Fu *et al. Heritage Science* (2023) 11:92
https://doi.org/10.1186/s40494-023-00926-3

Heritage Science

RESEARCH

Open Access

A multi-criteria decision-making approach to assessing the health risk of rockeries in Chinese classical gardens

Li Fu[1], Jie Pan[1], Yizhou Tang[1] and Qingping Zhang[1*]

Abstract

Owing to the lack of appropriate protection measures, natural and human factors have led to the deterioration of rockeries, which are a distinct cultural heritage with both aesthetic and historical value and an essential component of Chinese classical gardens. The state of rockeries is evaluated by craftsmen who assess the damage levels based on their experience. While this is a common practice, it lacks standardization, which may cause a great uncertainty that influences the efficiency of the protection of rockeries. The preservation and risk mitigation of cultural heritages require the use of reliable tools that provide an accurate diagnosis of their conditions. Multi-criteria decision-making techniques have been applied in several previous studies and proven to be a reliable method for conducting vulnerability or risk assessment for cultural heritage. Therefore, this study developed a health risk assessment tool based on multi-criteria decision-making techniques that can be applied to rockeries in Chinese classical gardens. In contrast to other multi-criteria decision-making methodologies, the proposed method emphasizes the detailed analysis of the health state of rockeries based on impartial and objective data. Moreover, based on the ultimate risk rating for rockeries, the decision makers can arrange the priorities of action in a hierarchical manner, and the cost-efficient protection measures can be identified. Results from the application of four different case studies are illustrated to demonstrate the usefulness of the proposed method.

Keywords Chinese classical garden, Rockery, Preventive conservation, Health risk assessment, Multi-criteria decision-making (MCDM), Intervention priority

Introduction

Rockeries are one of the most essential elements that distinguish Chinese classical gardens from other great gardens of the world [1–3]. They are an integral part of the Chinese heritage and an irreplaceable expression of Chinese traditional culture. Stacking rockeries first became popular during the Tang Dynasty (A.D. 618–907) [4–6], with some of the rockeries in China are more than hundreds of years old. Rockeries not only have significant historic and artistic value, but also profoundly reflect the aesthetic preferences and economic environment of different feudal dynasties, which is why their conservation and maintenance are necessary. However, owing to the lack of appropriate protection measures, natural and human factors have caused rockeries to deteriorate over time [7, 8].

Rockeries are the most complex element of Chinese classical gardens. They are made of irregular materials and heterogeneous structures put together by extremely unique stacking techniques. Weather changes, plant growth, human activities, and subsidence may lead to cracks, tilting, or even collapse [8]. Given the characteristics of these structures and the necessity for minimal intervention, a preventive conservation approach is

*Correspondence:
Qingping Zhang
qpzh@njfu.edu.cn
[1] College of Landscape Architecture, Nanjing Forestry University, No. 159, Longpan Road, Nanjing 210037, Jiangsu, China

considered the best form of therapy, whereby the rockeries' health conditions and the factors endangering them are periodically monitored [9, 10]. However, few studies have developed such a preventive conservation approach specifically for rockeries in Chinese classical gardens [8, 11]. The existing literature mostly focuses on rockeries from the perspectives of their history, culture [4, 12–14], aesthetics, and craftsmanship [15–17]. With the application of digital and information technologies in the cultural heritage field, many studies have been conducted on the digital surveying of rockeries [18, 19], but only a few studies have been conducted on their diagnosis. Fu and Hu have discussed the strategy and technologies used in monitoring historical rockeries and accumulated a large number of data, but no quantified analysis of their health condition has been conducted [8, 11]. As such, despite numerous studies on the protection of rockeries in Chinese classical gardens, none have considered developing a systematic health state assessment tool that can promote the conservation of rockeries.

Existing practices of assessing the health state of rockeries are mostly carried out by rockery craftsmen, who base their evaluations on their own personal experiences and expertise in the field, which could lead to relatively subjective assessments and cause great uncertainty, possibly reducing the efficiency of the preservation work [11]. Consequently, the assessment of rockeries' health state tends to lack standardization as it is based upon subjective evaluations and measures. Because of the geometrical complexity of their structures and a lack of knowledge of past events that led to their degradation, assessing these rockeries' health state is of great importance in this context. Therefore, a comprehensive health risk assessment tool that can provide information on the health records of rockeries needs to be developed.

The protection projects of cultural heritages are not straightforward but require an interdisciplinary approach and methodology that can develop a thorough understanding of their respective states [20]. Therefore, a growing body of research has investigated the application of new technologies, such as minor destructive tests [21], non-destructive testing [22, 23], numerical modelling [24, 25] and other diagnostic technologies [26, 27] that facilitate the diagnosis of heritages. Together with in-situ surveys, such diagnostic technologies provide relevant and valuable information for the diagnosis of cultural heritages. Depending on the complexity of the heritage, any comprehensive health risk assessment process for unique monuments should consider information from all relevant diagnostic activities carried out [28]. As a result, other studies proposed a systematic risk assessment method derived from multi-criteria decision-making (MCDM) techniques, which consider information from a diverse set of diagnostic activities [28]. MCDM techniques can help analyze complex interactions between multiple divergent criteria, providing key benefits when approaching heritage investigations [28, 29]. In the literature, several examples of MCDM techniques being applied to risk assessment to help guide decisions for the preventive conservation of cultural heritages [20, 28, 30–34]. One such tool is the Masonry Damage Diagnostic System [35]. By creating a damage map, the system classifies and explains the preservation status and damage mechanisms of historic buildings and compiles their information and health records [36]. Applications of this diagnostic technique have produced satisfactory outcomes, which reveals that the increase in systematization in the diagnostic process can assist heritage conservationists in identifying problems more quickly, and consequently enable them to seek the appropriate solutions. Successful applications of MCDM techniques indicate that it can be applied to provide meaningful guidance for decisions on heritage protection. However, no attempt has been made to apply MCDM techniques to assess the health risk of rockeries in Chinese classical gardens thus far.

Given the unique characteristics and irreplaceable value of rockeries in Chinese classical gardens, a comprehensive health risk assessment tool needs to be proposed based on the MCDM techniques. The objective of this study was to develop a specific health risk assessment tool based on MCDM techniques, which can provide scientific quantitative and standardized evaluation indicators to assist decision makers in the evaluation of the health state of rockeries. The proposed methodology was designed to provide a standardized method for the analysis of rockeries' health state, developed from the objective and quantitative data collected from technical surveys. The proposed method was applied to rockeries in four different Chinese classical gardens to illustrate its implementation.

Health risk assessment methodology for rockeries

In this study, rockery health risk assessment refers to the documentation, identification, and evaluation of the health risks of rockeries, and how rockeries in Chinese classical gardens respond to them. The health risk assessment of rockeries is a complex and comprehensive process. For better results, a scientific, rational, and standardized assessment system must be established following the relevant national heritage protection standards and using multiple interdisciplinary methods.

The proposed methodology is summarized in Fig. 1. It comprises the following steps. First, an in-situ investigation should be conducted to map out and create a record of the disease status of the rockeries. Second, as part of

