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Application of environmental risk assessment for strategic decision-making in coastal areas: case studies in China

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Environmental risk assessment (ERA) is a powerful technical tool for analyzing potential and extreme adverse environmental impacts, and has found wide application in supporting decision-making processes over the last two decades. However, to date there has been no interrelated application of ERA to support the processes of strategic decision-making (SDM), especially in coastal areas.

In this paper, we attempt to verify the feasibility of the proposed integrated ERA–SDM approach and its methodology by applying it to two case studies (in Xiamen Bay and Luoyuan Bay) of the principal coastal functional zoning (PCFZ, a kind of SDM and similar to the coastal and marine spatial planning in western). The results show that the integrated ERA–SDM approach could integrate ERA into the entire SDM process, directly support the PCFZ, and avoid or mitigate dire environmental risk that can be introduced by SDM processes.

Keywords: environmental risk assessment; strategic decision-making process; principal coastal functional zoning; Xiamen Bay; Luoyuan Bay; China

1. Introduction

Coastal areas face potential environmental risks attributed to rapid socioeconomic development and global change, increasingly serious resource conflicts, and destruction of coastal ecosystems (Fang *et al*. 2011). Environmental risk assessment (ERA) can provide the scientific basis for informing decision-making processes in coastal areas against global change and ecological vulnerability (USNRC 2007), and thus ensure a more sustainable coastal development.

ERA is a powerful technical tool for analyzing potential and extreme adverse environmental impacts, which is finding ever-wider applications in the arena of decision-making (Eduljee 2000; USNRC 2009). Many techniques of decision analysis (e.g. risk–cost–benefit analysis, risk assessment combined with multi-criteria decision analysis, etc.) have been developed for integrating the results of ERA into decision-making processes in order to support the selection of optimal options (UKDOE 1995; PCCRARM 1997; IMO 2002; USEPA 2003; Linkov *et al*. 2006; USACE 2010; Chen *et al*. 2011). More recently, Retier *et al*. (2013) proposed an integrated framework for informing coastal and marine ecosystem management decisions, and used scenario prediction to meet management goals against management constraints. Their objective

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was to select the "optimal option" for a management action in an adaptive-management process. All of these applications of ERAs to decision-making processes only focus on providing relevant approaches and methods for the decision-making or management processes at the project or sectoral level. This leaves a gap in that there is no interrelated systematic research and application of ERA to support the processes of strategic decision-making (SDM) (Wu and Zhang 2014).

SDM can be viewed as a special kind of decision-making under regionality, integrality, and uncertainty, and has a much higher level than the project or sectoral decision-making (Schwenk 1984; Yin 2010). SDM involves activities of goal formulation, problem identification, alternatives generation, alternatives evaluation/selection, and management and actions (Schwenk 1984, 1995; Yin 2010). However, the SDM process may lead to more significant and irreversible losses to society and the environment than project or sectoral decision-making processes (Wu and Zhang 2014). Thus, it is necessary to develop relevant ERAs for SDM to ensure that potential environmental risk from the SDM process is avoided or properly mitigated (Wu and Zhang 2014).

As a kind of SDM, marine spatial planning has been actively promoted in many countries (e.g. Europe, North America, and Australia) in recent years as an essential tool for ecosystem-based management to resolve various coastal conflicts (Douvere 2008; Fang *et al*. 2011). Only recently, marine function zoning and principal coastal functional Zoning (PCFZ) in China have been characterized as the practices of marine spatial planning (Douvere 2008; Fang *et al*. 2011). However, prior to our study, there have been no published applications of ERA in marine spatial planning, marine function zoning, or PCFZ (Wu, Zhang, and Fang 2014), except very recent work by Stelzenmüller *et al*. (2015).

The objectives of the project "Approach, methods and pilot project of PCFZ" were to establish the approach and methodology of SDM to support PCFZ (Mu 2013). In this, a new multi-dimensional decision-making (MDDM) approach was developed to apply to non-structured regional- and integrated SDM processes for decision analysis. It required the researchers to (1) identify all dimensions related with SDM, (2) collect all available information for all dimensions, and (3) obtain the final results of all dimensions by using the traditional assessment and an expert judgment. Thus, this approach uses the MDDM model and the expert judgment to support decision-making processes, and thereby helps us define the impacts and relationships between environmental dimensions and the alternatives of SDM (Zhang, Mu, and Zhang 2014). The seven dimensions: society, economics, location, resources, environment, ecosystem, and risk, were determined as environmental dimensions, and take environmental risk as an important dimension of SDM to support the PCFZ process (Mu 2013). The purpose of this study is to apply the proposed integrated ERA−SDM approach and its methodology to the two case studies of PCFZ in Xiamen Bay and Luoyuan Bay, China, and verify its feasibility.

