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Progress in the Development of Environmental Risk Assessment as a Tool for the Decision-Making Process

Kankan Wu, Luoping Zhang*

College of the Environment and Ecology, Xiamen University, Xiamen, China
Email: *lpzhang@xmu.edu.cn

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Abstract

Environmental Risk Assessment (ERA) is a powerful technical and analytical set of instruments for analyzing adverse environmental impacts, and has found some application in supporting the decision-making process over the last two decades. In this paper, the progress of ERA, including history, types, approaches and methods, are introduced, and the current problems and development prospects of ERAs for decision-making processes are discussed.

Keywords

Environmental Risk Assessment, Progress, Types, Approaches, Methods, Decision-Making

1. Introduction

Environmental Risk Assessment (ERA) is a process that evaluates risks to environment caused by human activities and natural disasters, it also assesses the appropriate level of precaution and interrelated risk management measures to reduce and mitigate hazards, and their adverse impacts so as to achieve an acceptable risk level [1]. ERA as an important component and useful technical method of Environmental Impact Assessment (EIA), thus helps to evaluate, prevent and alleviate extremely adverse environmental impacts. In this way, it can provide scientific evidence for environmental decision-making, and therefore has been widely applied across the world over the past several decades [1] [2].

Much historical experience suggests that incorrect decision-making will cause adverse, long-term, and even irreversible environmental impacts [3]. For instance, the "Central Asia Planning" developed by the Union of Soviet Socialist Republics has caused serious coastline erosion and frequent "White Strom" disaster around

*Corresponding author.

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Caspian Sea and Karakum Desert since 1954 [3]; In China, irreversible changes and serious sedimentation problems have frequently occurred in the main deep-water lanes of the Yangtze River, the effects of which were amplified by harbor construction and the shipping management measures since 1983 [4]. Therefore, consideration of extremely adverse impacts and developing the relevant ERAs in response to this will help support decision-making and the services derived from it. In that way, the ERA can play a more important role in avoiding and alleviating environmental risks that may derive from the process of decision-making. However, the adoption of ERA, as a formalized analytical process applied to environmental issues, and latterly as a policy tool to assist regulators in decision-making process (DMP), is a relatively recent development, when techniques broadly similar to the ERA of today were used in 1930s to set permissible occupational exposure limits for chemicals in the workplace[2] [5].

In this paper, the research progress of ERA, *i.e.*, development history, types, approaches and methods of ERA and its applications in DMP, are introduced and reviewed.

2. Progress of ERA

2.1. History of ERA

ERA has made great progress, and developed many approaches and methods over the past several decades. Although the formal assessments of environment risks from toxic substances to human health in ambient and occupational settings have been conducted since the 1930s, a systematic and overall quantitative approach to ERA can be traced to the work of US National Research Council (USNRC) in 1983 [6].

The 1980s and 1990s saw great strides in developing and improving tools to apply to risk assessment [7], e.g., this includes low dose extrapolation model, physical and physico-chemical models and statistical models. The advent of computer-assisted modeling and data handling techniques had transformed the conduct of ERA in the1980s and 1990s. As a technique, ERA has developed from human health risk assessment and has been subsequently extended to other environmental problems, including accident risk assessment, natural disaster risk assessment, ecological risk assessment and regional comprehensive risk assessment [5] [8].

With the development of decision analysis techniques, the application of ERA has widened since the late of 1980s to provide scientific evidence for environmental management [2] [5]. For example, risk evaluation based on Risk-Cost-Benefit (RCB) [1] [9] [10], Comparative Risk Assessment (CRA) based on the methods of Multi-Criteria Decision Analysis (MCDA), e.g., Multi-Attribute Utilize Theory (MAUT), Analytic Hierarchy Process (AHP) and Outranking [11]-[14]. In a word, the use of ERA has developed from single types of risk assessment to regional comprehensive risk assessment, and recently in its widest application of supporting environmental DMP [8] [15].

