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A Multicriteria-based Integrated Framework for Sustainable Assessment of Contaminated Site Management Options

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Research Article

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Posted Date: June 8th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-529355/v1

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Title

A multicriteria-based integrated framework for sustainable assessment of contaminated site management options

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Abstract

Contaminated site management is a multiple objective decision-making task that generally involves several factors, such as performance of technology, environmental effects, cost, and social influence. However, the decision on contaminated site management in China have been principally driven by practical factors such as cost and time. In this study, we adopted a sustainable assessment method and developed a multicriteria-based integrated framework that satisfy the requirement of green and sustainable development of contaminated site. We integrate remediation sustainable assessment and redevelopment sustainable assessment in one framework, and allows the optimization of indicators. The framework started with definition of site management type, then investigating site characterization, screening indicators, quantification of indicator, selecting assessment model, selecting primary options, assessment with uncertain analysis, and determine preferred options. To demonstrate the utility of the framework, results are presented in a contaminate site in southwest China for two management type, site remediation and site redevelopment. We used different approaches to evaluate the stability and robustness of assessment results, including Monte Carlo simulation, scenario analysis and sensitivity analysis. The demonstration showed that attention has to be paid to the proper description of the site, the principles of the procedure and the decision criteria.

1. Introduction

The arable land of China is less than half of the world average, the country simply cannot afford to lose any more available land due to increasing problems with pollution (Zuo et al. 2018; Yun, 2015; UNESCO 2012). According to the National Soil Pollution Prevention and Treatment Action Plan of China, the safe utilization rate of contaminated land should be above 90% by 2020, and above 95% by 2030 (SCC, 2016). On the other hand, China has been the fastest growing market globally for contaminated land remediation, and probably the largest remediation market in the world (Coulon et al., 2016; Hou et al., 2018; Liu et al., 2020). Local governments have increased demand for remediation and redevelopment of contaminated sites because land-transferring fees contribute to their income (accounted for 39.9% in 2015) (Qu et al. 2016). Since 2017, China’s provincial capital cities have successively announced to the public the status of 174 contaminated sites in their jurisdiction. In provincial capital cities alone, there are more than 144 contaminated sites are being remediated of which 109 are expected to redevelopment recently, and 25% of the contaminated sites have been sold, with a total amount of 104.96 billion RMB (Greenpeace and LIEEN, 2019).

However, the remediation industry of China is still in its infancy, as well as redevelopment industry (Song et al., 2018). In the past years around the world, the development of contaminate site remediation has evolved in a more sustainable direction (Hou and Altabbaa, 2014; Lies and Cappuyns, 2017). The acts of remediation and redevelopment have been considered as a sustainable form of development, based on practices focused on reusing existing infrastructure (utilities, roads, etc.), relieving pressure on greenfield development, and yielding additional environmental benefits in water and air quality as well as reductions in greenhouse gas emissions among others (US EPA, 2015). A set of technical guidelines have been developed to support the emergent soil and groundwater remediation industry in China (CAEPI, 2019; Chiang and Gu, 2015; Hou et al., 2014b). However, the remediation of contaminated soil and groundwater based on generic guideline values, which are not strictly sustainable-based, has been questioned. It turned out that in China, the direct costs, time and environmental risk reduction are still the critical criteria involved in selecting contaminated sites remediation technologies (An et al., 2017; Yang et al., 2019). Other factors, such as social impacts, have generally been ignored or at least they have not been systematically assessed. Due to lack of an integrated framework of decision-making to support sustainable-based remediation in China, many contaminate site restoration projects have resulted either in secondary pollution or otherwise incomplete outcomes (Coulon et al., 2016). In addition, some of the existing redevelopment assessment focus on sites planning of industrial areas rather than on redevelopment of a site (Ruiz et al., 2012).

The multi-criteria decision analysis (MCDA) is a normally technique applied to facilitate decision-making when processing and aggregating a multitude of and sometimes conflicting attributes, including decision-making of contaminated site management (Sorvari and Seppala, 2010; Rosen et al., 2015; Demesouka et al., 2019). MCDA can accommodate both qualitative data and quantitative data. While using subjective data will introduces uncertainty of assessment (Sam et al., 2017). In fact, data of contaminated sites is often limited, particularly information that associated with social impacts. While multicriteria-based sustainable assessment has been adopted in prioritization of remediation techniques and site redevelopment options in other countries (Sorvari and Seppala, 2010; Stezar et al., 2013; Soderqvist et al., 2015; Braun et al., 2019), there are few published cases of using it in site redevelopment option prioritization in China. Moreover, many available assessment methods suffer a lack of uncertain analysis; and at the same time, they need regular updating.

There is no integrated method in China to simultaneous systematically study the decision-making of various contaminated site management types. Therefore, developing a multicriterial-based method, that would evaluate the different management decisions in a single, unified framework became the main objective of our study. We address this gap by proposed a multicriteria-based integrated framework as a complement to existing technical guidelines for sustainability assessment of site management options, considering key attributes in environmental, economic, social, and technology domains. The framework was demonstrated over two case studies within a heavy metal polluted site in Southwest China.

2. Material and methods

2.1. Integrate framework

The conceptual assessment framework was proposed based on well-established sustainable theory, to help making decision of best site management option. The framework involves eight steps as shown in Fig. 1: (1) define site management type, (2) investigate site characterization, (3) select potential management options, (4) build indicator set, (5) indicator quantification (6) select appropriate assessment model (7) assessment with uncertain analysis, (8) determine preferred options.

Fig.1. Proposed framework for sustainable assessment of contaminated site management options.

2.2. Define site management type

The first step is to define which type of management need to be decision-marking. This step is of major importance in terms of subsequent analysis, since different management problem will influence boundaries of indicator set building (section 2.3) and indicator quantification (section 2.4). In this study, the framework was proposed for three commonly site management type: site prioritization, sustainable remediation assessment, sustainable redevelopment assessment.

2.3. Investigate site characterization

The next step was to investigate site characterization to obtain basic data of site (step 2) by environment investigation and social investigation. Data include measurement of concentrations of potential concern chemicals (i.e. heavy metal, petroleum hydrocarbon), sensitivity receptors (i.e. farmland, communities, river, and residential), former activities (i.e. production process), geographic information (i.e. coordinate, distance, terrain) and hydrogeology information (i.e. aquifer, rainfall). These data provide the necessary information for subsequent indicator scoring (section 2.5.1).

2.4. Select potential options

The sixth step of the proposed framework is choosing potential management options applicable for a specific site for the final decision. For a type of site management, there are often a wide variety of option can be applied. For example, for site remediation, there are more than twenty technologies can be used (e.g., In-situ bio-ventilation, monitored natural attenuation, soil washing, thermal desorption, and stabilization/solidification), which does not include hybrid approach. Among the whole range of existing options, the application of certain options may not be feasible due to the specific characteristics of the site-specific circumstances. Therefore, options that are inapplicable or unworkable for the case under study should be identified in this step and screened out before next process.

2.5. Establish indicator set

Indicator set are used as a link between sustainability management goal and practice options, and allows for a fair comparison of options. The building of indicator set can be selected from previous research, also can be established according to the understanding and demand of sustainable. Several principles were suggested to comply, including completeness, operationality, decomposability, absence of redundancy and minimum size, in developing new indicator (see Keeney and Raiffa, 1976; VonWinterfeldt and Edwards, 1986). In practice, the selected indicators should be adapted to case-by-case basis to suit the site-specific circumstances along with the magnitude and complexity of the management project. In order to operate conveniently or reduce information redundancy, the index set can be optimized to a smaller scale.