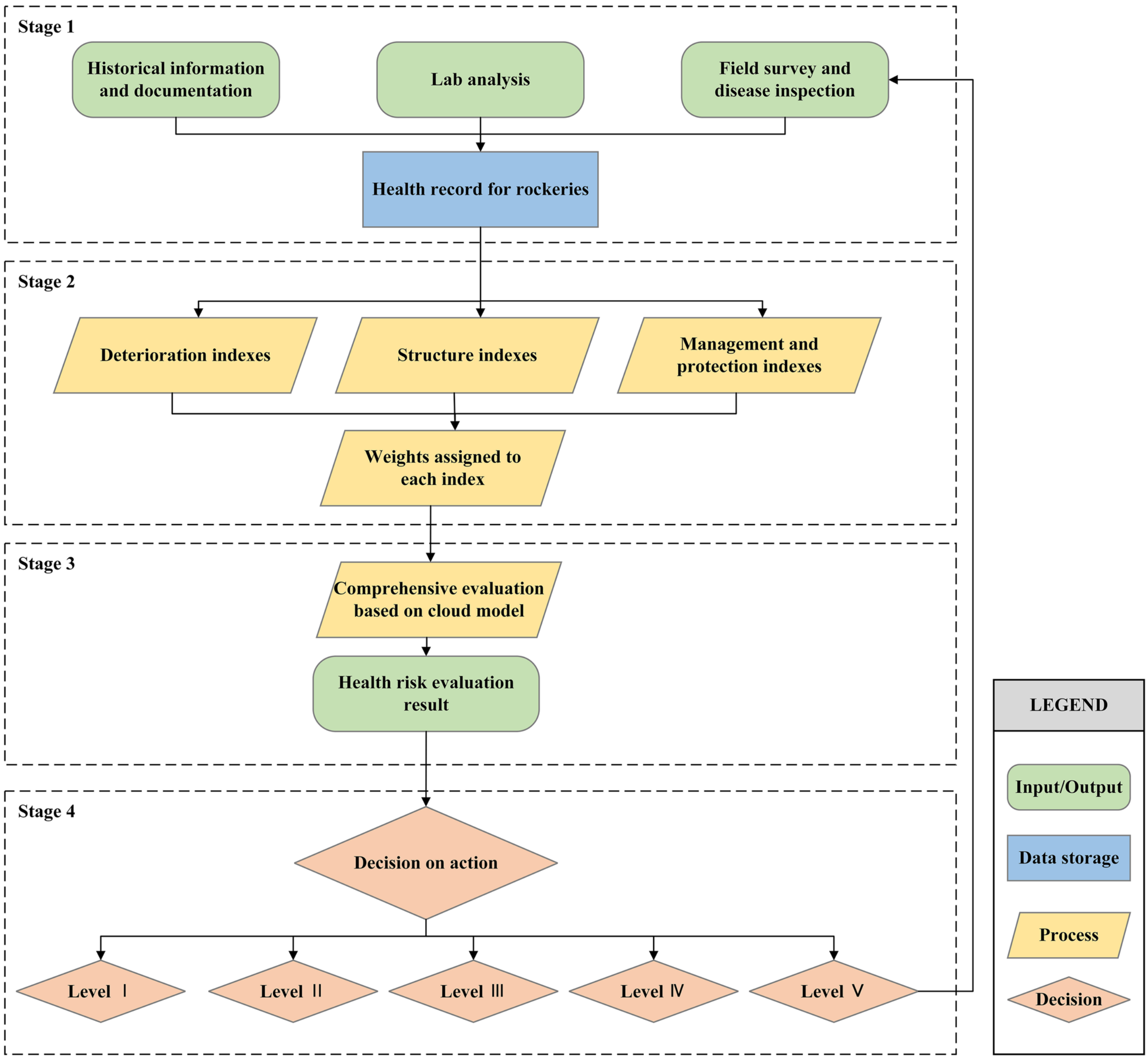

Fig. 1 Flowchart for the proposed health risk assessment method

this health risk assessment method, key indexes should be introduced to evaluate the health risk of rockeries, following which a comprehensive health risk assessment index system can be developed. After collecting all relevant data and information, the weights of different indexes should be determined [37, 38]. Third, with the weights of each index, a reliable and efficient risk assessment method must be chosen for the risk level to be calculated. While the analytical hierarchy process (AHP) and fuzzy comprehensive evaluation methods have been successfully used [39–41], the failure to account for randomness and uncertainty in the risk assessment process limits these methods [42]. To address these limitations, several studies have proposed utilizing the cloud model in the regional scale risk assessment process to obtain accurate and comprehensive results [43, 44]. The cloud model, as a quantitative and qualitative uncertainty conversion model, can produce more objective and accurate evaluation results [44, 45]. Fourth, once the health risk levels of the rockeries have been evaluated, the corresponding decision of which protection method will be used to safeguard the rockeries must be made. Finally, after the decisions on possible actions are made, the health risk assessment process must be repeated at least once every year to test whether the protection measures were effective.

Health record for rockeries

A health record and the creation of a long-term health record can help monitor historical information and detect changes within the rockeries. Therefore, prior to the beginning of the assessment process, all relevant documents and information should be gathered and analyzed. An in-situ inspection should be conducted to map out the signs of decay and damage and create a record of the disease status of the rockeries. Further, a 3D scanning technique can be used to create a digital twin model of the rockeries, which can provide a digital reference of the rockeries for future protection. Lab analysis to provide the material properties of the rockeries is recommended. All these documents should be included in the health records of the rockeries for the deterioration to be observed regularly in subsequent conservation work and for the process of change to be clarified.

Health risk assessment index system

As rockeries are preserved in the natural environment, many risk factors affect their health. Evaluating their health risk is a complex process, and the comprehensiveness of the indicators of rockeries' health risk evaluation is the key to a systematic and thorough assessment. Considering those comprehensive aspects, a health risk assessment index system was established according to the rockeries in Chinese classical gardens, as shown in Fig. 2.

The health risk faced by rockeries is the result of combined factors such as their structural condition, environmental factors, long-term weathering, geological activity, and human activity. Therefore, the evaluation of these factors should include the relevant indicators of their physical properties, the disease condition of the heritage, the management and protection level, and other factors. Subsequently, within the proposed health risk assessment index system, deterioration indexes are introduced to monitor the deterioration risk level of rockeries. The deterioration indexes were selected in reference to the illustrated glossary on stone deterioration patterns issued by the International Scientific Committee for Stone [46]. The indexes also provide information about the history of rockeries and the material proprieties that are introduced, which can help understanding of the structural condition of the rockeries. Lastly, management and protection indexes were introduced to assess the level of protection. This health risk assessment index system includes 15 quantitative parameters in total.

After the index system had been established, the weight value of each index was calculated by the analytical hierarchy process (AHP) [47]. This popular decision analysis method allows an analyst to conduct a rational and consistent assessment of weights by establishing pairwise comparisons judgement matrix among parameters. A questionnaire survey of 10 experts was conducted to construct the judgement matrix. To ensure that the results fit better with the characteristics of rockeries in Chinese classical gardens, the experts were selected to meet two conditions: firstly, their research interests must have been directly related to rockeries in Chinese classical gardens, and secondly, they must have conducted field research on the rockeries in Chinese classical gardens.

As shown in Fig. 2, rockeries deterioration indexes are very important when compared to the other two sets of parameters. This is partly because deterioration indexes can provide quantitative estimates of the health state of rockeries based on deterioration patterns, and within the deterioration indexes, crack (*D1*) is the most important one. This is partly because the cracks are the most common and serious deterioration of rockeries, and often determine which rockeries need to be restored. The second most influential set of parameters is the rockeries structure indexes, which involve laboratory material tests. Such tests can provide key information on the structural condition of the rockeries. Finally, information from the management and protection indexes was assigned the lowest weight. This does not mean that the management activity is superfluous, as it is important in the preventive protection process. However, the choice of a lower weight is partly due to the limited quantitative indexes to estimate the level of management.

Rockeries deterioration indexes

Visual inspections as in-situ surveys were used to collect data on the deterioration information of the rockeries. After analyzing the data collected from the in-situ survey, the deterioration indicators were obtained. Crack (*D1*) refers to cracks on the stones made up of rockeries, cracks on the adhesive between stones is not included in this deterioration indicators. *D1* is one of the main deterioration patterns of the rockeries. According to previous study [48], the index to decide the severity of these patterns includes four parameters: total number of cracks per rockery (n), maximum width of cracks per rockery (w), maximum length of cracks per rockery (l), and maximum depth of cracks per rockery (h). To avoid crack indexes (*D1*) that are too small or too large, the compensation constant t was assumed as 10^{-3}. The *D1* can be obtained based on Eq. (1) as follows:

$$D1 = n \times w \times l \times h \times t. \quad (1)$$

Except for the "crack" deterioration patterns, the deterioration indexes (*DI*) of the other six deterioration patterns (*D2*–*D7*) could be measured according to the proportion of the deterioration area to the surface