2.2. Types of ERA

Integrating the basic concept of ERA from USEPA [1], the characters of different risk sources, or the different evaluating objects of ERA [16], and the different space scale of ERA [17], the main types of ERA were concluded as follows:

(1) Traditional ERA, including health risk assessment, accident risk assessment, natural disaster risk assessment, and regional comprehensive risk assessment;

(2) ERA for DMP, including all actions of ERAs involved in the process of DMP and supporting the selection and determination of preferred alternatives of DMP.

It is remarkable that the generalized ERA also includes ecological risk assessment, which was derived from initial human health risk assessment, but mainly focuses on the risks to ecosystems, excluding humans. However, this paper mainly discusses the adverse impacts on human health and relevant abiotic environment, in order to reflect the difference between the environmental risk and ecological risk. Thus the review on ecological risk assessment did not be involved in the next contexts, and would be took as another special type of risk assessment to be discussed in other papers.

2.3. Approaches and Methods of ERA

2.3.1. Traditional ERA

A) *Approaches*

(1) Health risk assessment

Health risk assessment is a type of ERA which originated in the USA, and has among all ERA the longest history and widest application around the world. In considering a conceptual framework for the identification and assessment of risks to human health, USNRC [18] created a process comprising the following four stages: hazard identification, exposure assessment, toxicity assessment, and risk characterization. This seminal contribution of USNRC has influenced the conduct of risk assessment world-wide.

USEPA proposed a potential approach (**Figure 1**) in 1992 [19] redrawn from the conceptual framework proposed by USNRC in 1983, which comprised the following three stages: problem formulation, problem analysis including exposure assessment and impacts analysis, and risk characterization and uncertainty identification. This approach has been widely suitable for human health risk assessment (or ecological risk assessment) associated with chemical and toxic substances pollution.

Subsequently, other organizations and countries, Health Council of the Netherland [20], World Health Organization (WHO) [21], and Australian and New Zealand [22], proposed similar approaches on the basis of USEPA scheme.

(2) Accident risk assessment

Accident risk assessment emphasizes the use of relevant mathematic models to calculate the risk (probability) and its corresponding consequence. United Kingdom Department of the Environment (UKDOE) proposed a common framework (**Figure 2**) in 1995 [23], which comprised the following six stages: hazard and consequence identification, probability and consequence estimation, risk estimation and evaluation, risk assessment, the proposal of risk management measures, and risk monitoring.

However, special processes of various accident risk assessment would differ in detail due to their different risk sources. The common approaches of various accident risk assessment were concluded in **Table 1**.

(3) Natural disaster risk assessment

Natural disaster risk assessment is a relatively recent type of ERA, which developed from the late of 1980s and mainly emphasized the analysis of the relationship between vulnerability to disaster and other hazards. The common approach of risk assessment for natural disaster (e.g. flood, seismic, typhoon, avalanche and so on) could be concluded as follows: historical data collection, disaster-inducing factors identification, the probability estimation of each disaster-inducing factor under different risk intensity, the vulnerability analysis of disaster-affected body, corresponding consequence estimation under different risk intensity, and risk evaluation and characterization [32] [33].

(4) Regional comprehensive risk assessment

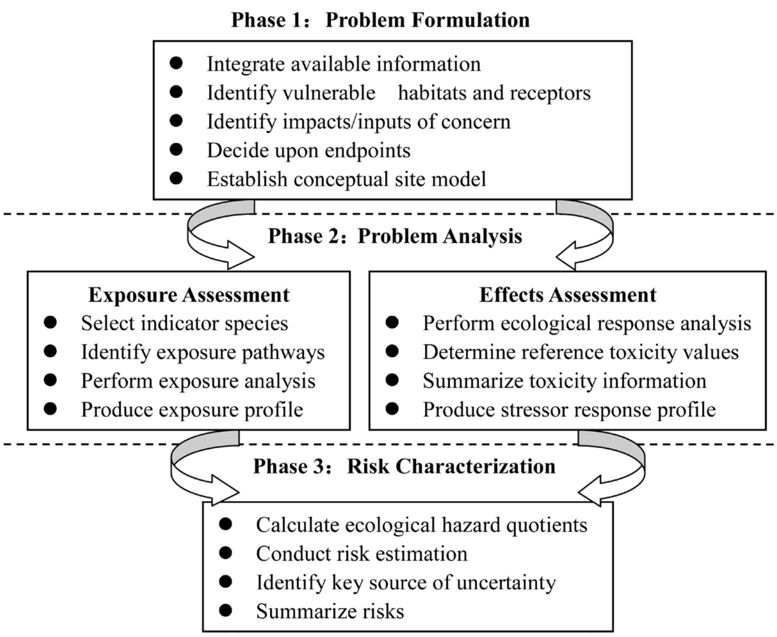

Figure 1. The three phases of healthy risk assessment [19].