2.6. Indicator quantification

In order to make the evaluation as objective as possible, it is necessary to conduct quantificational research. While the values of indicators are the key factor which influence the final assessment result. The indicator value assignment process is called Indicator quantification. There are two types of indicator quantification, which is Indicator scoring and Indicator weighting, respectively.

2.6.1. Indicator scoring

Indicator scoring can be performed using semi-quantitative method or quantitative method. The semi-quantitative method can be performed using expert judgement, questionnaires, and/or individual interviews according to classification standard. Examples of semi-quantitative methods include a classification standard. The scoring value of indicator should represent the expected effect, given available information. The quantitative method is often performed using ratio method, such as the ration of measured indicator value to basic value.

2.6.2. Indicator weighting

After the indicator scoring, the next step is indicator weighting. This stage needs to assign the degree of importance using weights for each indicator. Many different techniques have been proposed to assign weights. The simplest way is the equal method, which distributes weights equally among all considered indicators. There are also other methods which consider the different relative importance, which can be divided broadly into two categories: objective methods and subjective methods. The objective methods are type of mathematical methods, based only on the analysis of the initial measured data. While the subjective methods depend on the preferences of stakeholders. Examples of subjective weighting methods include procedures such as direct point allocation, trade-off weighting. In order to calculate conveniently, the values of weight normally sum of weight should equal 1.

2.7. Select appropriate assessment model

How to handle multidimensional data mentioned above into a comprehensive index to assess the degree to which option is global reasonable is the task of this step. Such decision-making problem is usually solved by assessment model, or MCDA. Many MCDA exist to aid decision-making. According to compensation degree, including compensatory method, non-compensatory method, and partially compensatory method. In compensatory method, the effects of different indicators can accept each other, while non-compensatory method is on the contrary. Partially compensatory method meaning that some compensation is accepted between the different decision criteria but a minimum level of performance is required from each of them. Therefore, assessment model selection was arbitrary, mainly based on purpose, needs, and stakeholder preferences.

2.8. Assessment with uncertain analysis

Due to lack of knowledge and natural variability, it is almost impossible to measure the effects exactly of the different management options on receptors, that is creates uncertainty. The former type of uncertainty is epistemic uncertainty, while the latter is type of aleatory uncertainty. Uncertainty in MCDA can have a significant effect on rankings, and mislead decision makers. Especially in the field of site management, human subjectivity/preference can result in obvious uncertainty. In site management decision-marking, uncertainty mainly comes from the indicator scoring and weight assignment. To understand the accuracy and reliability of results, it is essential to evaluate the effect of indicator variability and weight sensitivity on the final output. Some commonly used uncertain evaluation methods including stochastic simulation, sensitivity analyses, and scenario analysis.

2.9 Determine preferred options

The preference of each management option is guided by a total score derived by assessment process, which often the higher the score the better the option (higher preference). It is notable that the assessment with uncertain analysis will produce probabilistic-based output. In other words, the output does not give a certain result, but give a suggestion.

3. Case study

3.1. Study area

The study area, Luoma site, is located in Southwest China and has a long history of production of arsenic. In 2001, the factory had been closed. Due to lack of proper disposal and safe landfll, the waste residues caused serious pollution to the surrounding environment of the chemical plant. The site soil was mainly contaminated by heavy metals, including Pb, As, Cu, Zn and Ni. Investigations and risk assessment of soil showed unacceptable contamination risk levels for humans with respect to As and Pb. Detailed information about site characterization was provided in Li et al., (2019).

Fig. S1. Overview of the study area and location of sampling site

3.2. Implications for site remediation techniques assessment

3.2.1. Potential options

An initial screening among the variety of possible management options was carried out to eliminate those that were clearly ineffective or unworkable at the site. Due to the site soil is contaminated by heavy metal, four different remediation technologies were selected, including solidification/stabilization, phytoremediation, Co-processing in Cement Kiln, and excavation and washing. These options (technologies) were based on the knowledge of the most common heavy metal remediation methods used at present and the most relevant new technologies. A brief description of each option is included in Table S1.

Table S1

Description of four common remediation technology for heavy metal contaminated site.

Different remediation techniques of contaminated sites have different effects on remediation of heavy metals at different concentrations. Multiple restoration techniques may be used simultaneously at the same contaminated site. Therefore, this study set up two types of areas, high concentration area and low concentration area, and screened the contaminated site remediation technology respectively. In addition, there are differences between the effects of repair techniques during and after repair. In the process of sustainable evaluation, repair and post-repair were evaluated respectively.

3.2.2. Indicators selection

The indicators of environmental, economic and social cannot be substituted by others, were considered as first-class indicators. The second-class indicators (sub-indicators) were selected from existing indicators based on goals and scope of sustainable, well-acknowledged among remediation practitioners, measurable (quantitatively or qualitatively), representative, and independent. The identified second-class indicators are listed in Table S2. The environmental effects were represented by four environmental media (Soil, Groundwater, Atmosphere, and Surface water), one pollution source (Solid waste), and ecosystem.

Table S2. The identified second-class assessment indicators.

3.2.3. Indicator quantification

Each first-class indicator value was sum of each sub-indicator value. Semi-quantitative scoring approach is used to quantize the sub-indicator, as follow: Very positive effect: +6 to +10; Positive effect: +1 to+5; No effect: 0; Negative effect: −1 to −5; Very negative effect: −6 to −10. The scorings are performed using available data, expert judgement, questionnaires, and/or individual or group interviews. The scoring procedure is supported by a guidance matrix for each indicator. Examples of guidance can be seen in Table S3, Table S4, and Table S5.

Table S3. Reference example of environmental element soil index scoring.

Table S4. Reference example for scoring of public participation indicators of economic factors.

Table S5. Reference example of social factor comfort index scoring.

3.2.4. Assessment model

A remediation sustainable index (RSI) was calculated for each option using Eq. (1), which aggregated indicator scores with weights to provide a final value for each option.

$$RSI = \sum e_i \times W_E + \sum s_j \times W_S + \sum cb_k \times W_{CB}\text{n} \quad (1)$$

where RSI is sustainable index, e_i is score of ith sub-indicator e of environmental, W_E is weight of environmental, s_j is score of jth sub-indicator s of social, W_S is weight of social, cb_k is kth score of sub-indicator cb of economic, W_{CB} is weight of economic.

3.2.5. Uncertainty analysis

For indicator scoring caused uncertainty, Monte-Carlo simulation, which is based on the stochastic simulation of different values for indicators, is used for this purpose. After indicator scoring step, the indicator scoring uncertainty category level (high, medium, or low) was additional assigned based on strength of evidence. The uncertainty category level was high if the scoring evidence is strong (less subjective), medium if the scoring evidence is strong (medium subjective), low if the scoring evidence is weak (much subjective). Then the indicator scores are represented by beta distribution with standard deviation values of 1.82、 1.37、 0.91 for high, medium, and low level, respectively. The assessment of each indicator was then performed more than 1000 runs (2000 runs in this study). The assessed most likely scores and standard deviation σ parameters calculated from the equation (Rausand and Høyland, 2004).

$$s = \frac{\alpha-1}{\alpha+\beta-2} \quad (2)$$

$$\sigma = \sqrt{\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}} \quad (3)$$

Where α, β is the parameter of the beta distribution, which can be checked from the following well known facts.