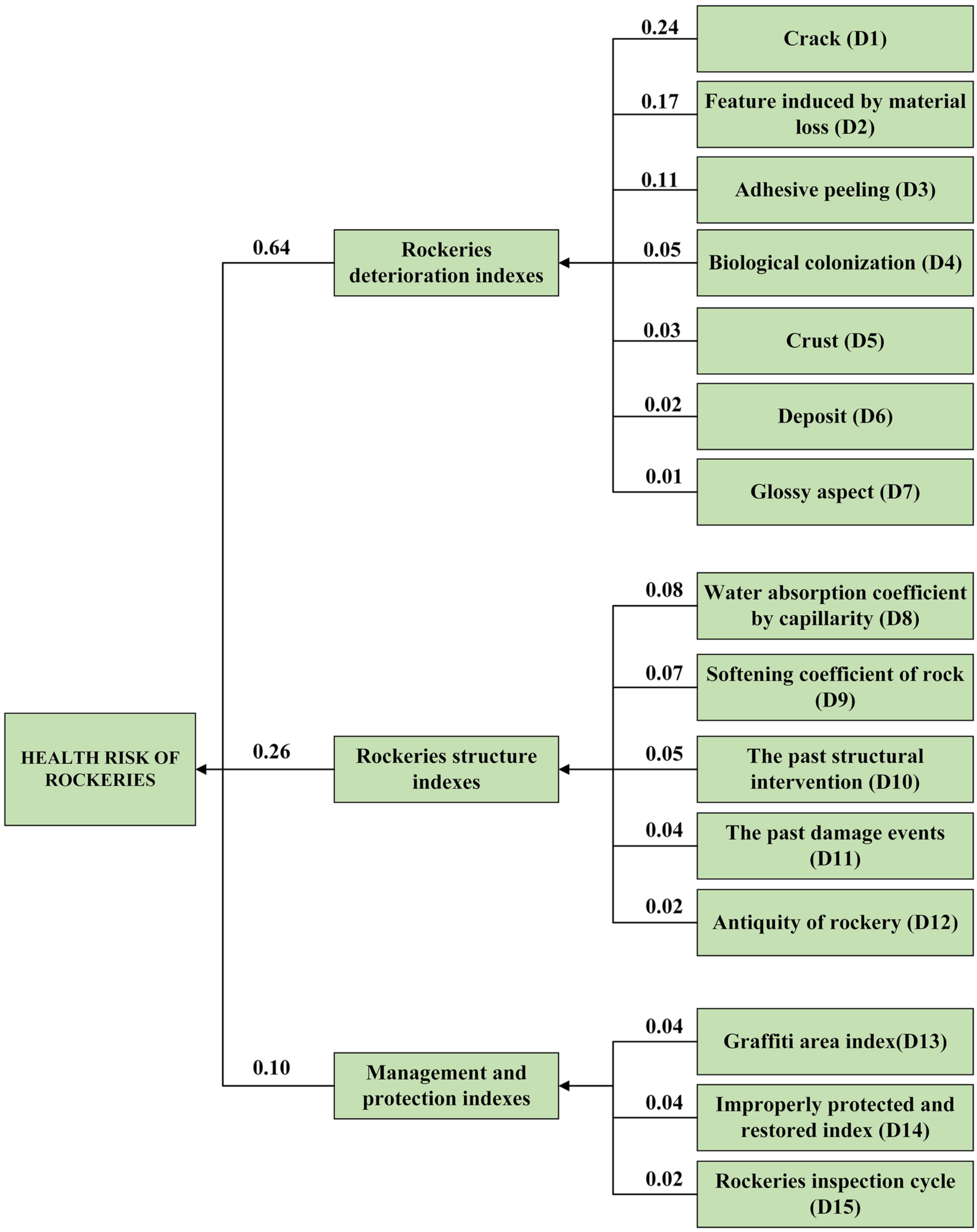

Fig. 2 Criteria tree for the health risk index of rockeries

area of the rockery [48]. To avoid a value that is too insignificant, the DI can be calculated as follows:

$$DI_i = \frac{S_i}{S} \times 100, \quad (2)$$

where S is the surface area of rockeries, and S_i is the area of a certain disease.

Rockeries structure indexes

The rockeries structure indexes include physical property indexes and historical information indexes. It is important to include physical property indexes in the index system because the organization and structure of the rockery have gone through years of weathering and impact of external forces, which result in changes in their physical properties and the production of rockery disease. Historical information indexes must also be included because it is necessary to consider the consistency of the rockeries' structure over time to judge whether they are healthy or not.

The physical property indexes were measured using the water absorption coefficient by capillarity (*D8*) and the softening coefficient of the rock (*D9*). The *D8* can be used to measure the water absorption performance of the rock surface, which can reflect the degree of weathering and porosity on the surface of the rockery. High water absorption performance means low performance of the engineering use. According to related standards [49], the *D8* can be calculated using Eq. (3):

$$D8 = \frac{W}{\sqrt{t}}, \quad (3)$$

where W is the water absorption rate per unit area (kg/m^2), and t is the time (h).

The softening coefficient of the rock (*D9*) can be used to measure the effect of water on the strength of rocks. It is an important indicator for the evaluation of the quality of the rock. The softening coefficient can be calculated using Eq. (4):

$$D9 = \frac{I_w}{I_d}, \quad (4)$$

where I_w is the compressive strength of rock in uniaxial saturation, and I_d is the compressive strength of the rock under a uniaxial dry condition.

The historical information indexes are measured based on past structural intervention (D10), past damage events (D11), and antiquity of rockery (D12). Past structural intervention (*D10*) refers to the modification of the original structure of the rockeries owing to changing garden owners. In the centuries-old history of the rockeries since their construction, their original structures have been modified to adapt to the preferences of different owners. These interventions have caused instability in the structure of the rockeries. The value of this index can be quantified as the number of past structural intervention in the rockeries' history and can be obtained by exploring the historical literature.

Past damage events (*D11*) refer to natural disasters such as earthquakes and rainstorms that damaged the structure of rockeries that had been preserved in their natural environment for a long time. The value of this index can be quantified as the number of past damage events in the rockeries' history and can be obtained by exploring the historical literature.

Antiquity of rockery (*D12*) was used as a proxy for the rockeries' heritage value. The value of this index can be quantified as the years after the completion of the rockeries' construction and can be obtained by exploring the historical literature.

Management and protection indexes

Humans' production and living activities, as well as the certain misbehavior by tourists, can cause a certain degree of damage to the rockeries. Simultaneously, owing to the improper selection of methods, imperfect technical facilities, unskilled operation, and other factors that constitute "protective damage" are also considered anthropogenic damage that occurs during the protection and restoration process. Management and protection indexes can be used to reflect the level of rockeries protection management and were measured based on the following:

Graffiti index (*D13*): Graffiti is generally the result of an act of vandalism conducted by tourists. The graffiti index can reflect the management level of the rockeries and is measured according to the number of graffiti markings found on the rockery. The value of this index can be obtained from the in-situ survey of the rockeries.

Improperly restored area index (*D14*): The improperly restored area index reflects the rockery's restoration level, which is measured by the proportion of the improperly restored area to the surface area of the rockery. It can be calculated using Eq. (5):

$$D14 = \frac{S_{14}}{S} \times 100, \quad (5)$$

where S is the surface area of rockeries, and S_{14} is the improperly restored area.

Rockeries inspection cycle (*D15*). The rockeries inspection cycle reflects their protection level and is measured by the number of inspections per year. The value of *D15* can be obtained by exploring the management profile of the rockeries.

Health risk assessment based on a cloud model

Definition of cloud model

The cloud model was first presented by Li in 1995 based on fuzzy sets theory and probability concepts [50]. The cloud model is a concrete implementation method of the cloud, which incorporates cloud operation, reasoning, and control. It can realize the transformation of qualitative and quantitative concepts. The cloud model is described by linguistic values to represent the uncertain relationship between a specific qualitative concept and its quantitative expression, thus effectively integrating the randomness and fuzziness of concepts [51].

Suppose U is the set, and x is a quantitative concept related to U. The Q is a qualitative concept corresponding to U, which has a random variable with stable distribution for number x. The distribution of x on U is called a cloud, and each x is defined as a cloud drop [43, 52]. The membership degree of x in U is a random variable with a probability distribution in the context of discourse. In this study, the membership degree of each cloud can reflect its degree of affiliation with each health risk level. The production process of cloud drops represents the uncertainty of conversion between qualitative concept and quantitative values [53].

$$Q : U \to [0,1], \forall x \in U, x \to Q(x). \tag{6}$$

The cloud model is represented through three digital parameters: expected value (*Ex*), entropy (*En*) and deviation (*He*). *Ex* represents the fundamental certainty of the qualitative concept, is the expectation of the cloud drop in the universal set and can best represent this qualitative concept. *En* represents the uncertainty of qualitative concepts, determined by how many elements could be accepted in the qualitative concepts. *He* is an uncertainty measure of *En* and controls the cloud's thickness. The three digital parameters can be determined as follows.

First, considering the characteristics of the rockeries and based on previous studies and relevant standards, the health risk assessment indexes were divided into five risk levels namely the lowest, lower, medium, higher, and highest levels, which are respectively labeled as Levels I–V [48, 53] (Table 1).

After achieving the grading standards of each index, the digital parameters of the cloud model can be calculated using the following calculation formula [43]:

Table 1 Grading standard of health risk indexes

Indexes	Level I	Level II	Level III	Level IV	Level V
D1	0.0–0.1	0.1–0.3	0.3–0.6	0.6–0.8	0.8–1.0
D2	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0
D3	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0
D4	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0
D5	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0
D6	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0
D7	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0
D8	0–0.1	0.1–0.5	0.5–1	1–2	2–10
D9	5–1	1–0.8	0.8–0.6	0.6–0.3	0.3–0.0
D10	0–1	1–3	3–6	6–8	8–10
D11	0–1	1–3	3–6	6–8	8–10
D12	0–200	200–400	400–600	600–800	800–1000
D13	0–2	2–4	4–6	6–8	>8
D14	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0
D15	0.0–1.0	1.0–3.0	3.0–6.0	6.0–8.0	8.0–10.0

$$Ex_{ij} = \frac{\left(x_{ij}^1 + x_{ij}^2\right)}{2}, \tag{7}$$

$$En_{ij} = \frac{\left|x_{ij}^1 - x_{ij}^2\right|}{2.355}, \tag{8}$$

$$He = k, \tag{9}$$

where x_{ij}^1 and x_{ij}^2 represent the lower and upper boundary values of the assessment grade, j is the assessment grade, and i is the index number. *He* is a constant k that controls the granularity of cloud drop, it should be adjusted according to the practical cloud discrete degree [43, 53]. In this study, k is assumed as 0.05 to make sure the cloud thickness is appropriate. The other two digital parameters were calculated using Eqs. (7) and (8). The calculation results are presented in Table 2.