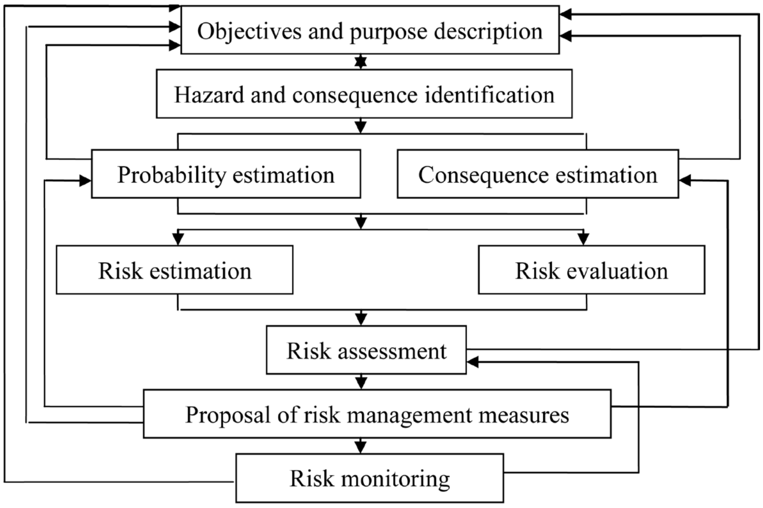

Figure 2. The framework for risk assessment and management of UK [23].

Table 1. The common approaches of various accident risk assessment.

Risk sources	Common approach
Nuclear accidents (The leakage of oil depots and natural gas)	Historical data analysis, risk identification and hazard analysis, probability estimation and impacts prediction, and the proposal of preventive actions and emergency plan [24]-[26]
Chemical and toxic substances (The leakage of chemical and toxic substances)	Pollution scope identification, physical and chemical analysis of sample, main pollutants identification, dose-response assessment, risk evaluation and characterizations [27] [28]
Marine accident and oil spills (Petrochemical industry accidents and other projects accidents on the sea)	Retrospective and status-quo assessment, risk source identification, predicted analysis including the probability and corresponding consequences, and risk evaluation and characterizations [29]-[31]

Because the development of regional comprehensive risk assessment started late, there has been relatively little research done in China or elsewhere. Regional comprehensive risk assessment emphasized the integration and ranking of different types of risks in each research region, and Yang and Xie [34] described its common approach (**Figure 3**) as follows: historical data collection, regional risk sources identification, probability estimation of signal risk type, impact estimation of signal risk type, risk assessment to single risk type, comprehensive assessment to types of regional risks and regional management and zoning. Similar approaches included other representative processes proposed by Calamari and Zhang [35], Xu and Liu [36] and others.

B) *Methods*

Some methods commonly used in traditional ERA are summarized as follows.

(1) Expert judgment

Expert judgment is a qualitative or semi-quantitative method, which has been used to develop risk identification, risk analysis and risk characterization through collecting experts' opinions, or their scores in situations where data are lacking. For example, expert judgment has been used to deal with the issue of inadequate data in the risk source identification of human health and contaminated environmental media [2] [14] [37]. USNRC [31] identified the risk causes of oil spills from vessels around Aleutian Islands by collecting historical information and experts' opinions. Moreover, expert judgment has also been applied to qualitatively evaluate the hazard indexes of natural disasters (e.g. seismic, typhoon) and the vulnerability indexes of any disaster-affected body when there is a lack of abundant data to estimate them [38].