For indicator weighting caused uncertainty, several scenarios of weights with the aim of covering a wide range of possible viewpoints is used. In this study, the first-class indicators are weighted with respect to their relative importance. Some researchers considered environmental, social, economic are equally important. Therefore, the weight of the three first-class indicator is the same, and equal to one third (equal-weighted). However, some researchers think the environment is the fundamental domain. Within the environmental domain there is a social domain, which in turn includes an economic domain. That is to say the environmental weight should be largest, and the economic weight should be smallest. In such case, the weights of environmental, social, economic were assigned 0.5, 0.3, 0.2 (unequal-weighted).

3.3. Implications for site redevelopment options assessment

3.3.1. Potential options

The first step of redevelopment project evaluation of contaminated sites is to define the type of redevelopment project so as to facilitate the follow-up research. In this study, we setup four common land use type of contaminated site redevelopment in China, including commercial land, landscape land, residential land, and Industrial land.

3.3.2. Establish indicator set

Contaminated land management involves a wide range of stakeholders, such as site owners, regulators, local community, environmental groups, academic, etc. Each of stakeholder has their unique demand in adopting sustainability in redevelopment, and sometimes overlapped each other. A survey questionnaire of redevelopment options on the impact indicators was designed following an extensive literature review on redevelopment, and according to general questionnaire survey guidance. An indicator identified/established questionnaire test was conducted with site owners, regulators, local community, environmental groups, academic. Nineteen survey indicators were identified as initial indicators.

3.2.3. Indicator quantification and optimization

After initial indicators identification, a scoring questionnaire test was conducted with the same interviewees for Indicator quantification of commercial land, landscape land, residential land, and Industrial land. A total of 30 effective responses were received (Table S6, Table S7, Table S8, and Table S9).

Table S6. Indicator scores of commercial land use.

Table S7. Indicator scores of landscape land use.

Table S8. Indicator scores of residential land use.

Table S9. Indicator scores of industrial land use.

3.2.4. Indicator optimization

Then principal component analysis (PCA) was used to conduct dimensionality reduction treatment of initial indicators to obtain the minimum indicator sets, which can also reflect the critical demands of stakeholders while avoiding double-counting effects. Total variance explained and rotated component matrix (four principal components selected) for different land use type based on PCA was presented in Table S10.

Table S10. Total variance explained and rotated component matrix (four principal components selected) for different land use type.

3.3.5. Assessment model

A sustainable redevelopment index (SRI) was calculated for each option using Eq. (4), which aggregated indicator scores with weights to provide a final value for each option.

$$SRI = \sum I_i \times W_i \tag{4}$$

where I_i is the ith indicator, W_i is the ith indicator weight.

3.3.6. Uncertain analysis

For weight assignment caused uncertainty, scenario simulation, which used different values for weights, is used. We conducted uncertainty analysis by setting 7 different scenarios of one indicator weight to explore how different criteria indicator weight impact rank ordering of options. In each scenario, one indicator is considered as key indicator and given one value to its weight (1, 0.75, 0.6, 0.5, 0.4, 0.25, and 0), while other indicators are given the same weight. For example, when there are four indicators, if one indicator is given 0.4 of the total weight, other three indicator weight were given the same 0.2, respectively. In extreme scenario, when one indicator is given to 0 of the weight, other 3 indicator weight become 1/3, when one indicator is given to 1, the other three indicators can be ignored (the weight is 0).

4. Results

4.1. Remediation techniques assessment

Input values based on guidance for the Luoma site in the environmental domain, social domain, and economic domain under four remediation technologies were showed in Table 1. In the process of indicator scoring, the remediation technologies were assigned to high concentration and low concentration scenarios respectively. At the same time, values are assigned to indicators at two stages: in remediation and after remediation. After scoring, the uncertainty evaluation of the assignment is carried out according to the subjective degree of the indicators. Indicators with large subjective differences were evaluated as high uncertainty, indicators with normal subjective differences were evaluated as medium uncertainty, and indicator with small subjective differences were evaluated as low uncertainty.

Table 1

Input values for the Luoma site in the environmental domain, social domain, and economic domain under four remediation technologies.

According to the uncertainty evaluation results, monte Carlo simulation was carried out for indicators. The value distribution of the four alternatives after Monte Carlo simulation is shown in Figure S2. The confidence intervals of different first-class indicators are obviously different, with order of social > environmental > economic. The first-class indicators of social have three second-class indicators with high uncertainty, while The first-class indicators of environmental have six second-class indicators with low and medium uncertainty. Therefore, the confidence interval difference of indicators is determined by both the number of indicators and the degree of uncertainty of indicators.

Figure. S2. The value distribution of the four alternatives after Monte Carlo simulation.

Fig.2 shows the RSI value distribution of four alternatives under two weight scenarios (equal-weighted and unequal-weighted). In the high concentration scenario, the RSIs of solidification stabilization and phytoremediation in unequal-weighted scenarios were higher than in equal-weighted scenarios. The environmental indicator score of solidification and stabilization was relative higher than social and economic, so the weight of environmental indicator improved the RSIs increased. For phytoremediation, the economic indicator score was relative lower than social and environment, so the weight of economic indicator reduced the RSIs on the contrary. For co-processing in cement kiln, and excavation and washing, the RSIs in unequal-weighted scenarios were lower than in equal-weighted scenarios. This is because these two potential options have relative higher score in economic factors, so the weight of economic factors is reduced, will leading to a decrease in the overall RSI value. In the low-concentration scenario, the environmental indicator scores of the four potential options were all higher than social and economic, so the RSIs of the four potential options in unequal-weighted scenarios were all higher than in equal-weighted scenarios.

Fig.2. The RSI value distribution of four potential scenario under two weight scenarios (A: equal-weighted; B: unequal-weighted).

Fig. 3 shows the highest probabilities of being the most sustainable option. In the high-concentration scenario, the probability of solidification stabilization is always the best remediation technique in both equal-weighted scenarios and unequal-weighted scenarios. While in the low-concentration scenario, the probability of phytoremediation is always the best remediation technique in both equal-weighted scenarios and unequal-weighted scenarios. Therefore, for the Luoma site, using solidification stabilization in high heavy metal concentration area and using phytoremediation in low heavy metal concentration area is the optimal choice.

Fig.3. Probabilities of best potential option under different concentration scenarios and different weight scenarios.

4.2. Site redevelopment assessment

The SRI under 7 under different key factors with 7 weight scenarios can be seen in table S11. Fig. 4 presents the results of potential options ranking under different key factors with 7 weight scenarios. The prioritization of potential option for redevelopment with 7 scenarios was some differences. When soil quality was sensitivity indicator with high weight ($W \geqslant 0.5$), landscape was considered as the first option. When funding source was sensitivity indicator with high weight ($W>0.5$), the highest priority land-use type turned out to be industry land-use. In addition to these two situations, the option ranked first was residence land-use type. It is noted that, in situation where remediation proportion is sensitivity indicator, all scenarios led to the same ranking order.

Table S11

The sustainable redevelopment index under different key factors with 7 weight scenarios.

