1	0	0	0	0
D10	0	0.33	0.67	0	0
D11	0	0	0	0	1

a "medium" level, two as having a "lower" level, and one was classified as having a cumulative impact risk level of "lowest."

The assessment results confirmed that the urbanization process in Suzhou City has had an impact on the Suzhou Classical Gardens because 85.72% of the gardens have a cumulative impact risk level at or higher than the medium risk level. Moreover, among the nine high-risk Suzhou Classical Gardens, seven are located at the edge of the protection boundary of the historical and cultural city, and only two are located in the center (Fig. 4). This finding underscores the significance of historical and cultural cities in preserving Suzhou Classical Gardens.

Table 6 Integrated correlation degree and risk levels of the cumulative impact of 21 Suzhou Classical Gardens

Garden name	Integrated correlation degree					
	F1	F2	F3	F4	F5	Risk level
The Master of Nets Garden	0.1378	0.2667	0.4786	0.0398	0.0771	III
The Ke Garden	0.1359	0.2440	0.2824	0.0674	0.2702	III
The Pu Garden	0.1486	0.2936	0.1220	0.0923	0.3435	IV
The Xi Garden	0.2840	0.1391	0.1435	0.0061	0.4273	V
The Couple's Garden	0.1826	0.1391	0.2553	0.2258	0.0445	IV
Quanjin Hall	0.1700	0.2699	0.2495	0.3092	0.0014	III
Yuhan Hall	0.2599	0.1842	0.1136	0.0840	0.3582	IV
The Yi Garden	0.1378	0.1378	0.1582	0	0.5662	V
The Chai Garden	0.1479	0.5170	0.2394	0.0084	0.0873	II
North Temple Tower	0.3073	0.0731	0.3253	0.1584	0.1359	III
Hanshan Temple	0.3073	0.0731	0.3253	0.1584	0.1359	III
The Lingering Garden	0.2570	0.1843	0.0515	0.0803	0.4269	V
Huanxiu Shanzhuang	0.1918	0.2746	0.1372	0.0021	0.3943	III
The Sui Garden	0.3267	0.1599	0.2603	0.0624	0.1908	III
Tianxiang Xiaozhu	0.0292	0.4228	0.1482	0.1475	0.2524	III
The Inkwell Garden	0.6492	0.0701	0.1447	0	0.1359	I
The Mu Garden	0.2085	0.1687	0.1115	0.0058	0.5055	V
The North Half Garden	0.3463	0.2950	0.1193	0.0802	0.1592	II
Shangzhi Hall	0.1962	0.2234	0.2023	0.1231	0.2551	III
The Humble Administrator's Garden	0.0549	0.1979	0.1300	0.0035	0.6137	V
The Ying Garden	0.1497	0.1571	0.1301	0.3389	0.2208	IV

Discussion

This study developed a risk-based CIA framework that incorporates a set of indexes to assess the impact of urbanization on urban cultural heritage. In contrast to the other CIA method, this study built a risk-based CIA method that relies on describing the probability of adverse impact, which is useful for managing excessive scientific complexity and uncertainties. Different from other CIA methods, future adverse impacts were considered in this study and index like Areas of new construction land (D2) and percentage of surrounding commercial land (D3) were added in this study. Moreover, unlike other research, game theory was introduced in this study to obtain a more reasonable weight of each index.

Table 7 Risk levels of 21 Suzhou Classical Gardens

Risk level	Total number	Percent (%)
Highest risk level	5	23.81
Higher risk level	4	19.05
Medium risk level	9	42.86
Lower risk level	2	9.52
Lowest risk level	1	4.76

Although the 21 gardens selected in this study are all located in the Suzhou Historical and Cultural City Protected Area, the results of the study show that Suzhou's urbanization has inevitably affected these historic gardens. According to the combination weight obtained by game theory (Table 4), the area of new construction land, the area of the cultural heritage and the harmony index of neighboring building form are three of the most important indexes in this study. All three indexes are related to the surrounding urban environment. Therefore, urbanization impact on 21 gardens is probably due to the increase in construction projects, subway construction, and commercial land use in the vicinity of the historic gardens as a result of the city's tourism development in recent years. Therefore, more restrictive management of buffer zone construction are needed for Suzhou Classical Gardens to guarantee their heritage integrity. Meanwhile, among the nine high-risk Suzhou Classical Gardens, seven are located at the edge of the protection boundary of the historical and cultural city. This demonstrates that the establishment of Suzhou National Historical and Cultural City has a positive impact on the protection of Suzhou Classical Gardens. Moreover, six out of the nine high-risk gardens are below the national-level-protected, which indicates