Cloud generator

The cloud generator is a cloud generation algorithm that aims to achieve the relationship between qualitative concepts and quantitative characteristics, which can be realized in the software. Normally, the cloud generator can be divided into two types: the forward cloud generator and the backward cloud generator [53]. The forward cloud generator is the most basic and important method for the cloud model and was used to calculate the membership degree of each cloud drops in this study. Input contained *Ex*, *En*, *He*, and the number of drops n. In this study, n was set as 2000 to make sure the cloud droplet met the requirements for it to be formed into a cloud. The output contained n cloud drops and their membership degrees. The forward cloud generator according to *Ex*, *En*, and *He* is defined as follows:

A) Generate a normally distributed random number $En_i^{'}$ with expectation *En* and variance He^2.
B) Generate a normally distributed random number x_i with expectation *Ex* and variance $En_i^{'2}$.
C) Calculate $u_i = e^{-\frac{(x_i - E_x)^2}{2En_i^{'2}}}$, and x_i with membership degree u_i is a cloud drop in the domain.
D) Repeat Steps 1 to 3 until n cloud drops are generated.

With the three digital parameters of the cloud model (*Ex*, *En*, and *He*), the cloud drop map can be created by the forward cloud generator and the MATLAB 2021b software (Fig. 3). The distribution of membership degrees of five risk levels were calculated and are illustrated in Fig. 3. The abscissa represents the actual value of health

Table 2 Digital parameters of the cloud model

Levels	D1		D2		D3		D4		D5	
	Ex	En	Ex	En	Ex	En	Ex	En	Ex	En
I	0.05	0.04	0.50	0.42	0.50	0.42	0.50	0.42	0.50	0.42
II	0.20	0.08	2.00	0.85	2.00	0.85	2.00	0.85	2.00	0.85
III	0.45	0.13	4.50	1.27	4.50	1.27	4.50	1.27	4.50	1.27
IV	0.70	0.09	7.00	0.85	7.00	0.85	7.00	0.85	7.00	0.85
V	0.90	0.08	9.00	0.85	9.00	0.85	9.00	0.85	9.00	0.85
Levels	**D6**		**D7**		**D8**		**D9**		**D10**	
	Ex	**En**	**Ex**	**En**	**Ex**	**En**	**Ex**	**En**	**Ex**	**En**
I	0.50	0.42	0.50	0.42	0.05	0.04	3.00	1.70	0.50	0.42
II	2.00	0.85	2.00	0.85	0.30	0.17	0.90	0.08	2.00	0.85
III	4.50	1.27	4.50	1.27	0.75	0.21	0.70	0.08	4.50	1.27
IV	7.00	0.85	7.00	0.85	1.50	0.42	0.45	0.13	7.00	0.85
V	9.00	0.85	9.00	0.85	6.00	3.40	0.15	0.13	9.00	0.85
Levels	**D11**		**D12**		**D13**		**D14**		**D15**	
	Ex	**En**	**Ex**	**En**	**Ex**	**En**	**Ex**	**En**	**Ex**	**En**
I	0.50	0.42	100.00	84.93	0.50	0.42	18.00	5.10	1.00	0.85
II	2.00	0.85	300.00	84.93	2.00	0.85	9.00	2.55	3.00	0.85
III	4.50	1.27	500.00	84.93	4.50	1.27	5.00	0.85	5.00	0.85
IV	7.00	0.85	700.00	84.93	7.00	0.85	3.00	0.85	7.00	0.85
V	9.00	0.85	900.00	84.93	9.00	0.85	1.00	0.85	9.00	0.85

risk indexes, and the ordinate represents the membership degree.

Comprehensive assessment and final results

The cloud model was used to generate the membership degree matrix Z shown in Eq. (10), wherein the element r_{ij} in Z represents a raster layer of membership degree. The comprehensive membership degree M can be obtained by Eq. (11) after determining the index weight W and the matrix Z.

$$Z = \begin{bmatrix} r_{11}r_{12}\ldots r_{15} \\ r_{21}r_{22}\ldots r_{25} \\ \ldots\ldots\ldots\ldots \\ r_{i1}r_{i2}\ldots r_{i5} \end{bmatrix} (i = 1, 2, \ldots, 15), \tag{10}$$

$$M = W \times Z = [w_1, w_2, \ldots, w_i] \times \begin{bmatrix} r_{11}r_{12}\ldots r_{15} \\ r_{21}r_{22}\ldots r_{25} \\ \ldots\ldots\ldots\ldots \\ r_{i1}r_{i2}\ldots r_{i5} \end{bmatrix} = [m_1, m_2, \ldots, m_5], \tag{11}$$

where W is the indicator weight vector, and m_1, m_2, m_3, m_4, and m_5 are the comprehensive membership degrees. The final assessment result can then be obtained based on the maximum membership principle.

From risk assessment to decision making

After the health risk assessment results have been obtained, specific protection measures need to be taken to reduce the risks faced by rockeries. In this study, the health risk of rockeries was divided into five levels: lowest, lower, medium, higher, and highest. The proposed method aimed to promote risk mitigation actions that are resource-efficient. Corresponding measures are shown in Fig. 4, which indicates how the health risk level of rockeries can be used to determine the best preservation method for rockeries.

After a corresponding risk mitigation action has been taken, a systematic updating of the risk assessment needs to be carried out. This is to ascertain that the mitigation action is efficient. If the assessment results remain the same, further actions need to be applied. Therefore, the health risk assessment is a long-term process that needs