Fig.4. Sensitivity analysis of the ranking of potential options under 7 weight scenarios.

In general, the assessment results for each redevelopment scenario depend on the degree to which different stakeholders focus on environmental, economic, social, and governance technology development. Landscape land is considered to be the best development plan when environmental factors are emphasized. While residential land is considered to be the best development plan when economic and governance technology development factors are emphasized, and commercial and industrial land are considered to be the best development plan when social factors are emphasized. When all factors are considered equally important, residential land is considered the best choice.

5. Discussion

A sustainable assessment of contaminated site management options should be based on the inclusion of environmental, economic, social and technical factor for the potential options to be selected as the best management option. Stakeholders, who may have different preference on environmental, economic, social and technical factor will influence the sustainable assessment results. Therefore, it is essential to make communication and information exchange between the stakeholders to avoid conflicts. The proposed framework allows a systematic comparison of different potential options for both remediation and redevelopment. The framework used multicriteria theory makes it possible to consider subjective opinions of stakeholders in decision-making with objective basis.

Our framework is flexible compared with previous methods. In our framework, the indicators are established based on understanding and demand of sustainable from previous research. In other words, the indicators established in this study are not straightforwardly applicable to other situations. However, the indicators could be adapted in the case of similar sites. If initial indicators have redundant information, we using dimensionality reduction method (e.g. PCA) to optimize indicator set. In indicator quantification, indicator scoring and weighting are separate assign. In case of site remediation techniques assessment, the indicator was scored based on a guidance matrix by researchers. While in case of site redevelopment options assessment, the indicator was scored by subjectivity judgment of stakeholders. For weighting process, we also provide multiple choice to cover as many possibilities as possible. Nevertheless, both of indicator scoring and weighting process will inevitable introduce uncertain for sustainable assessment. The Monte-Carlo simulation is proved to be an effective tool to evaluate uncertainty caused by indicator scoring. The most sustainable option was determined not by one assessment index but by probability derived from lots of simulations. Such assessment will have more robustness.

It is well known that the weights reflect each person’s individual values and attitudes, personal and professional history, education, cultural background, knowledge level, the stakeholder group he/she represents etc. However, in this study, though the weights have changed, in most scenario the ranking order of management options remains unchanged. This is not agreement with previous studies that different people varied considerably resulting in different preference management options. In this sense, the multicriteria-based integrated framework for prioritization management options, described in this study, can be a useful tool that reduce uncertainty in decision making. The framework is particularly useful if one potential option has advantage in key factors.

6. Conclusion

It is noted that, we use compensatory assessment methods in two cases, which allow different factor's impact can be tradeoffs each other. However, in reality, the decisionmakers might be unwilling to accept such tradeoffs. In such situation, it is necessary to study the applicability of other assessment model to solve our study problem. In addition, with the increase of repair evaluation cases, the uncertainty of relevant parameters of the model will gradually decrease. In the future, the indicators with high uncertainty should be refined to reduce the uncertainty.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Authors Contributions

Conceptualization: [Jin Wu]; Methodology: [Jin Wu], …; Formal analysis and investigation: [Yanna Xiong]; Writing - original draft preparation: [Yinxin Ge, Yanna Xiong]; Writing -

review and editing: [Yanna Xiong, Wenchao Yuan]; Funding acquisition: [Jin Wu]; Resources: [Yanna Xiong]; Supervision: [Yanna Xiong], All authors read and approved the final manuscript.

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.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Acknowledge

This study was financially supported by National Natural Science Foundation of China (No. 41807344).

Reference

An, D., Xi, B., Ren, J., Wang, Y., Jia, X., He, C., Li, Z. (2017). Sustainability assessment of groundwater remediation technologies based on multi-criteria decision-making method. Resources Conservation and Recycling, 36-46.

Braun, A. B., Trentin, A. W., Visentin, C., Thome, A. (2019). Proposal for an optimized method for sustainable remediation evaluation and application: implementation of a multi-criteria process. Environmental Science and Pollution Research, 26(35), 35996-36006.

Brinkhoff, P., 2011. Multi-criteria analysis for assessing sustainability of remedial actions applications in contaminated land development. A Literature ReviewChalmers University of Technology, Department of Civil and Environmental Engineering, Gothenburg, Sweden (Report 2011:14)

CEPIA, China Environmental Protection Industry Association, Technical guide for environmental supervision in the process of contaminated sites remediation, T/CAEPI-22-2019.

Chiang SYD, Gu Q (2015) Brownfeld sites remediation technology overview, trends, and opportunities in China. Remediat J. 25(3):85–99.

Coulon F, Jones K, Li H et al (2016) China’s soil and groundwater management challenges: lessons from the UK’s experience and opportunities for China. Environ Int 91:196–200.

Demesouka, O. E., Anagnostopoulos, K. P., Siskos, E. (2019). Spatial multicriteria decision support for robust land-use suitability: The case of landfill site selection in Northeastern Greece. European Journal of Operational Research, 272(2), 574-586.

Greenpeace, LIEEN (Lishui Institute of Ecology and Environment of Nanjing Universiity). (2019). Problems and Countermeasures in the development and utilization of polluted urban land in China. Report. https://www.greenpeace.org.cn/redeveloping-the-polluted-land-under-chinas-cities-problems-and-solutions-report/.

Hou, D., Li, G. Nathanail, P. An emerging market for groundwater remediation in China: Policies, statistics, and future outlook. Front. Environ. Sci. Eng. 12, 16 (2018). https://doi.org/10.1007/s11783-018-1027-x

Hou, D., Altabbaa, A. (2014a). Sustainability: A new imperative in contaminated land remediation. Environmental Science Policy,, 25-34.

Hou D, O'Connor D , Al-Tabbaa A. (2014b) Comparing the Adoption of Contaminated

Land Remediation Technologies in the United States, United Kingdom, and China. Remediation Journal, 33-51.

Huysegoms, Lies, and Valerie Cappuyns. "Critical review of decision support tools for sustainability assessment of site remediation options" Journal of Environmental Management (2017): 278-296.

Keeney RL, Raiffa H. Decisions with multiple objectives: Preferences and value tradeoffs. New York: John Wiley Sons; 1976. 569 pp.

Li J., Fan J., Jiang J. (2019) Human health risk assessment of soil in an abandoned arsenic plant site: implications for contaminated site remediation. Environmental Earth Sciences, 78(24).

Liu G., Shi Y., Guo G.L., Zhao L, Niu J.J., Zhang C. (2020) Soil pollution characteristics and systemic environmental risk assessment of a large-scale arsenic slag contaminated site, Journal of Cleaner Production, 251.

MEP, Technical guidelines for site soil remediation (HJ25.4-2014), 2014.

Qu C, Shi W, Guo J et al (2016) China’s Soil pollution control: choices and challenges. Environ Sci Technol 50:13181–13183.

Rausand, M., Høyland, A., 2004. System Reliability Theory. Models, Statistical Methods and Applications. 2nd edition. Wiley.

Rosen, L., Back, P., Soderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Doberl, G. (2015). SCORE: A novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation. Science of The Total Environment, 621-638.

Sam, K., Coulon, F., & Prpich, G. (2017). A multi-attribute methodology for the prioritisation of oil contaminated sites in the Niger Delta. Science of The Total Environment, 1323-1332.