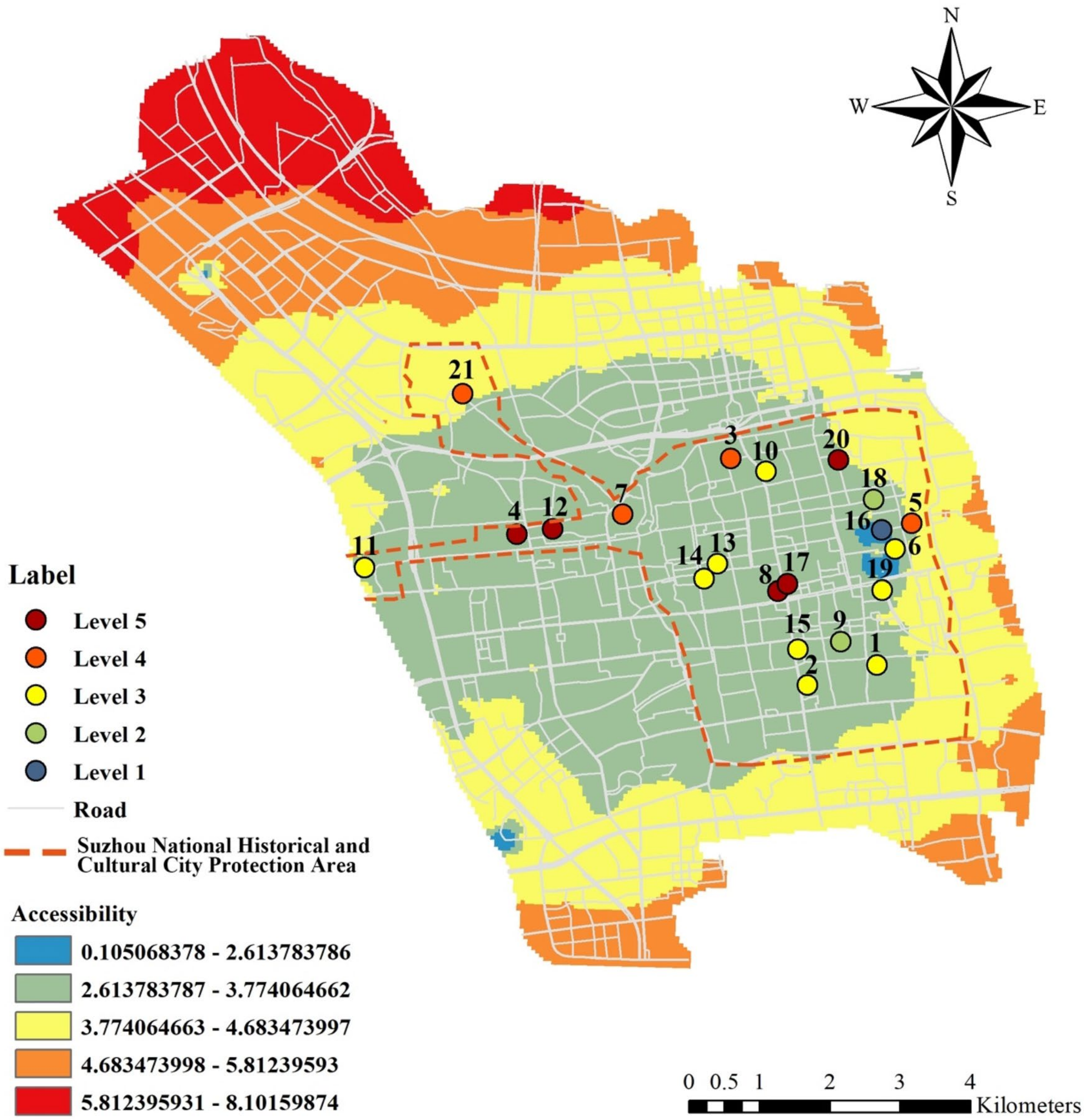

Fig. 4 Spatial distribution of the cumulative impact level of Suzhou Classical Gardens in the Gusu district

that the current protection measures for gardens with a low level of protection are weak.