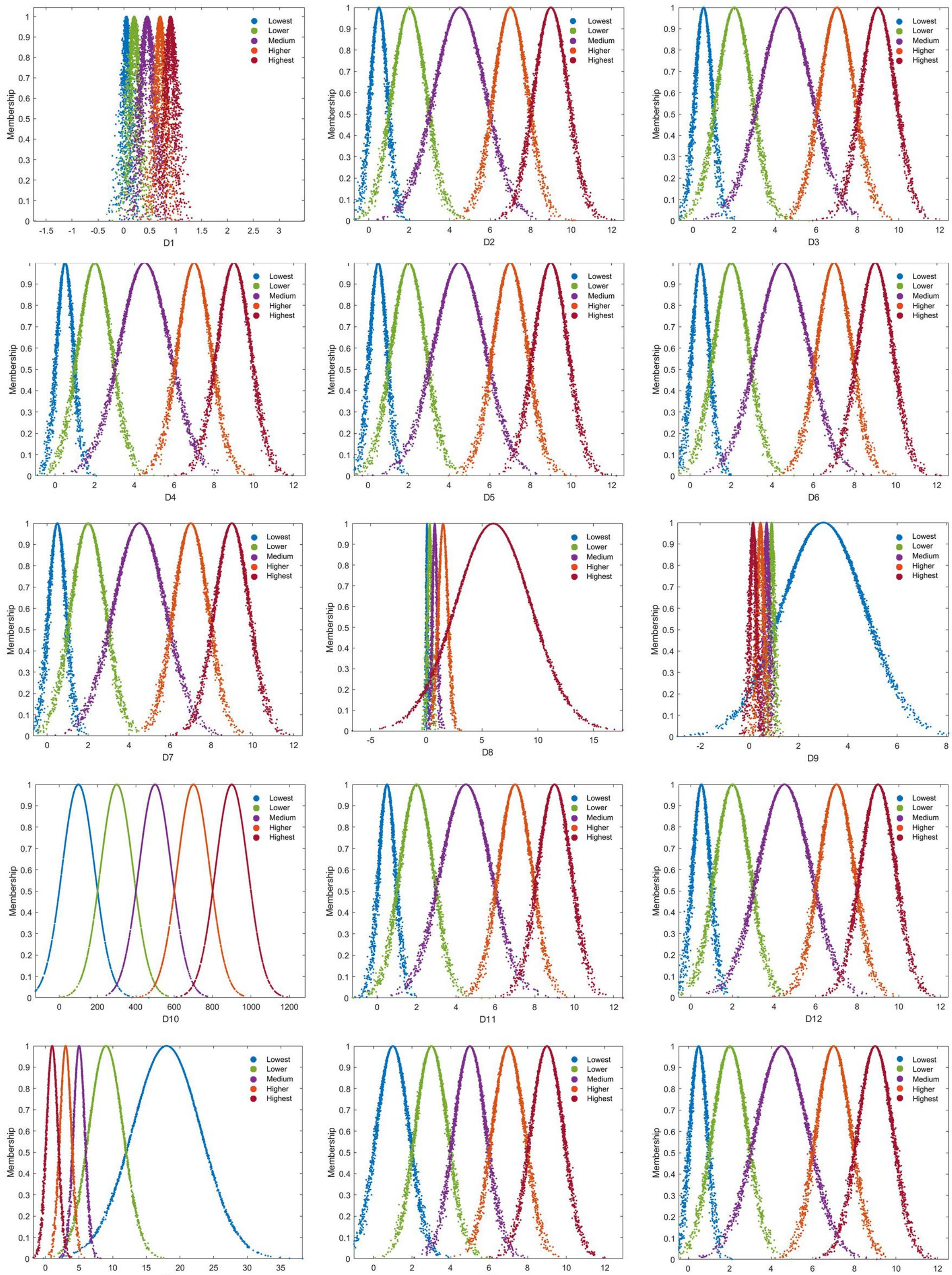

Fig. 3 Cloud models of different health risk indexes at various risk levels

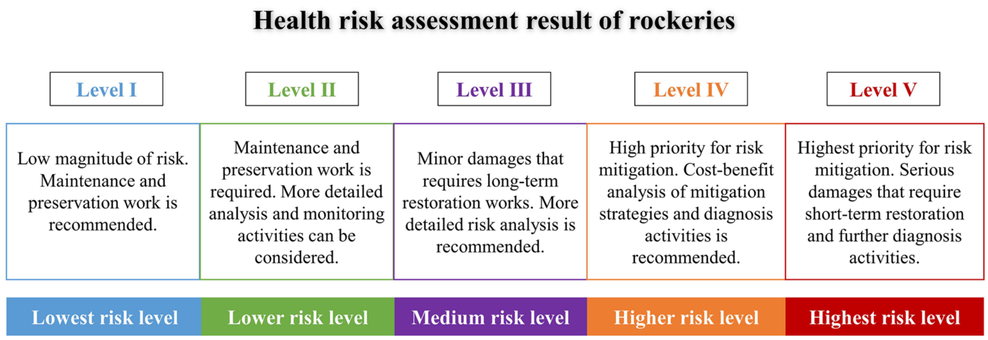

Fig. 4 Decision matrix demonstrating how the risk assessment results can be used to facilitate decisions

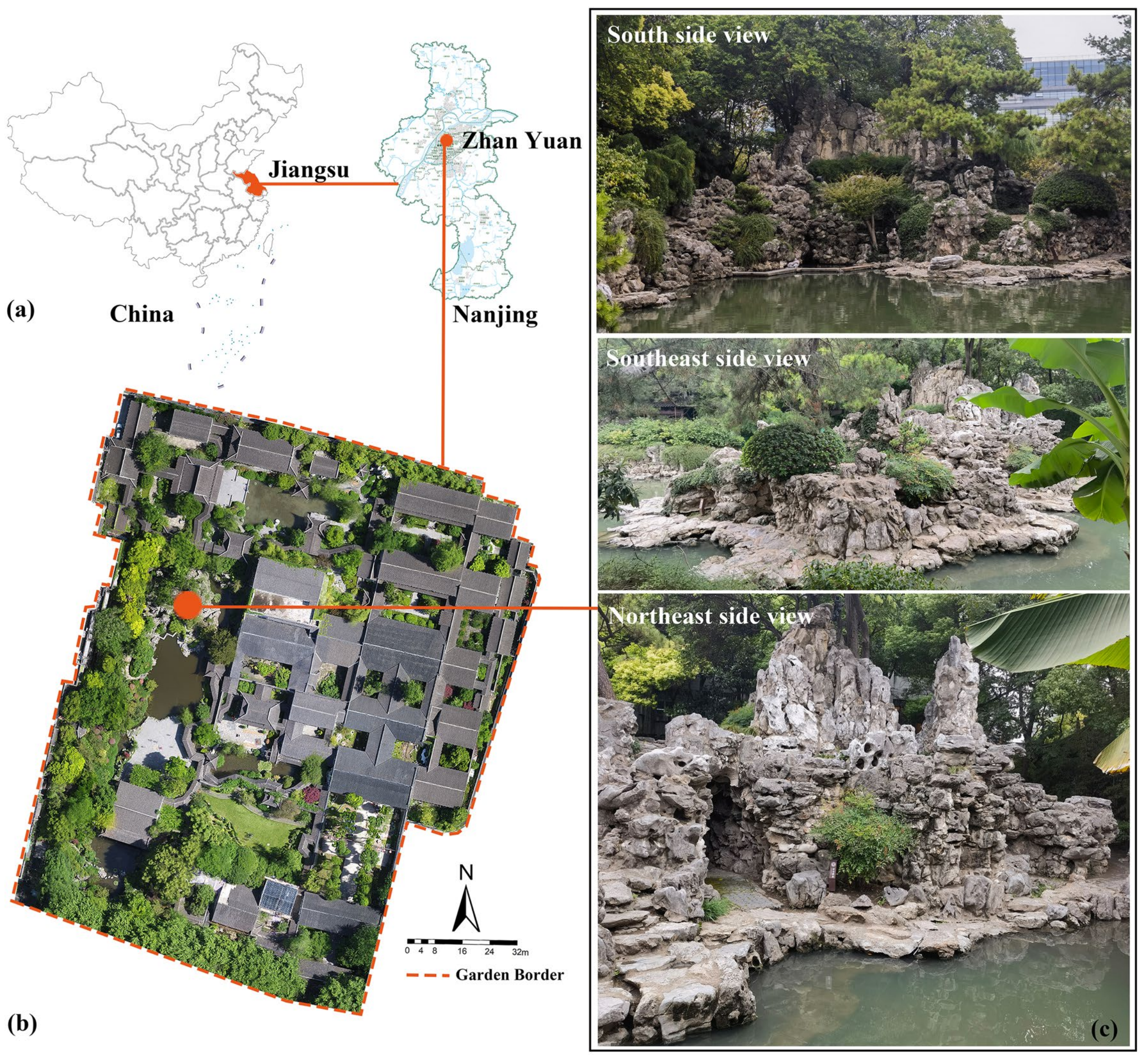

Fig. 5 The Zhan Garden and its surroundings; **a** location of the case study; **b** overview orthoimage of the Zhan Garden; **c** photographs of the North Rockery

to be executed within a certain period, which can be determined by the health condition of the rockeries.

Application and results

Application to North Rockery at Zhan Garden, Nanjing, China

The North Rockery at Zhan Garden was selected to illustrate the utility of the proposed health risk assessment method. The North Rockery was originally built during the Ming Dynasty (A.D. 1507–1566) [54]. It is the highest and most precipitous point in the Zhan Garden (ZG), which is one of the four greatest classical gardens in the regions south of the Yangtze River (Fig. 5). Because of its zigzag spaces and various landscapes, it is deemed to be one of the finest rockeries in China and attracts many visitors.

Understanding stone deterioration processes requires systematic observation and analysis of field data, ideally supported by in-depth laboratory research. This allows researchers to contain information from other fields and conduct a more comprehensive investigation to understand the deterioration phenomena [55]. To assess the health risk of the North Rockery at Zhan Garden, several preliminary in-situ investigations were carried out to gain thorough insight into the health state of the rockeries. Owing to rapid technological developments, especially advances in non-destructive testing techniques and improvements in evaluation and modeling methods, the possibilities for obtaining heritage diagnoses continue to increase. However, these new methods are generally only a few years old, and the test results are largely incomparable to those obtained using previous methods [56]. As the monitoring of rockeries must be evaluated over a longer period—from several years to several decades—we had to choose relatively simple methods that are less technically demanding and can be used in the same or similar way decades later.

First, visual inspections and a 3D scan of the North Rockery at ZG were carried out to obtain deterioration information and the digital twin model of the rockery. All deterioration patterns were measured and documented in the deterioration map of the rockery (Fig. 6a). The deterioration map should be included in the health profile of the rockery to serve as a reference for future health evaluation (Fig. 6b). The digital twin model of the North Rockery was obtained by collecting high-precision rockery point cloud data (Fig. 6c). These can be used as a digital record of the North Rockery, and the 3D model can be used to calculate its surface area. Second, several laboratory tests were also performed to learn more about the mechanical properties of the North Rockery's materials. This includes the test of dry and wet compressive strength, which can obtain the value of D9 [57], and the test of water absorption coefficient by capillarity, which can obtain the value of D8 [49]. With the permission of the rockery management department, specimens were collected from the North Rockery. Then, the dry and wet compressive strength test was carried out using an MTS CMT4204 microcomputer-controlled electronic testing machine. The cubic specimens ($17 \times 50 \times 50$ mm^3 per unit) were subjected to increasing loads to determine the ultimate strength of the specimen (Fig. 6).