SCC (State Council of the People's Republic of China) (2016) The National Soil Pollution Prevention and Treatment Action Plan of China. http://www.gov.cn/zhengce/content/2016-05/31/content_5078377.htm (in Chinese).

Sorvari, J., Seppala, J. (2010). A decision support tool to prioritize risk management options for contaminated sites. Science of The Total Environment, 408(8), 1786-1799.

Soderqvist, T., Brinkhoff, P., Norberg, T., Rosen, L., Back, P., & Norrman, J. (2015). Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land.. Journal of Environmental Management,, 267-278.

Song Y., Hou D., Zhang J.L.,. (2018) Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: A case study at a mega-site in China[J]. Science of the Total Environment, 610:391-401.

Stezar, I., Pizzol, L., Critto, A., Ozunu, A., & Marcomini, A. (2013). Comparison of risk-based decision-support systems for brownfield site rehabilitation: DESYRE and SADA applied to a Romanian case study.. Journal of Environmental Management,, 383-393.

UNESCO (United Nations Educational, Scientific and Cultural Organization) (2012) The Fourth United Nations World Water Development Report: managing water under risk and uncertainty (WWDR4), UNESCO, Marseilles. https://unesdoc.unesco.org/ark:/48223/pf0000215644

US EPA, 2015. Superfund Community Involvement Handbook. http://www2.epa.

gov/superfund/community-involvement-tools-and-resources#tab-2.

Von Winterfeldt D, Edwards W. Decision analysis and behavioral research. New York: Cambridge University Press; 1986. 624 pp

Yang, J., Zhang, Q., Fu, X., Chen, H., Hu, P., Wang, L. (2019). Natural attenuation mechanism and health risk assessment of 1,1,2-trichloroethane in contaminated groundwater. Journal of Environmental Management, 457-464.

Yun, W.J. (2015). Problems and Countermeasures in the development and utilization of polluted urban sites in China. Bulletin of Chinese Academy of Sciences, 4, 484-491.

Zuo, L., Zhang, Z., Carlson, K.M. et al. Progress towards sustainable intensification in China challenged by land-use change. Nat Sustain 1, 304–313 (2018). https://doi.org/10.1038/s41893-018-0076-2

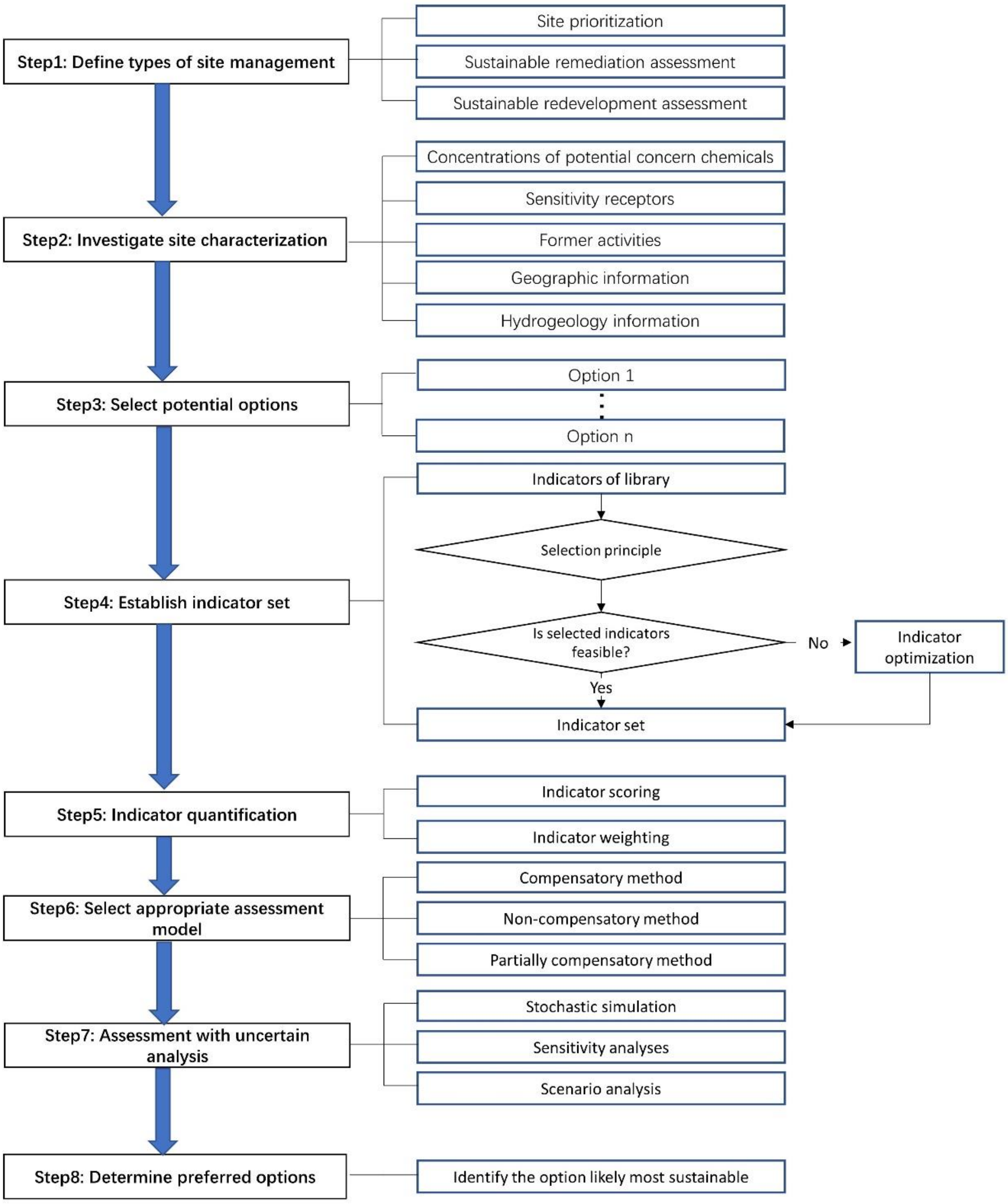

Fig.1. Proposed framework for sustainable assessment of contaminated site management options

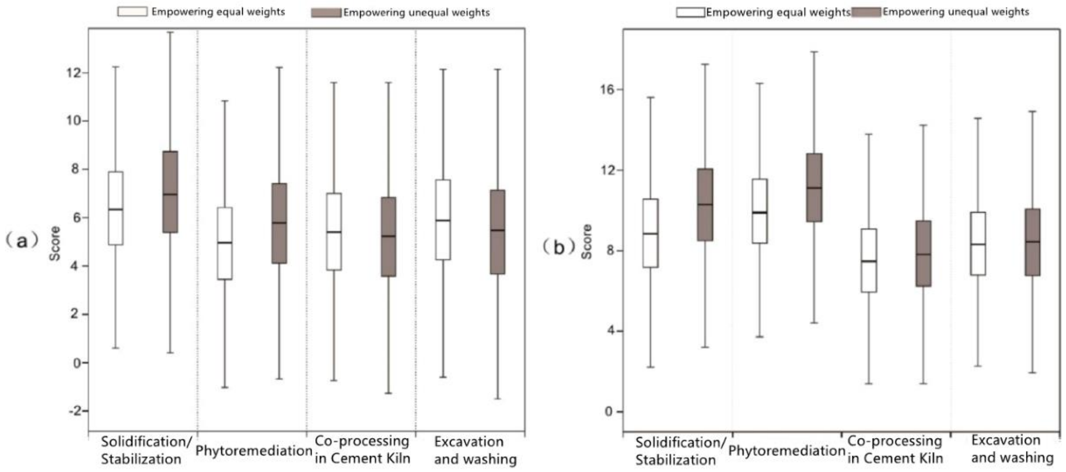

Fig.2. The RSI value distribution of four alternatives under two weight scenarios (A: equal-weighted; B: unequal-weighted).