While the proposed risk-based cumulative impact assessment method yields clear results on the impact of urbanization on cultural heritage, some limitations must be clarified. First, this method was developed using a reduced set of indexes, and a more thorough assessment result can be obtained by including more indices and data. This method aimed to provide a standardized risk-based CIA method for cultural heritage sites that can be modified and improved by including additional indicators. Second, the study focused on one type of cultural heritage, the Suzhou Classical Gardens. The assessment index system should be modified when applied to other types of cultural heritage based on their characteristics. When adopting the suggested approach to analyze the cumulative impact of urbanization on urban cultural heritage, it is vital to account for these limitations. Third, urbanization is a complex activity that can be affected by social and economic factors. Building future risk scenarios for all anthropogenic activities and pressures that could impact cultural heritage sites is a significant challenge. This index-based CIA method is a first-level analysis of cultural heritage sites. To obtain more accurate assessment results, the next stage of the risk-based CIA method should focus on future risk scenario building and identifying feasible quantitative models and methods.

Conclusions

This study proposed a risk-based CIA method to evaluate the impact of urbanization on urban cultural heritage sites at a regional level. This method is based upon the SPA theory and uses 11 indexes as assessment factors, and the combined weight of the indexes was rationally obtained using the game theory. The effectiveness of this method was demonstrated through its successful implementation in 21 classical gardens in Suzhou, China, to assess the impact of urbanization on urban cultural heritage sites. The assessment results show that the Suzhou Classical Gardens, which are important cultural heritage sites in China, are inevitably affected by urbanization. This is because 85.72% of the case studies have a cumulative impact risk level at or higher than the "medium" risk level. The proposed method is based on objective and unbiased data and can provide standardized outcomes for decision-makers, which allows them to prioritize cultural heritage sites with a higher cumulative impact.

The CIA method aims to provide an overall understanding of the conservation status of cultural heritage sites, identify potential sources of impact such as development projects or transportation infrastructure, and then provide conservation agencies with a picture of the impact of the current value of cultural heritage sites and guidance by proposing targeted conservation strategies. The CIA method proposed can help fill the gap between city development demands and heritage protection by facilitating the determination and efficient implementation of mitigation strategies in the decision-making process. Meanwhile, the universality of the suggested risk-based CIA method is beneficial for cultural heritage protection, as input datasets are easily obtainable and analysis processes are reproducible for other kinds of cultural heritage sites. Furthermore, the index system can be adapted to different regions and different types of cultural heritage. Therefore, we argue that the risk-based CIA method can be a strategic approach used before the urban planning process, making it easier to communicate key aspects of heritage protection recommendations to decision makers.

Abbreviations

AHP	Analytic hierarchy process
CIA	Cumulative impact assessment
EW	Entropy weight
HIA	Heritage impact assessment
SPA	Set pair analysis

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Author contributions

LF analyzed the data and wrote the manuscript. QZ, YT, and JP collected the data and conducted field research for this study. QL reviewed and revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used in this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

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.

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References

1. Sukwai J, Mishima N, Srinurak N. Balancing cultural heritage conservation: visual integrity assessment to support change management in the buffer zone of Chiang Mai historic city using GIS and computer-generated 3D modeling. Land. 2022. https://doi.org/10.3390/land11050666.
2. Rössler M, Lin RC-H. The cultural landscape in world heritage conservation and cultural landscape conservation challenges in Asia. Built Heritage. 2018;2:3–26. https://doi.org/10.1186/BF03545707.
3. Ashrafi B, Kloos M, Neugebauer C. Heritage impact assessment, beyond an assessment tool: a comparative analysis of urban development impact on visual integrity in four UNESCO world heritage properties. J Cult Herit. 2021;47:199–207. https://doi.org/10.1016/j.culher.2020.08.002.
4. Seyedashrafi B, Ravankhah M, Weidner S, Schmidt M. Applying heritage impact assessment to urban development: world heritage property of Masjed-e Jame of Isfahan in Iran. Sustain Cities Soc. 2017;31:213–24. https://doi.org/10.1016/j.scs.2017.01.002.
5. Veillon R. State of conservation of world heritage properties. A statistical analysis (1979–2013). Paris: UNESCO World Heritage Centre; 2014. https://whc.unesco.org/en/documents/134872.
6. Wang Q, Yang C, Tian L, Lu J, Wu F, An J. Safety risk assessment of heritage buildings in metro construction based on SPA theory: a case study in Zhengzhou, China. Herit Sci. 2020;8:100. https://doi.org/10.1186/s40494-020-00439-3.
7. Vidović K, Hočevar S, Menart E, Drventić I, Grgić I, Kroflič A. Impact of air pollution on outdoor cultural heritage objects and decoding the role of particulate matter: a critical review. Environ Sci Pollut Res Int. 2022;29:46405–37. https://doi.org/10.1007/s11356-022-20309-8.
8. Jelinčić DA. Indicators for cultural and creative industries' impact assessment on cultural heritage and tourism. Sustainability. 2021;13:7732. https://doi.org/10.3390/su13147732.
9. Longo S, Tabacco C, GbossiGramaglia F. Impact assessment of cultural heritage projects. Vienna: Interreg Central Europe for Heritage; 2020.
10. Patiwael PR, Groote P, Vanclay F. Improving heritage impact assessment: an analytical critique of the ICOMOS guidelines. Int J Herit Stud. 2019;25:333–47. https://doi.org/10.1080/13527258.2018.1477057.
11. Stelzenmüller V, Coll M, Mazaris AD, Giakoumi S, Katsanevakis S, Portman ME, et al. A risk-based approach to cumulative effect assessments for marine management. Sci Total Environ. 2018;612:1132–40. https://doi.org/10.1016/j.scitotenv.2017.08.289.