(2) Retrospective and status-quo assessment

Retrospective and status-quo assessment includes some traditional methods e.g., *in-situ* investigation, statistical analysis and analogy analysis, which has been applied to identify and analyze risk source and their historical probability and impacts. These have also provided evidence for the prediction of risk trend (prediction im-

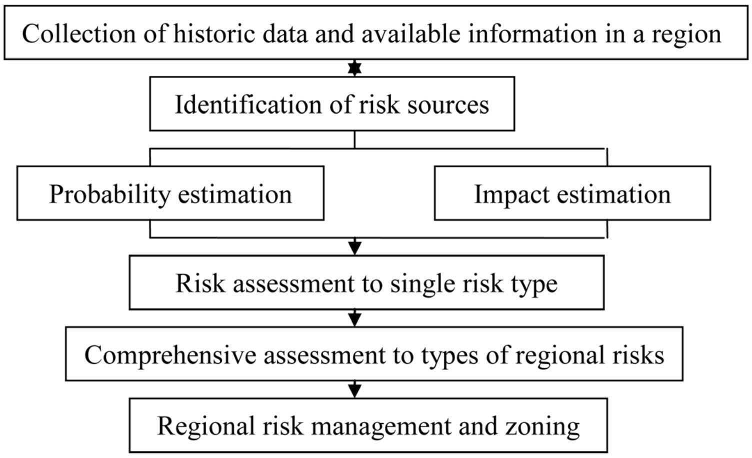

Figure 3. The framework for regional comprehensive environmental risk assessment [34].

plies the future) by collecting and analyzing historical information. For example, Van Drop *et* al. [39] and Merrick *et al.* [40] used retrospective and status-quo assessment to identify the possible causes of vessel accidents and estimate the probability of each cause by collecting and analyzing relevant historical data in San Francisco Bay and Washington State, respectively. Zhang *et al.* [41] collected historical data and used retrospective and status-quo assessment to analyze and conclude the cause and the average loss from typhoons in the southeast coastal area of China.

(3) Scenario analysis

Scenario analysis has been used to qualitatively or quantitatively identify and predict the potential risks including their risk probability and corresponding consequences when there is a change in their risk causes (factors). For example, Kepner *et al.* [42] used scenario analysis to define future scenarios in the form of land-use/land-cover grids, and examine their environmental impacts including relevant risks on surface-water conditions in San Pedro River, Mexico. Duinker and Greig [43] reviewed the development of scenario analysis, and discussed how to use scenario analysis to predict the risk impacts under the situation of climate change. USNRC [31] used scenario analysis to predict and analyze different risk sources of oil spills from vessels and the impacts of different oil spills under different types of vessels.

(4) Fault-event tree

Fault-event tree was mainly applied in accident risk assessment to identify and analyze risk causes, as well as estimate the probability and corresponding consequence of each risk through logistic inference. For example, IMO [10] described the event tree model of oil spills from vessels, and used this method to identify and conclude the main causes of oil spills from vessels. Zhao *et al.* [44] used fault tree analysis to find the key factors that would cause the leakage from an oil depot and propose some prevention measures. Zhang *et al.* [45] conducted the fault tree analysis model to analyze risk causes of oil spills from vessels, estimate the probability of each risk cause, and then summarized them to attain the total probability of oil spills from vessels.

(5) Mathematic models

Mathematic models have been widely applied to predict risk probability and analyze uncertainty and variability of relevant model permeates.

For health risk assessment, dose-response and exposure model, e.g. passion model, logistic model, low dose extrapolation model, time series, multiple regression model and so on, have been applied to estimate the hazard indexes of toxic and carcinogenic substances caused by contaminated water and other environmental medium. They have also been used to reflect relationships between the exposure probability and risks for both chronic and acute exposure [46]. Monte Carlo Simulation and Bayesian models have been used in dealing with uncertainty and variability problems involved in the parameters selection in different dose-response and exposure models [2] [48].

For accident risk assessment, the probability statistic model [48] has been applied to estimate directly risk probability by combining historic data with analogy analysis. Yan and Ma [49] used the fuzzy mathematic model to conduct multi-criteria system in risk assessment of oil spills from vessels, and applied subordinating degree function and expert judgment to estimate corresponding weights of each risk cause of oil spills.