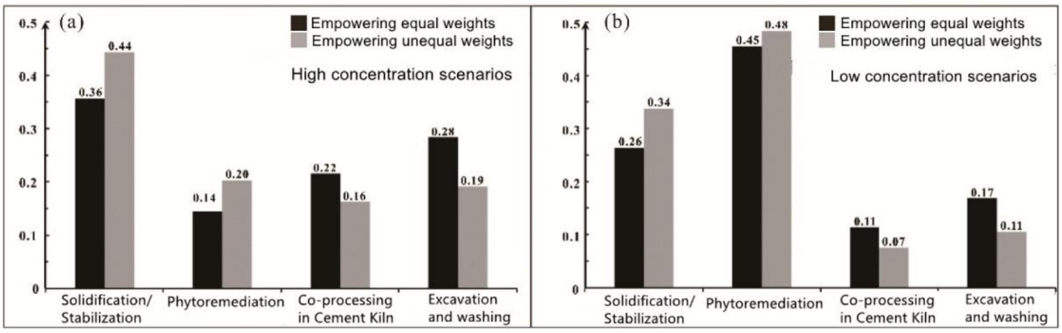

Fig.3. Probabilities of best potential option under different concentration scenarios and different weight scenarios.

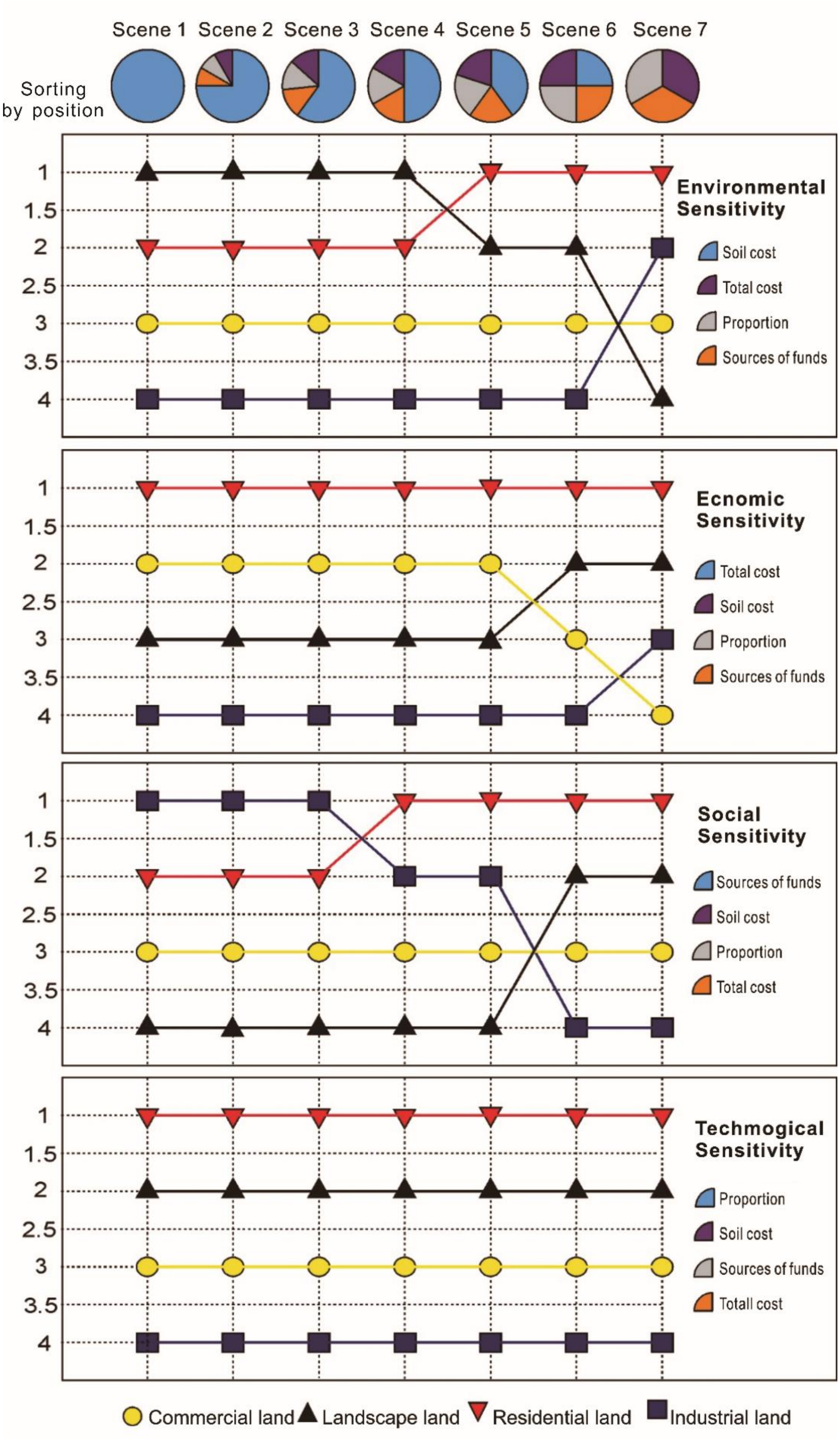

Fig.4. Sensitivity analysis of the ranking of potential options under 7 weight scenarios.

Table 1
Input values for the Luoma site in the environmental domain, social domain, and economic domain under four remediation technologies.

Indicators	Status	Solidification/stabilization			Phytoremediation			Excavation and washing			Co-processing in Cement Kiln		
		A	**B**	**Uncertainty**	**A**	**B**	**Uncertainty**	**A**	**B**	**Uncertainty**	**A**	**B**	**Uncertainty**
Ecological factor	Repairing	-2	-1	Low	-2	-1	Low	-2	-1	Low	-2	-1	Low
	After repair	4	5	Low	6	8	Low	4	5	Low	4	5	Low
Soil factor	Repairing	-4	-3	Low	-2	-1	Low	-4	-2	Low	-4	-2	Low
	After repair	4	5	Low	5	6	Low	4	4	Low	4	4	Low
Groundwater	Repairing	-2	-1	Low	-4	-3	Low	-2	-1	Low	-2	-1	Low
	After repair	6	7	Low	5	7	Low	6	6	Low	6	6	Low
Solid waste	Repairing	-1	-1	Low	-6	-6	Low	-4	-4	Low	-4	-4	Low
	After repair	1	1	Low	1	1	Low	1	1	Low	1	1	Low
Atmospheric factors	Repairing	-1	-1	Medium	-1	-1	Medium	-1	-1	Medium	-1	-1	Medium
	After repair	1	1	Medium	1	1	Medium	1	1	Medium	1	1	Medium
Surface water factors	Repairing	-2	-2	Medium	-2	-2	Medium	-2	-2	Medium	-2	-2	Medium
	After repair	4	4	Medium	4	4	Medium	4	4	Medium	4	4	Medium
Comfort	Repairing	-1	-1	High	-1	-1	High	-3	-3	High	-3	-3	High
	After repair	0	0	High	2	2	High	0	0	High	0	0	High
Safety	Repairing	-1	-1	High	0	0	High	-3	-3	High	-3	-3	High
	After repair	2	2	High	2	2	High	2	2	High	2	2	High
Fairness	Repairing	4	4	High	5	5	High	4	4	High	4	4	High
	After repair	4	4	High	5	5	High	4	4	High	4	4	High
Time costs	Repairing	-4	-3	Medium	-6	-4	Medium	-1	-1	Medium	-2	-1	Medium
Repair costs	After repair	-3	-2	Medium	-4	-1	Medium	-2	-1	Medium	-2	-1	Medium
	Repairing	-1	-1	Medium	-3	-1	Medium	-4	-3	Medium	-1	-1	Medium
Land added value	After repair	5	5	High	8	8	High	2	2	High	2	2	High
Public participation	Repairing	3	3	High	1	1	High	6	6	High	6	6	High
	After repair	3	3	High	1	1	High	6	6	High	6	6	High