After all the in-situ investigations and laboratory tests of the North Rockery at Zhan Yuan have been completed, the value of each index can be calculated based on the equations and descriptions from the previous section (Table 3).

Based on the cloud model method discussed in the previous section, by inputting the value of each index into the forward cloud generator, the membership degree matrix of the five risk levels can be calculated. Then, with the weight of each index illustrated in Fig. 2, the comprehensive membership degrees can be obtained by Eq. (11). Lastly, based on the maximum membership principle, the health risk assessment result of the North Rockery is presented in Table 4. The health risk assessment indexes were divided into five risk levels namely the lowest, lower, medium, higher, and highest levels, which are respectively labeled as Levels I–V.

Application to other case studies

Besides the application to the North Rockery at ZG, applications to the other three rockeries in Suzhou, China are presented to demonstrate how the health risk assessment method can function under different conditions of complexity (Fig. 7).

The three rockeries are located in three different Chinese classical gardens: the Humble Administrator's Garden (HAG), the Lingering Garden (LG), and the Canglang Pavilion (CLP). These three historic gardens were added to the UNESCO World Heritage list in 1997. Despite being one of their most important components, the health state of the rockeries in these gardens has never been evaluated. Therefore, detailed in-situ investigations and laboratory tests were performed to evaluate their health states. The resulting health risk level for all the four case studies after the health risk assessment process are summarized in Table 5. The values of the certainty degrees of the five risk levels are also listed. As shown in Table 5, two of the case studies are at the lowest risk level, one is at the lower risk level, and one is at the medium risk level. It can be said that the rockeries in the four case studies have been preserved in good condition.

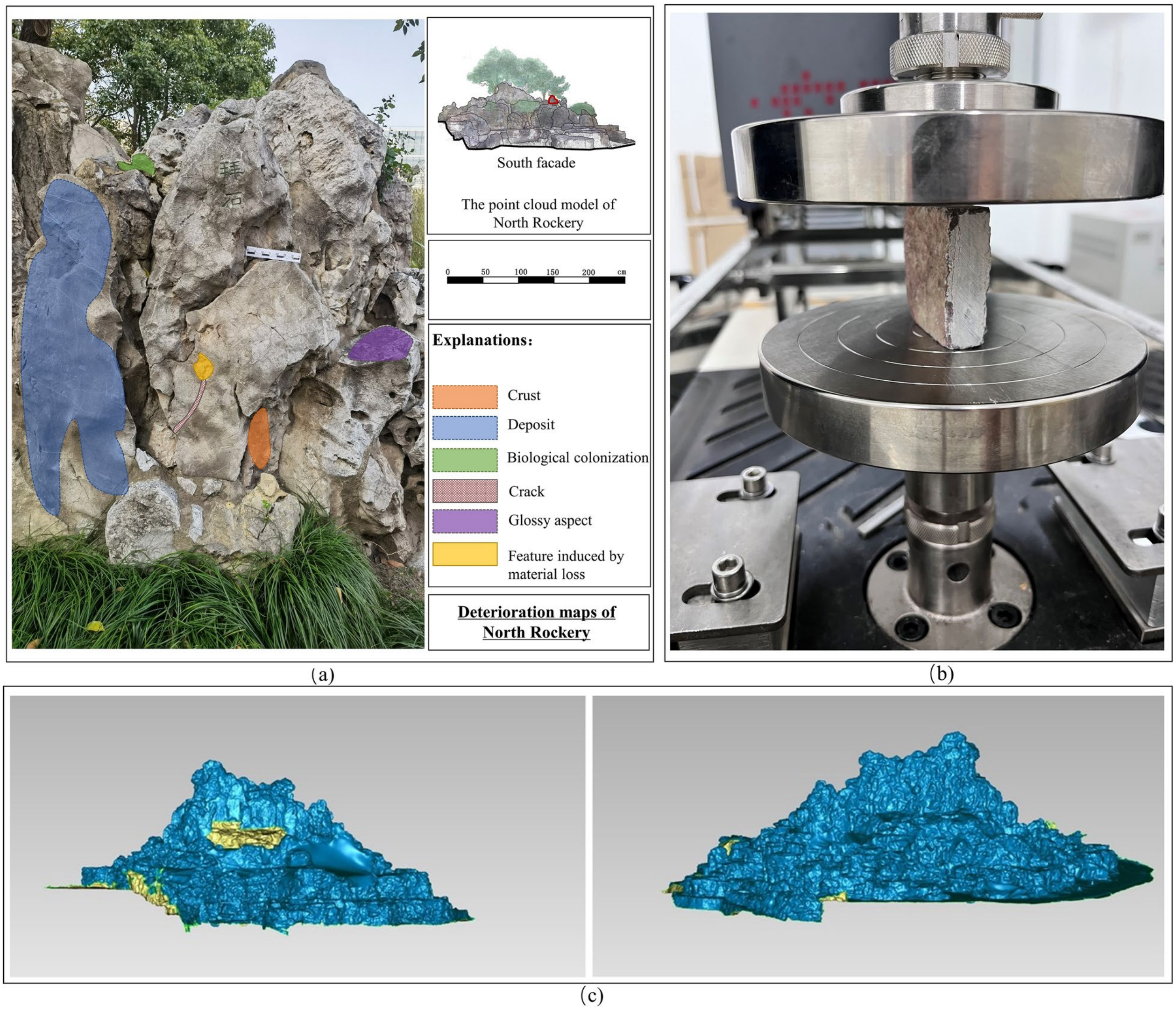

Fig. 6 **a** Deterioration map of North Rockery; **b** compressive strength test of rockery specimen; **c** reality-based 3D models of North Rockery

Table 3 Index value of North Rockery at Zhan Yuan

Indexes	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15
Values	0.22	0.7	0.3	2	1	0.5	0.1	0.15	0.8	3	2	654	0.2	12	5

Table 4 Final certainty degrees and final assessment result of North Rockery at Zhan Garden

Comprehensive membership degrees					Risk level
Level I	Level II	Level III	Level IV	Level V	
0.3671	0.4880	0.1692	0.0501	0.0174	II

Aside from the useful insights provided by the final risk level, the recommended lists of best activities also correspond to the final risk level. Three of the rockeries studied need maintenance and preservation to keep their health risk at a low level. Only the rockery at LG requires long-term restoration and more detailed analyses.

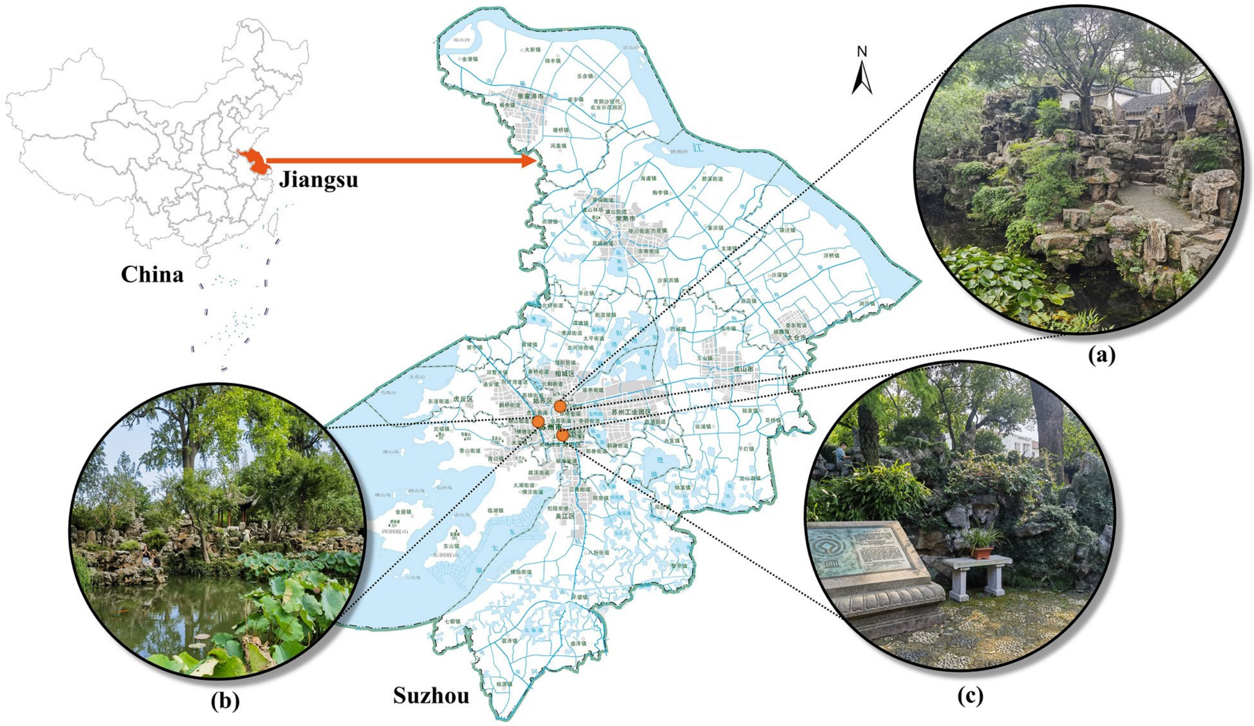

Fig. 7 Location of the case studies; **a** rockery at the Humble Administrator's Garden; **b** rockery at the Lingering Garden; **c** rockery at the Canglang Pavilion