For natural disaster risk assessment, some mathematic models such as "disaster loss-exceeding probability curve" [50], "entropy weigh method" [51], have been used semi-quantitatively to estimate the various hazard and vulnerability indexes of disasters, and describe relationships between hazard of disaster-inducing factors and a disaster-affected body.

(6) Risk matrix model

Risk matrix model is a popular format for presenting the qualitative or semi-quantitative risk analysis with columns corresponding to various levels of consequence and rows to different levels of likelihood. It has been used to characterize the risk levels of project accidents, natural disaster, and maritime accidents by combining with expert judgment, public involvements, and its relevant judgment criteria of risk frequency/probability and its corresponding consequences. For example, Lin [52] used a risk matrix model to semi-quantitatively evaluate and characterize the risk level of typhoons in Xiamen Bay. USNRC [31] introduced the basic model of risk matrix, and used it to characterize risk level of maritime accidents around Aleutian Island; Sun *et al.* [53] estimated the sensitive indexes and risk probability of oil spills, and then used risk matrix model to characterize regional risk level of oil spills in Bohai Bay.

(7) Comprehensive risk index method

Comprehensive risk index is a method that estimates regional comprehensive risk index (value) by distributing the weight for each risk factor and estimating their weighted mean on the basis of using the normalization method and expert judgment. Comprehensive risk index method combined with GIS has been widely applied to semi-quantitatively estimate the natural disaster indexes including hazard indexes, vulnerability indexes, defense capacity indexes and so on, to evaluate the integral risk level of natural disaster and develop relevant regional zoning of natural disaster [39] [54]. Moreover, Comprehensive risk index method has also been combined with Analytic Hierarchy Process (AHP) and expert judgment to qualitatively, or semi-quantitatively estimate signal type of risk index, or regional comprehensive risk index when there is lack of data to be quantified in a given research area [34] [54] [55].

(8) Fuzzy comprehensive assessment method

Fuzzy comprehensive assessment method has been applied to evaluate and characterize regional comprehensive risk level. This method is derived from the fuzzy mathematic model, the objectives of which are to integrate and consider all risk sources in a given research region. It is used to set up a set of factors, distribute the corresponding weights for risk factors to conduct a set of judgment, and then characterize the level of each risk factors and regional comprehensive risk, through establishing the subordinating degree function and estimating the weighted average. For example, Xue *et al*. [56] used fuzzy comprehensive risk assessment method to establish a model of regional comprehensive risk in the Tarim Basin, China. Sun *et al.* [51] used fuzzy comprehensive assessment method to identify the potential risk resources of oil spills, estimate the comprehensive risk value of oil spills in Bohai Bay, and identify which harbor has the highest risk value.

(9) Regional risk zoning model

The German Advisory Council on Global Change [58] firstly proposed "Regional risk zoning model" in 2000, which constituted the relevant grading criteria to divide regional risk into three grades including normal area, transitional area and prohibited area. However, this method has not been widely applied to characterize the regional comprehensive risk due to there being many criteria that are hard to quantify and judge in this model.

2.3.2. ERA for Decision-Making Process

A) *Approaches*

The procedure of ERA serviced for DMP could be divided into two different approaches by using two types of decision-making tools.

(1) The approaches of risk evaluation based on RCB

First is the approach put forward by US Presidential/Congressional Commission on Risk Assessment and Risk Management (PCCRARM) [9], which can be considered in six main steps: problem/objectives definitions; risk assessment; options formulations; decision-making according to the result of risk assessment (selection and determination of the managerial options); take actions; monitoring, evaluation and feedback. Moreover, this approach emphasized that stakeholder involvement should be integrated in to the overall DMP. Other representative approaches similar to this approach, included that proposed by USEPA [1], International Maritime Organization (IMO) [10], Ricci [46] and others. These approaches of risk evaluation based on RCB commonly emphasize using a quantitative economical method "Benefit-Cost Analysis" (BCA) as the main technical tool to support the selection and determination of any preferred managerial option which has the highest benefit and the lowest cost from risk perspective.