Figures

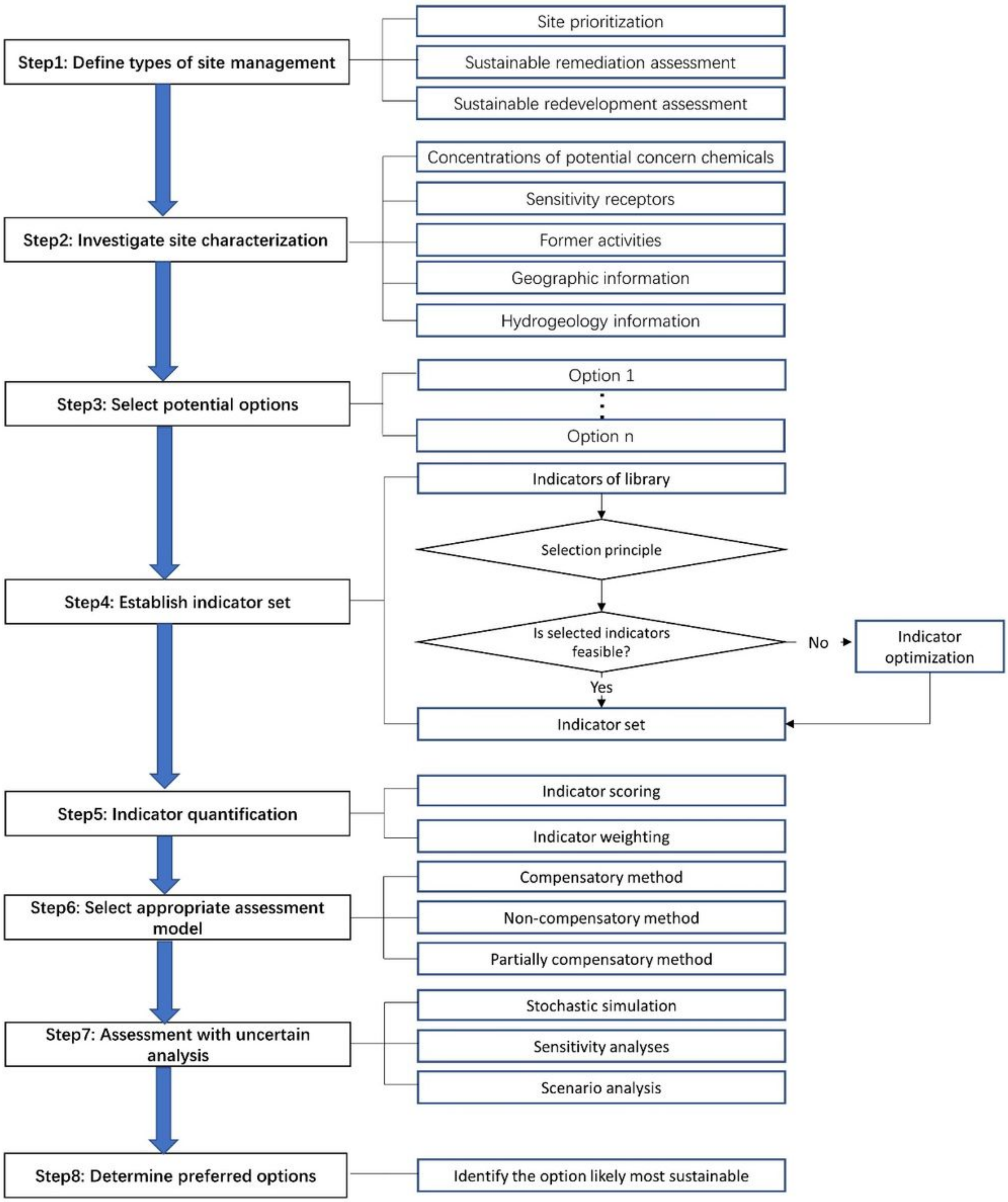

Figure 1

Proposed framework for sustainable assessment of contaminated site management options

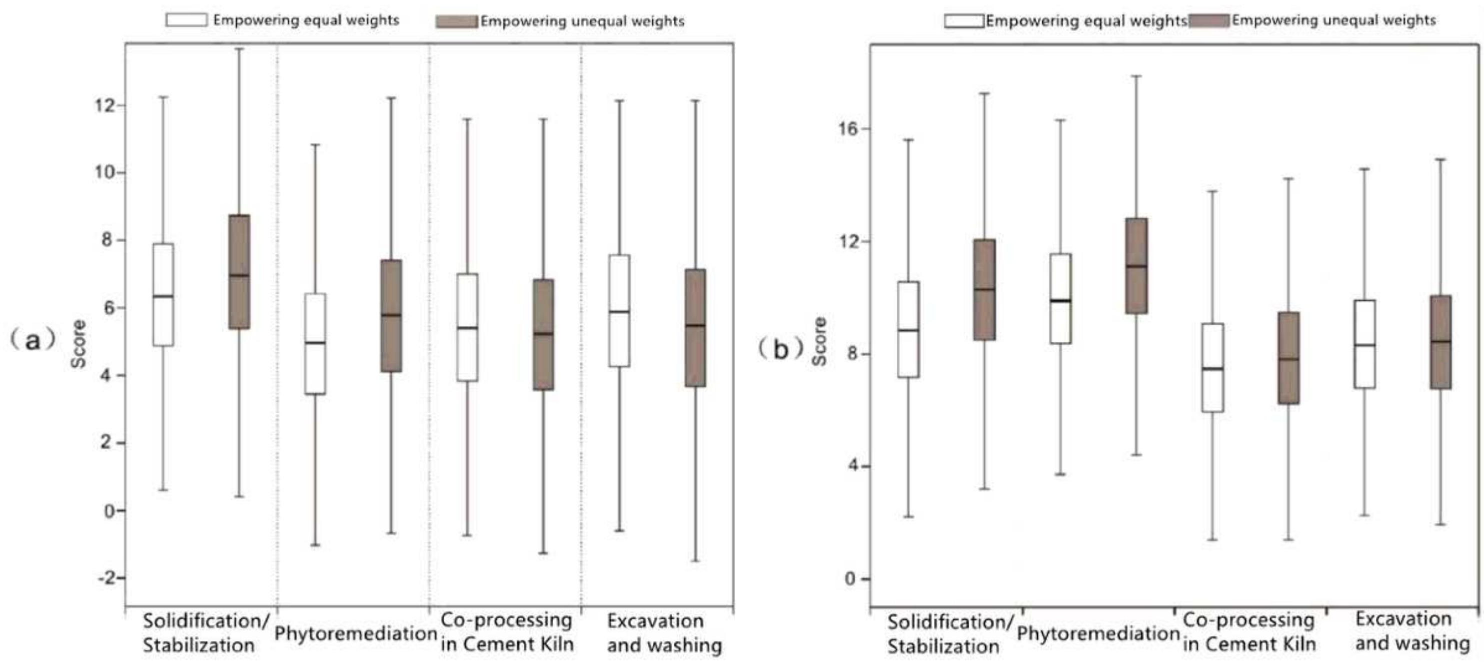

Figure 2

The RSI value distribution of four alternatives under two weight scenarios (A: equal-weighted; B: unequal-weighted).