12. Jones FC. Cumulative effects assessment: theoretical underpinnings and big problems. Environ Rev. 2016;24:187–204. https://doi.org/10.1139/er-2015-0073.
13. Stelzenmüller V, Coll M, Cormier R, Mazaris AD, Pascual M, Loiseau C, et al. Operationalizing risk-based cumulative effect assessments in the marine environment. Sci Total Environ. 2020;724:138118. https://doi.org/10.1016/j.scitotenv.2020.138118.
14. Blakley J, Russell J. International progress in cumulative effects assessment: a review of academic literature 2008–2018. J Environ Plan Manag. 2022;65:186–215. https://doi.org/10.1080/09640568.2021.1882408.
15 Folkeson L, Antonson H, Helldin JO. Planners' views on cumulative effects. A focus-group study concerning transport infrastructure planning in Sweden. Land Use Policy. 2013;30:243–53. https://doi.org/10.1016/j.landusepol.2012.03.025.
16. Canter L, Ross B. State of practice of cumulative effects assessment and management: the good, the bad and the ugly. Impact Assess Proj Appraisal. 2010;28:261–8. https://doi.org/10.3152/146155110X12838715793200.
17. Menegon S, Depellegrin D, Farella G, Gissi E, Ghezzo M, Sarretta A, et al. A modeling framework for MSP-oriented cumulative effects assessment. Ecol Indic. 2018;91:171–81. https://doi.org/10.1016/j.ecolind.2018.03.060.
18. Mazaris AD, Germond B. Bridging the gap between climate change and maritime security: towards a comprehensive framework for planning. Sci Total Environ. 2018;635:1076–80. https://doi.org/10.1016/j.scitotenv.2018.04.136.
19. Ihde TF, Townsend HM. Accounting for multiple stressors influencing living marine resources in a complex estuarine ecosystem using an Atlantis model. Ecol Modell. 2017;365:1–9. https://doi.org/10.1016/j.ecolmodel.2017.09.010.
20. Bednaršek N, Harvey CJ, Kaplan IC, Feely RA, Možina J. Pteropods on the edge: cumulative effects of ocean acidification, warming, and deoxygenation. Prog Oceanogr. 2016;145:1–24. https://doi.org/10.1016/j.pocean.2016.04.002.
21. Vanacker M, Quindroit P, Angeli K, Mandin C, Glorennec P, Brochot C, et al. Aggregate and cumulative chronic risk assessment for pyrethroids in the French adult population. Food Chem Toxicol. 2020;143:111519. https://doi.org/10.1016/j.fct.2020.111519.
22. Morin S, Bonet B, Corcoll N, Guasch H, Bottin M, Coste M. Cumulative stressors trigger increased vulnerability of diatom communities to additional disturbances. Microb Ecol. 2015;70:585–95. https://doi.org/10.1007/s00248-015-0602-y.
23 Kortenkamp A. Which chemicals should be grouped for mixture risk assessments of male reproductive disorders? Mol Cell Endocrinol. 2020;499:110581. https://doi.org/10.1016/j.mce.2019.110581.
24. Giles-Hansen K, Li Q, Wei X. The cumulative effects of forest disturbance and climate variability on streamflow in the Deadman River watershed. Forests. 2019;10:196. https://doi.org/10.3390/f10020196.
25. Imbeau L, St-Laurent M-H, Marzell L, Brodeur V. Current capacity to conduct ecologically sustainable forest management in northeastern Canada reveals challenges for conservation of biodiversity. Can J Forest Res. 2015;45:567–78. https://doi.org/10.1139/cjfr-2014-0123.
26. Goodale MW, Milman A. Assessing the cumulative exposure of wildlife to offshore wind energy development. J Environ Manage. 2019;235:77–83. https://doi.org/10.1016/j.jenvman.2019.01.022.
27. Lapointe NWR, Cooke SJ, Imhof JG, Boisclair D, Casselman JM, Curry RA, et al. Principles for ensuring healthy and productive freshwater ecosystems that support sustainable fisheries. Environ Rev. 2014;22:110–34. https://doi.org/10.1139/er-2013-0038.
28. Bayne EM, Campbell J, Haché S. Is a picture worth a thousand species? Evaluating the human perception of biodiversity intactness using images of cumulative effects. Ecol Indic. 2012;20:9–16. https://doi.org/10.1016/j.ecolind.2011.12.020.
29. Arnold LM, Hanna K, Noble B. Freshwater cumulative effects and environmental assessment in the Mackenzie Valley, Northwest territories: challenges and decision-maker needs. Impact Assess Proj Appraisal. 2019;37:516–25. https://doi.org/10.1080/14615517.2019.1596596.
30. Merriam ER, Petty JT, Strager MP, Maxwell AE, Ziemkiewicz PF. Scenario analysis predicts context-dependent stream response to land-use change in a heavily mined central appalachian watershed. Freshw Sci. 2013;32:1246–59. https://doi.org/10.1899/13-003.1.