(2) The approaches of CRA based on the methods of MCDA

CRA has been most commonly applied in the area of environmental policy analysis [12] [58] [59]. Central to CRA is the construction of a two-dimensional decision matrix that contains project alternatives scores on various criteria [12]. A CRA is generally comprised of three components [58]: 1) problem list—determination of the set of environmental problems areas to be analyzed and compared; 2) criteria for evaluating problem—a set of analytical criteria to define what the participant thinks is important to measure, such as pollution level or other risks to human health, ecosystem, or quality of life; 3) ranking—a process that participants use to sort out data and draw conclusions about the relative severity of the problems or their sub-components.

Although CRA lacks a structured method to identify an optimal project alternative, the MCDA methods do provide a systematic and complementary way for CRA to integrate risk levels, uncertainty and valuation [12]. Thus, CRA based on the methods of MCDA, has been a prevailing methodology for environmental decision-making [8] [12]. Linkov and Ramadan [59] proposed this approach in the following **Figure 4**. This approach emphasized on that the DMP process not only includes the integration of models and techniques of environmental (risk) assessment and decision analysis, but also includes the interaction among policy makers, scientists and stakeholders.

Similar approaches included other representative processes proposed by Khadam and Kaluarachchi [11], Linkov *et al.* [12], USACE [13], Topuz [14], Department of Energy (DOE) [60]. These approaches consider multiple criteria including economical, ecological, environmental, social and other factors in decision-making options and comparing risk related with different options based on MCDA methods, *i.e.*, MAUT, AHP and Outranking, to determine the optimal managerial option from risk perspective.

B) *Methods*

Some methods commonly used in ERA for DMP are summarized as follows.

(1) Benefit-Cost Analysis

BCA is a central method to RCB, which has been used to help formulate risk management policies and priorities and identify risk management goals that maximize net benefits across various levels of protection. For example, Power and McCarty [61] applied BCA to analyze the differences between various managerial options of risk reduction. Finney [62] used BCA to monetize the impacts of natural disaster on infrastructure and ecological value, and guide the risk planning and management. Ricci [46] used a dose-response and exposure model to evaluate the human health risk of carcinogens, and applied BCA to select the optimal managerial option for preventing the adverse impacts of carcinogens.

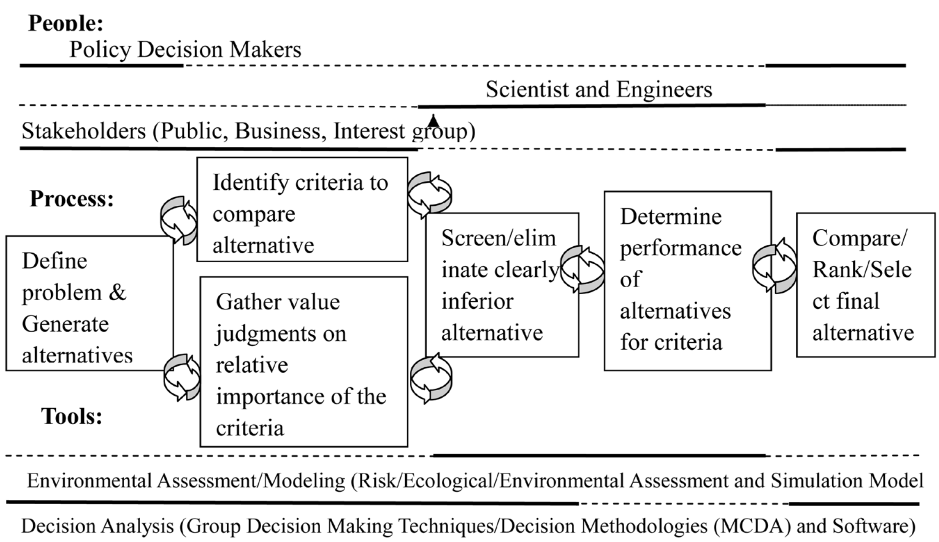

Figure 4. A potential approach for DMP based on CRA and MCDA [59].

(2) Decision-tree analysis

Decision-tree analysis has been used to predictably describe various potential environmental risks caused by different alternatives of decision-making, and estimate and compare their expected risk value to select the preferred alternative of decision-making from an environmental risk perspective. For example, Ricci [46] applied decision-tree analysis and RCB to select the optimal managerial option for preventing exposure to toxic substances from a human health risk perspective. Linkov and Kiker [63] used decision-tree analysis to assess multi-criteria risk (e.g. economic risk, environmental and ecological risk, and social risk) in an artificial marine ecosystem.