Table 5 Final certainty degrees and final assessment result for all the case studies

Case study	Final certainty degrees					Risk level	Recommendations
	Level I	Level II	Level III	Level IV	Level V		
ZG	0.3671	0.4880	0.1692	0.0501	0.0174	**II**	Maintenance and preservation works are recommended. Detailed analysis and monitoring activities can be considered
HAG	0.3887	0.3667	0.1671	0.0070	0.0737	**I**	Maintenance and preservation works are recommended
LG	0.2804	0.1999	0.3021	0.1691	0.0671	**III**	Minor damages requiring long-term restoration works. More detailed risk analysis is recommended
CLP	0.3918	0.1903	0.1984	0.1947	0.1220	**I**	Maintenance and preservation works are recommended

Discussion

This study proposed a health risk assessment method based on MCDM techniques for rockeries based on objective and unbiased data obtained from in-situ investigations and laboratory tests. Using this method, decision makers can glean from the health risk level of the rockeries and identify priority actions that need to be taken. Compared with evaluation results based on rockery craftsmen's experiences, the health risk assessment results from this study are clearer and more comprehensive. That is, while rockery craftsmen can evaluate the risk of one typical type of deterioration pattern based on their experience, they cannot obtain comprehensive assessment results based on multiple factors through that method. By contrast, the proposed health risk assessment method is a more comprehensive process that considers risks from different factors related to the rockeries' health and can provide more reliable and objective results.

While the proposed health risk assessment method yields clear results on the health risk level of the rockeries in the four Chinese classical gardens, some limitations must be clarified. First, it is critical to note that the results of the proposed method are intended to be used as a useful reference for the initial prioritization of rockeries with potentially high health risk levels and should therefore not be regarded as the final results. A more detailed level of analysis should be carried out to diagnose the structure and deterioration patterns of the rockeries. Second, owing to the limitation of diagnostic techniques, this research was based on a reduced set of indicators. A more comprehensive analysis can be obtained to include more indicators and diagnostic techniques. This study intended to provide a standardized health risk assessment procedure for rockeries that can be modified and improved by including more indicators. Third, this study focused on rockeries made of Taihu stone in the region south of the Yangtze River. Based on differences in climate and material properties, the evaluation criteria might need to be modified for rockeries of different materials and locations.

To inform the future development of the protection of rockeries, it is important to build a database to facilitate the inspections and data capture of the rockeries, as well as the standardized assessment procedure. This database should include their health state profiles and the results of technical surveys. Since the state of their health must be evaluated over years or even decades, this database can serve as an important reference for future protection and restoration activities.

Conclusions

As one of the most important components of Chinese classical gardens, rockeries draw extensive interest globally. However, research concerning the protection of rockeries is still insufficient. This study therefore proposed a health risk assessment method based on MCDM techniques. The health risk assessment method proposed in this study was successfully implemented for four rockeries in Chinese classical gardens to demonstrate its feasibility as a standardized health risk assessment method for rockeries. In this study, a cloud model was introduced to calculate the health risk level of rockeries. This model can convert the fuzziness and randomness of indexes to certainty and determinacy by calculating the membership degree of the indexes and selecting the value that best reflects the corresponding risk level as the final results. Compared with the practice of assessing damage levels based on the rockery craftsmen's experience, the proposed method is more reliable and efficient as it proposes the use of a decision-making tool in the form of a standard objective index that considers information from a diverse set of diagnostic activities, including damage surveys, material characterization tests, and laboratory tests. The proposed method can provide quantitative and standardized evaluation results for decision makers to identify rockeries with a high health risk level.

The proposed health risk assessment method can be viewed as an initial step toward incorporating relevant technical aspects into decision support systems for rockeries in Chinese classical gardens. Moreover, the standard outputs provide the possibility of making it easier to communicate key aspects of recommendations to non-technical stakeholders. Therefore, this approach is strongly recommended for assessing the health risk level of rockeries in Chinese classical gardens.

Abbreviations

AHP	Analytical hierarchy process
MCDM	Multi-criteria decision-making
ZG	The Zhan Garden
HAG	The Humble Administrator's Garden
LG	The Lingering Garden
CLP	The Canglang Pavilion

Acknowledgements

We thank the editor and anonymous reviewers for their helpful comments and valuable suggestions. We would like to thank Editage (www.editage.cn) for English language editing.

Author contributions

LF was responsible for most of the work and writing of the manuscript. JP and YT were responsible for the data analysis of the manuscript. QZ was responsible for the review and revision of the manuscript. All authors read and approved the final manuscript.

Funding

This work was supported by the National Natural Science Foundation of China (No. 51878353), the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), Postgraduate Research & Practice Innovation Program of Jiangsu Province and Jiangsu Provincial Culture and Tourism Key Laboratory Research Project.

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.

Received: 10 January 2023 Accepted: 4 April 2023
Published online: 09 May 2023

References

1. Thacker C, Keswick M. The Chinese garden: history, art and architecture. Gard Hist. 1978;7(1):20. https://doi.org/10.2307/1586713.
2. Paolillo M. Forging the garden: the "Yuanye" and the significance of the Chinese garden in the 17th century. East West. 2003;53:209–39.
3. Lou L, Wei C, Wu H, Yang C. Cave feature extraction and classification from rockery point clouds acquired with handheld laser scanners. Herit Sci. 2022;10(1):1–22. https://doi.org/10.1186/s40494-022-00810-6.
4. Parkes G. Thinking rocks, living stones: reflections on Chinese lithophilia. Diogenes. 2005;52(3):75–87. https://doi.org/10.1177/0392192105055173.
5. Chen WY, Qin K. Rockery protection under the framework of World Heritage protection. J Landsc Res. 2019;11:61–4.
6. Liang H, Li W, Zhang Q. Semantic-based 3D information modelling and documentation of rockeries in Chinese classical gardens: a case study on the rockery at Huanxiu Shanzhuang, Suzhou. China J Cult Herit. 2019;37:247–58. https://doi.org/10.1016/j.culher.2018.11.015.
7. Xuewen C. Research on renovation techniques of classical gardens in Suzhou—in case of Yiyuan renovation. Jiangsu: Nanjing Southeast University; 2017. (**in Chinese**).