31. Lukanov BR, Krieger EM. Distributed solar and environmental justice: exploring the demographic and socioeconomic trends of residential PV adoption in California. Energy Policy. 2019;134:110935. https://doi.org/10.1016/j.enpol.2019.110935.
32. Su JG, Jerrett M, Morello-Frosch R, Jesdale BM, Kyle AD. Inequalities in cumulative environmental burdens among three urbanized counties in California. Environ Int. 2012;40:79–87. https://doi.org/10.1016/j.envint.2011.11.003.
33. GBBBP Authority, Great Barrier Reef region strategic assessment: Strategic assessment report; 2014
34. Judd AD, Backhaus T, Goodsir F. An effective set of principles for practical implementation of marine cumulative effects assessment. Environ Sci Policy. 2015;54:254–62. https://doi.org/10.1016/j.envsci.2015.07.008.
35. Brignon J-M, Lejart M, Nexer M, Michel S, Quentric A, Thiebaud L. A risk-based method to prioritize cumulative impacts assessment on marine biodiversity and research policy for offshore wind farms in France. Environ Sci Policy. 2022;128:264–76. https://doi.org/10.1016/j.envsci.2021.12.003.
36. Cormier R, Kannen A, Elliott M, Hall P, Davies IM, editors. Marine and coastal ecosystem-based risk management handbook. Copenhagen, Denmark: International Council for the Exploration of the Sea; 2013. https://repository.oceanbestpractices.org/bitstream/handle/11329/1187/CRR317.pdf?sequence=1&isAllowed=y. Accessed 20 June 2023.
37. Alexander D. The study of natural disasters, 1977–1997: some reflection on a changing field of knowledge. Disasters. 1997;21:284–304. https://doi.org/10.1111/1467-7717.00064.
38. Appiotti F, Assumma V, Bottero M, Campostrini P, Datola G, Lombardi P, et al. Definition of a risk assessment model within a European interoperable database platform (EID) for cultural heritage. J Cult Herit. 2020;46:268–77. https://doi.org/10.1016/j.culher.2020.08.001.
39 Iso I. Risk management–principles and guidelines. Geneva: International Organization for Standardization; 2009.
40. Cormier R, Kelble CR, Anderson MR, Allen JI, Grehan A, Gregersen Ó. Moving from ecosystem-based policy objectives to operational implementation of ecosystem-based management measures. ICES J Mar Sci. 2017;74:406–13. https://doi.org/10.1093/icesjms/fsw181.
41. Pham V-M, Van Nghiem S, Van Pham C, Luu MPT, Bui Q-T. Urbanization impact on landscape patterns in cultural heritage preservation sites: a case study of the complex of Huế Monuments, Vietnam. Landsc Ecol. 2021;36:1235–60. https://doi.org/10.1007/s10980-020-01189-0.
42. Wan-Qing LI, Guo HY, Meng WQ, Zhang YN. Evaluation model of safety risk for building construction project based on grey clustering and SPA. Math Pract Theor. 2012;42:168–73.
43. Han F, Yang Z, Liu X, Di F. Impact assessment and protection of outstanding landscape integrity in a natural heritage site: Fairy Valley, Kanas nature reserve, Xinjiang. China J Mt Sci. 2011;8:46–52. https://doi.org/10.1007/s11629-011-2067-x.
44. Jenks GF. The data model concept in statistical mapping. In: Bertelsmann Verlag C, editor. International yearbook of cartography. Gutersloh: Mohn & Co.; 1967. p. 186–90.
45 McMaster R. In memoriam: George F. Jenks (1916–1996). Cartogr Geogr Inform Syst. 1997;24:56–9. https://doi.org/10.1559/152304097782438764.
46 Chen J, Yang ST, Li HW, Zhang B, Lv JR. Research on geographical environment unit division based on the method of natural breaks (Jenks). 2013. Int Arch Photogramm Remote Sens Spat Inf Sci. https://doi.org/10.5194/isprsarchives-XL-4-W3-47-2013.
47. Zou Q, Liao L, Qin H. Fast comprehensive flood risk assessment based on game theory and cloud model under parallel computation (P-GT-CM). Water Resour Manage. 2020;34:1625–48. https://doi.org/10.1007/s11269-020-02495-7.
48. Danumah JH, Odai SN, Saley BM, Szarzynski J, Thiel M, Kwaku A, et al. Flood risk assessment and mapping in Abidjan district using multi-criteria analysis (AHP) model and geoinformation techniques (Côte d'Ivoire). Geoenviron Disasters. 2016;3:1–13.
49. Wang Y, Li Z, Tang Z, Zeng G. A GIS-based spatial multi-criteria approach for flood risk assessment in the Dongting Lake Region, Hunan, Central China. Water Resour Manage. 2011;25:3465–84. https://doi.org/10.1007/s11269-011-9866-2.
50. Lai C, Chen X, Chen X, Wang Z, Wu X, Zhao S. A fuzzy comprehensive evaluation model for flood risk based on the combination weight of