(3) MCDA methods

The MCDA includes methods of MAUT, AHP and Outranking.

1) MAUT

MAUT is a method to express overall performance of an alternative in a single, non-monetary number representing the utility of that alternative, which relies on the assumptions that the decision-maker is rational [12]. MAUT, for example, has been used in risk management of a radioactive site [64] and has also been utilized in the superfund cleanup process [65]. Wakeman [66] used the simple MAUT rating technique to analyze alternatives for degrading contaminated site in Montana. MAUT-based methods have also been applied to compare current and alternative water control plans in the Missouri River from a risk perspective [67].

2) AHP

The goal of AHP is to select the alternative that results in the greatest value of the objective function [59]. In AHP model, criteria weights and scores are based on pair-wise comparisons of criteria and alternatives, respectively [12]. For example, Apostolakis and his colleagues [68] developed AHP combined with risk assessment techniques to integrate the results of advanced impact evaluation techniques with stakeholder preferences. Sorvari and Seppälä [37] used AHP to identify the risk sources in a contaminated site and weight them by expert judgment to provide evidences for selecting the optimal managerial options. Chen *et al.* [69] use a redrawn AHP model—ANP model to identify the optimal allocation of an airport from the perspective of natural, social and building risk.

3) Outranking

Outranking is based on the principle that one alternative may have a degree of dominance over another [59]. Dominance occurs when one option performs better than another on at least one criterion, and no worse than other criteria [59]. For example, Ganoulis [70] used outranking to determine the optimal options of waste water recycling and risk management in the Mediterranean. Klauer *et al*. [71] applied outranking based on GIS to identify the risk source for the Rhine River and select optimal options for risk management.

2.4. Summary

The nature of ERA has been increasing mature developing and has formed a relatively integrated methodology since the 1930s. It has developed from single type of risk assessment, *i.e.*, health risk assessment, accident risk assessment, and natural disaster risk assessment, to a more regional comprehensive risk type of assessment. More recently, there has been a development of relevant ERAs to avoid and alleviate environmental risks derived from DMP, and support the selection of preferred alternatives. It has been a hot issue of ERA research internationally since the late of 1980s.

The approaches to ERA can vary in detail depending on their different evaluation objectives and space scales. The approaches of ERA processes for traditional ERAs (*i.e.*, health risk assessment, accidents risk assessment, natural disaster risk assessment and regional comprehensive risk assessments) and ERA for DMP (*i.e.*, risk evaluation based on RCB and CRA based on the methods of MCDA) were summarized in **Table 2**. The traditional ERA can be summarized by four steps. The processes of using ERA for decision-making are, however, relatively complicated because the emphasis is on combining the results of traditional ERA with decision analysis tools to provide scientific evidence for environmental management, which can be summarized in five steps (**Table 2**).

Different types of ERA have applied different methods. Most of the methods are summarized in **Table 3**. However, some methods could be used in several different types of ERA. For example, retrospective and status-quo assessment could be used in accident risk assessment, natural disaster risk assessment and regional comprehensive risk assessment. Expert judgment can be applied in any type of ERA when there is lack of data to develop sufficient quantitative information.

Table 2. Summarizations of ERA approaches.

Various types of ERAs		Elements of ERAs process	Summarization
Traditional ERAs	Health risk assessment	Analyzing the relationships between the dose of hazardous/toxic substance and the response of human health	Despite these variations, all types of traditional ERAs can be summarized by four steps: Hazard identification, risk analysis, risk evaluation/ characteristics, and risk management
	Accidents risk assessment	Using some mathematic models to estimate the risk probability and its corresponding consequence	
	Natural disaster risk assessment	Analyzing the relationship between vulnerability to disaster and other hazards	
	Regional comprehensive risk assessments	Integrating and ranking of different types of environmental risks in a given research region	
ERA for DMP	Risk evaluation based on RCB	Using a quantitative economical method "BCA" as the main technical tool to support the selection and determination of any preferred managerial option from risk perspective.	Despite the decision-making tool are different, these processes can be summarized in five steps: Problem identification, alternatives formulation, decision-making criteria and tool selection, alternatives evaluation and ranking, and preferred alternative selection.
	CRA based on the methods of MCDA	Considering multiple criteria including economical, ecological, environmental, social and other factors in decision-making options and comparing risk related with different options based on MCDA methods to determine the optimal managerial option from risk perspective.	