8. Cheng HF. Research on the heritage monitoring of the rockery in the mountain villa with embracing beauty. J Landsc Archit. 2021;37(02):5 (**in Chinese**).
9. Tamayo OV, Paolini A, Vafadari A, Cesaro G, Fakhoury L. Risk management at heritage sites: a case study of the Petra World Heritage Site. UNESCO; 2012.
10. Zan ML, Heras VC, Wijffels A, Cardoso F, Vandesande A, Santana M, et al. A value-based monitoring system to support heritage conservation planning. J Cult Herit Manag Sustain Dev. 2014;3(2):130–47.
11. Fu F, Zhang J, Shen F, Zhao C. The multi-tech protective monitoring of the Lion Forest Garden Stony Artificial Hills (Suzhou, China). Int Arch Photogramm Remote Sens Spat Inf Sci. 2020;44:335–42. https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-335-2020.
12. Xu P. An interdisciplinary study: rock worship in Chinese classical gardens. Int J Arts Sci. 2014;7(5):547.
13. Zheng J. Art and the shift in garden culture in the Jiangnan Area in China (16th–17th Century). Asian Hist Cult. 2013;5(2):1. https://doi.org/10.5539/ach.v5n2p1.
14. Zhou WZ, Chen X. A survey of rockery art history in traditional Chinese gardens. Acta Hortic. 2010;881(881):287–94.
15. Murck A. A Chinese garden court: the Astor court at the Metropolitan Museum of Art. Metropolitan Museum of Art; 1980.
16. Amante MG. The transformation of stone. Greenville: East Carolina University; 2010.
17. Jin-tao W. On specialization of rockery in Chinese classical garden. Chin Landsc Archit. 2008;24(1):91–4.
18. Dong Q, Zhang Q, Zhu L. 3D scanning, modeling, and printing of Chinese classical garden rockeries: Zhanyuan's south rockery. Herit Sci. 2020;8(1):1–15. https://doi.org/10.1186/s40494-020-00405-z.
19. 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.
20. Masciotta M-G, Roque JC, Ramos LF, Lourenço PB. A multidisciplinary approach to assess the health state of heritage structures: the case study of the Church of Monastery of Jerónimos in Lisbon. Constr Build Mater. 2016;116:169–87. https://doi.org/10.1016/j.conbuildmat.2016.04.146.
21. Pelà L, Roca P, Aprile A. Combined in-situ and laboratory minor destructive testing of historical mortars. Int J Archit Herit. 2018;12(3):334–49. https://doi.org/10.1080/15583058.2017.1323247.
22. Vasanelli E, Colangiuli D, Calia A, Sbartaï Z-M, Breysse D. Combining non-invasive techniques for reliable prediction of soft stone strength in historic masonries. Constr Build Mater. 2017;146:744–54. https://doi.org/10.1016/j.conbuildmat.2017.04.146.
23. Russo S. Integrated assessment of monumental structures through ambient vibrations and ND tests: the case of Rialto Bridge. J Cult Herit. 2016;19:402–14. https://doi.org/10.1016/j.culher.2016.01.008.
24. Blyth A, Napolitano R, Glisic B. Documentation, structural health monitoring and numerical modelling for damage assessment of the Morris Island Lighthouse. Philos Trans R Soc A. 2019;377(2155):20190002. https://doi.org/10.1098/rsta.2019.0002.
25. Hemeda S. Finite element assessment FEA of polymer anti-seismic piling techniques for protection of the underground culture heritage. Herit Sci. 2022;10(1):1–22. https://doi.org/10.1186/s40494-022-00677-7.
26. Ludeno G, Cavalagli N, Ubertini F, Soldovieri F, Catapano I. On the combined use of ground penetrating radar and crack meter sensors for structural monitoring: application to the historical consoli palace in Gubbio, Italy. Surv Geophys. 2020;41(3):647–67. https://doi.org/10.1007/s10712-019-09526-y.
27. Masciotta M-G, Ramos LF, Lourenço PB. The importance of structural monitoring as a diagnosis and control tool in the restoration process of heritage structures: a case study in Portugal. J Cult Herit. 2017;27:36–47. https://doi.org/10.1016/j.culher.2017.04.003.
28. Makoond N, Pelà L, Molins C. A risk index for the structural diagnosis of masonry heritage (RISDiMaH). Constr Build Mater. 2021;284(4): 122433. https://doi.org/10.1016/j.conbuildmat.2021.122433.
29. Jato-Espino D, Martín-Rodríguez Á, Martínez-Corral A, Sañudo-Fontaneda LA. Multi-expert multi-criteria decision analysis model to support the conservation of paramount elements in industrial facilities. Herit Sci. 2022;10(1):1–18. https://doi.org/10.1186/s40494-022-00712-7.
30. Ortiz R, Ortiz P. Vulnerability index: a new approach for preventive conservation of monuments. Int J Archit Herit. 2016;10(8):1078–100. https://doi.org/10.1080/15583058.2016.1186758.
31. Ruiz-Jaramillo J, Muñoz-González C, Joyanes-Díaz MD, Jiménez-Morales E, López-Osorio JM, Barrios-Pérez R, et al. Heritage risk index: a multi-criteria decision-making tool to prioritize municipal historic preservation projects. Front Archit Res. 2020;9(2):403–18. https://doi.org/10.1016/j.foar.2019.10.003.
32. Pinero I, San-Jose JT, Rodriguez P, Losanez MM. Multi-criteria decision-making for grading the rehabilitation of heritage sites. Application in the historic center of La Habana. J Cult Herit. 2017;26:144–52. https://doi.org/10.1016/j.culher.2017.01.012.
33. Zhang X, Wang H, Wang Z. Cultural relics health evaluation based on cloud model approved analytic of hierarchy process. Int J Inf Comput Sci. 2014;3:88–93.
34. Gutiérrez-Carrillo ML, Bestué Cardiel I, Molero Melgarejo E, Marcos CM. Pathologic and risk analysis of the Lojuela Castle (Granada-Spain): methodology and preventive conservation for medieval earthen fortifications. Appl Sci. 2020;10(18):6491. https://doi.org/10.3390/app10186491.
35. Van Balen K. Expert system for evaluation of deterioration of ancient brick masonry structures. Sci Total Environ. 1996;189:247–54. https://doi.org/10.1016/0048-9697(96)05215-1.
36. van Hees RP, Naldini S. MDCS—a system for damage identification and monitoring. In: Preventive conservation-from climate and damage monitoring to a systemic and integrated approach. Boca Raton: CRC Press; 2020. p. 113–8.
37. 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 (cote d'ivoire). Geoenviron Disasters. 2016;3(1):1–13.
38. 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 Manag. 2011;25(13):3465–84. https://doi.org/10.1007/s11269-011-9866-2.
39. Kazakis N, Kougias I, Patsialis T. Assessment of flood hazard areas at a regional scale using an index-based approach and analytical hierarchy process: application in Rhodope-Evros region, Greece. Sci Total Environ. 2015;538:555–63. https://doi.org/10.1016/j.scitotenv.2015.08.055.
40. Zou Q, Zhou J, Zhou C, Song L, Guo J. Comprehensive flood risk assessment based on set pair analysis-variable fuzzy sets model and fuzzy AHP. Stoch Environ Res Risk Assess. 2013;27(2):525–46. https://doi.org/10.1007/s00477-012-0598-5.
41. Cai T, Li X, Ding X, Wang J, Zhan J. Flood risk assessment based on hydrodynamic model and fuzzy comprehensive evaluation with GIS technique. Int J Disaster Risk Reduct. 2019;35: 101077. https://doi.org/10.1016/j.ijdrr.2019.101077.
42. Chowdary V, Chakraborthy D, Jeyaram A, Murthy Y, Sharma J, Dadhwal V. Multi-criteria decision making approach for watershed prioritization using analytic hierarchy process technique and GIS. Water Resour Manag. 2013;27(10):3555–71. https://doi.org/10.1007/s11269-013-0364-6.
43. 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 Manag. 2020;34(5):1625–48. https://doi.org/10.1007/s11269-020-02495-7.
44. Wu Z, Cui Y, Guo Y. A case study of flood risk evaluation based on emergy theory and cloud model in Anyang Region, China. Water. 2021;13(4):420. https://doi.org/10.3390/w13040420.
45. Xu G, Huang GQ, Fang J. Cloud asset for urban flood control. Adv Eng Inform. 2015;29(3):355–65. https://doi.org/10.1016/j.aei.2015.01.006.
46. Vergès-Belmin V. Illustrated glossary on stone deterioration patterns. ICOMOS; 2008.
47. Saaty TL. How to make a decision: the analytic hierarchy process. Eur J Oper Res. 1990;48(1):9–26. https://doi.org/10.1016/0377-2217(90)90057-I.
48. Xiaohong Z. Health risk assessment of open-air relics based on the Internet of Things. Xian University of Architecture and Technology; 2016. (**in Chinese**).
49. GB/T 9966.13-2021. Natural stone test methods-part 13: determination of water absorption coefficient by capillarity. (**in Chinese**).
50. Deyi L, Haijun M, Xuemei S. Membership clouds and membership cloud generators. J Comp Res Dev. 1995;32(6):15–20.

51. Lu H, Ren L, Chen Y, Tian P, Liu J. A cloud model based multi-attribute decision making approach for selection and evaluation of groundwater management schemes. J Hydrol. 2017;555:881–93. https://doi.org/10.1016/j.jhydrol.2017.10.009.
52. Cheng K, Fu Q, Meng J, Li T, Pei W. Analysis of the spatial variation and identification of factors affecting the water resources carrying capacity based on the cloud model. Water Resour Manag. 2018;32(8):2767–81.
53. Wang X, Yang W, Xu Z, Hu J, Xue Y, Lin P. A normal cloud model-based method for water quality assessment of springs and its application in Jinan. Sustainability. 2019;11(8):2248. https://doi.org/10.3390/su11082248.
54. Yuan R. From the Jiangnan Park to the royal garden: preliminary study on the gardening arts of Zhan Yuan and Ru Yuan, Southeast Cult. 2010(04):115–20 (**in Chinese**).
55. Rodrigues JD. Defining, mapping and assessing deterioration patterns in stone conservation projects. J Cult Herit. 2015;16(3):267–75. https://doi.org/10.1016/j.culher.2014.06.007.
56. Auras M, Meinhardt J, Snethlage R. Leitfaden Naturstein-Monitoring: Nachkontrolle und Wartung als zukunftsweisende Erhaltungsstrategien: Fraunhofer-IRB-Verlag; 2011.
57. GB/T 9966.1-2020. Test methods for natural stone-part 1: determination of dry, wet, and after freezing compressive strength. (**in Chinese**).

Publisher's Note