game theory. Nat Hazards. 2015;77:1243–59. https://doi.org/10.1007/s11069-015-1645-6.
51. Li Z, Luo Z, Wang Y, Fan G, Zhang J. Suitability evaluation system for the shallow geothermal energy implementation in region by entropy weight method and TOPSIS method. Renew Energy. 2022;184:564–76.
52. Saaty TL. How to make a decision: the analytic hierarchy process. Eur J Oper Res. 1990;48:9–26. https://doi.org/10.1016/0377-2217(90)90057-I.
53. Ding L, Shao Z, Zhang H, Xu C, Wu D. A comprehensive evaluation of urban sustainable development in China based on the TOPSIS-entropy method. Sustainability. 2016;8:746. https://doi.org/10.3390/su8080746.
54. Zhao K. Set pair analysis and its preliminary applications. Hangzhou: Zhejiang Science and Technology Press; 1994.
55. Wang W, Jin J, Li Y. Risk degree assessment of natural disaster based on set pair analysis method. J Sichuan Univ. 2009;41:6–12.
56. Song Z, Lai C, Wang Z. Evaluation model of flood risk based on set pair analysis. Water Resour Power. 2013;31:34–7.
57. Zhang T, Lian Z. Research on the distribution and scale evolution of Suzhou gardens under the urbanization process from the Tang to the Qing Dynasty. Land. 2021;10:281. https://doi.org/10.3390/land10030281.
58. Liang H, Li W, Lai S, Zhu L, Jiang W, Zhang Q. The integration of terrestrial laser scanning and terrestrial and unmanned aerial vehicle digital photogrammetry for the documentation of Chinese classical gardens—a case study of Huanxiu Shanzhuang, Suzhou, China. J Cult Herit. 2018;33:222–30. https://doi.org/10.1016/j.culher.2018.03.004.

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