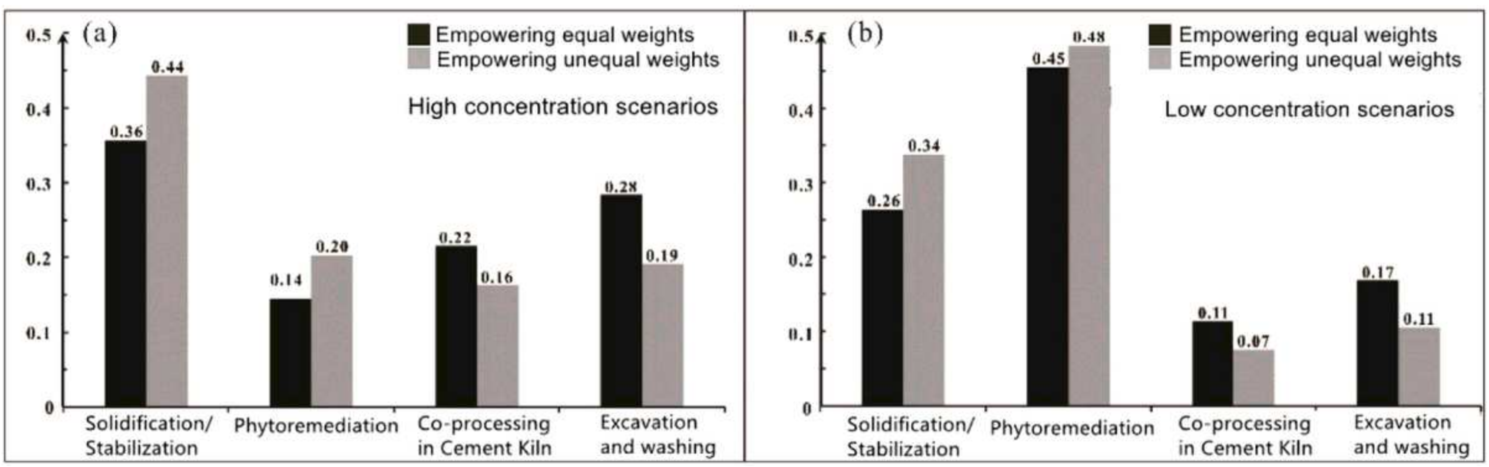

Figure 3

Probabilities of best potential option under different concentration scenarios and different weight scenarios.

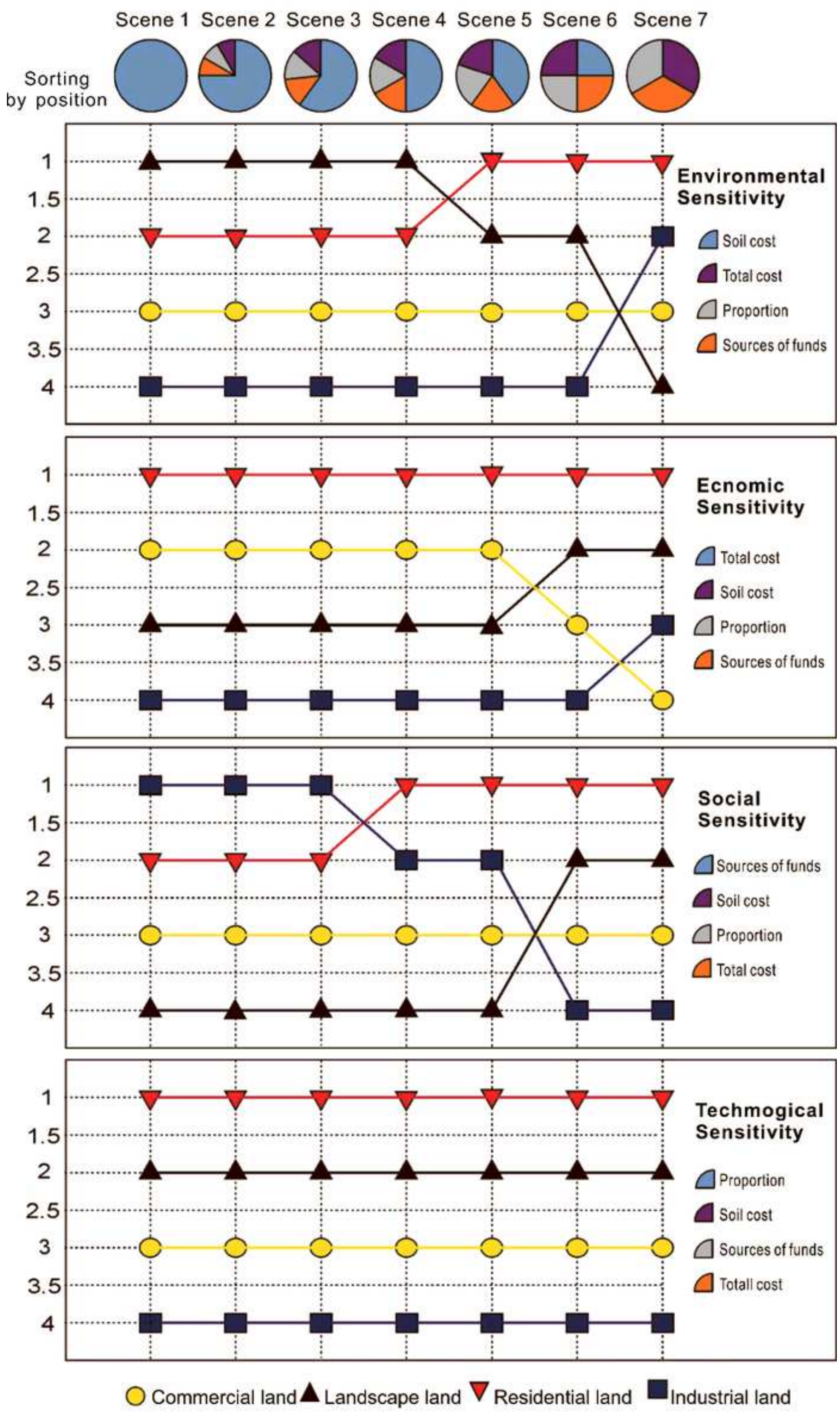

Figure 4

Sensitivity analysis of the ranking of potential options under 7 weight scenarios.

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