Table 3. The main methods for different types of ERA.

The type of ERA	Main Methods
Health risk assessment	Dose-response and exposure model (e.g. passion model, logistic model, time series, multi-regression model and so on), expert judgment, Monte Carlo Simulation, and Bayesian model
Accident risk assessment	Retrospective and status-quo assessment, scenario analysis, expert judgment, fault-event tree, probability statistic model, fuzzy mathematic model, and risk matrix model
Natural disaster risk assessment	Retrospective and status-quo assessment, disaster loss-exceeding probability curve", "entropy weigh" method, expert judgment, comprehensive risk index method, and risk matrix model
Regional comprehensive risk assessment	Except for methods for above three types of ERA, comprehensive risk index method, fuzzy comprehensive assessment method, expert judgment and regional risk zoning model were also commonly used
ERA for decision-making processes	BCA, Decision-tree analysis, MCDA including MAUT, AHP, and Outranking

3. Discussion/Conclusion

3.1. Problems in ERAs

Although the form and application of ERA has made great progress and there have been many new approaches and methods developed over past decades, some problems still exist in the current development of ERA. The main problems are as follows:

(1) Most applications of traditional ERA focused on project level. For example, all health risk assessments focused on the leakage of hazardous or toxic substances, and maritime accidents. Some applications of ERA focused on natural disaster risk assessment and regional comprehensive risk assessment. Although traditional ERA is an important support tool to provide scientific evidence for risk management, it only focuses on providing some technical procedure and corresponding methods for risk analysis and evaluation which are difficult to closely connect with DMP, and directly support and impact DMP and their final results [15].

(2) Many techniques of decision analysis (e.g. BCA, Decision-tree analysis, MCDA) have been developed for integrating the results of ERA into DMP to support the selection of optimal options for environmental management. However, most of present researches still focused on sectoral (managerial) DMP. There is no systematic research and interrelated application in China or internationally on the approaches and methods of ERA in strategic decision-making (SDM) processes.

(3) SDM can be viewed as a special kind of decision-making under "Long-term, Regionality, Integrality and Uncertainty" [72], and is much higher than a project or sectoral (managerial) decision-making that is located at the end of SDM process [73]. Therefore, all ERAs for project or sectoral decision-making are passive-active processes [8]. The predictability of adverse environmental consequences generally becomes weaker at strategic levels, than at the project or sectoral decision-making level, and complexity increases in terms of the numbers of actors involved in the decision [74]. Thus, most of approaches and methods of current ERAs could not avoid the environmental risk from the source of SDM processes and were unable to greatly impact the initial strategic arrangement and adequately predict the cumulative risk impacts of SDM.

3.2. Prospect

At present, it is accepted that the mistakes and environmental risk introduced by SDM process may lead to more significant and irreversible losses to society and the ecological environment than project or sectoral DMP. It is necessary to develop relevant approach and methodologies of ERAs for SDM to avoid the mistakes in SDM process.

Moreover, there is evidence that both pre-structured and pro-active EIA and EIA-based Strategic Environmental Assessment (SEA) are actually effective in improving decision making in terms of a better consideration of the environment consequence [75]. Furthermore, many practices suggest the assessment effect would be better if there was an inclusion of intervention time of SEA into the processes of decision-making at an early stage [76]. Thus, formal ERA (an important component of EIA) needs to be introduced as a pro-active instrument for addressing adverse environmental consequences before practical action of SDM.

From the above, there is an urgent need to propose potential approaches and methodological systems of ERA for SDM processes in order to intervene ERA into the overall process of SDM, and avoid environmental risk from the source of SDM. This is likely to be a future trend in the development and main objectives of ERA, and it should be of great significance for promoting sustainability of natural-social-economic systems.

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