2. Material and methods

2.1. Approach and methods of ERA for SDM in coastal areas

2.1.1. Approach

According to the process of SDM (Schwenk 1984, 1995), an integrated ERA−SDM approach (Figure 1) was proposed in the project of PCFZ (Wu, Zhang, and Fang 2014). This approach integrated ERA into three main SDM activities: the ERA procedure

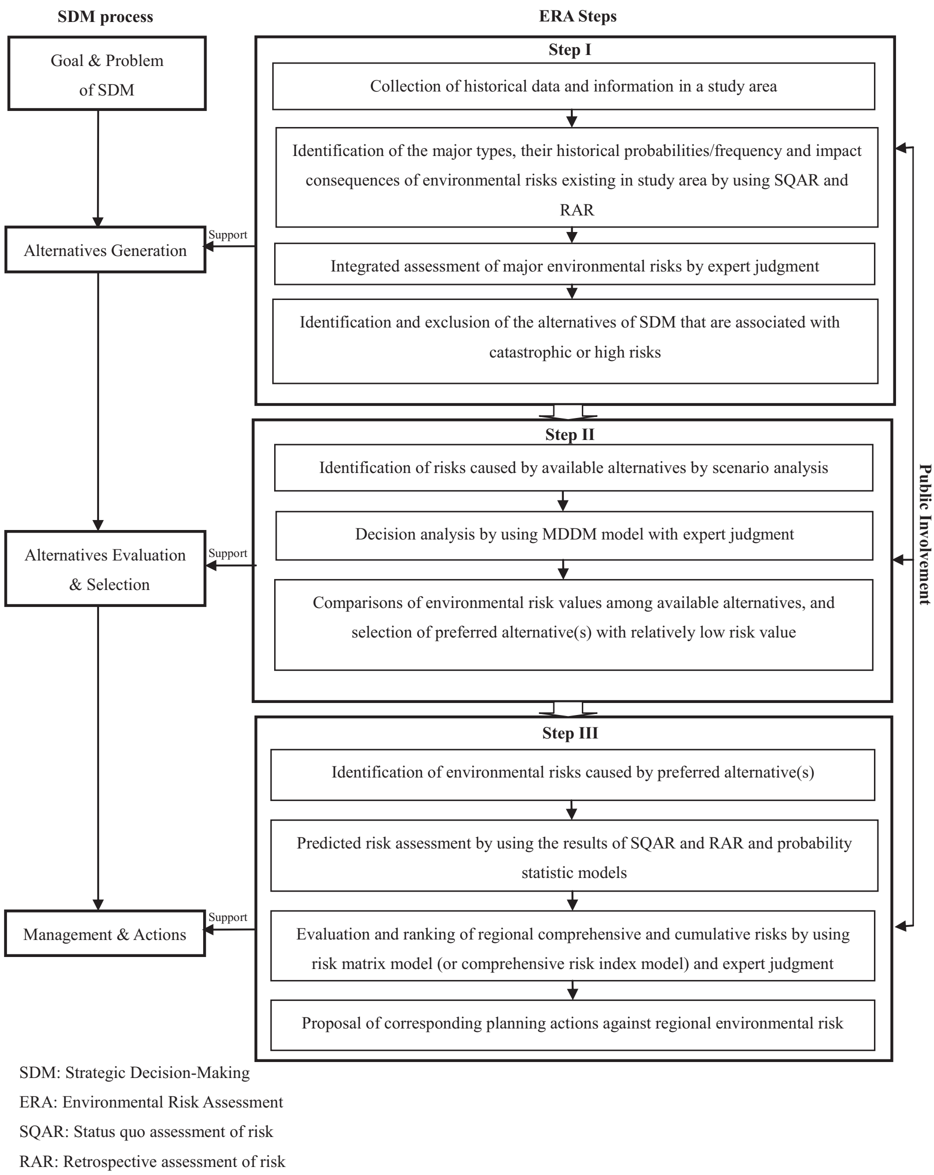

Figure 1. An integrated ERA–SDM approach.

supported the process of (1) alternative generation; (2) alternative evaluation/selection; and (3) management and actions after the goal formulation and problem identification of SDM were identified (Wu, Zhang, and Fang 2014).

2.1.1.1. Step 1. ERA in Step 1 is to support the generation of available alternatives from an environmental risk perspective. The objective is to select available alternatives of SDM to avoid faults in the beginning of the SDM process. It includes (1) collecting all available historical data and information related to ERA; (2) conducting status quo assessment of risk (SQAR) (Li *et al.* 2005) and retrospective assessment of risk (RAR)

(Bejarano, Levine, and Mearns 2013) to identify the major types, historical frequency, and impact consequences of environmental accidents that existed in the study area; (3) using the expert judgment (Leung and Verga 2007) to assess every hierarchy and final level of major environmental risks according to the results of SQAR and RAR; and (4) identifying if there exist catastrophic or high risk(s). The impractical alternatives that are highly associated with catastrophic or high risk would be excluded, and thereby support available alternative generation from an environmental risk perspective.

2.1.1.2. Step 2. The objectives of ERA in Step 2 are to support the evaluation and selection of preferred alternative(s) of SDM. It includes (1) adopting scenario analysis (Duinker and Greig 2007) with experts' experience to identify the specific types of environmental risk from each available alternative; (2) using the MDDM model (Zhang, Mu, and Zhang 2014) by the expert judgment to define the impacts and relationships between the environmental risk dimension and each available alternative of SDM; and (3) comparing environmental risk values, and selecting preferred alternative(s), which have a relatively low value of environmental risk.

2.1.1.3. Step 3. The objectives of ERA in Step 3 are to predict, assess, and rank the regional environmental risks caused by preferred alternative(s), and to assist the formulation of regional environmental risk-based planning for management and actions. It includes (1) identifying specific types of environmental risks if preferred alternative(s) of SDM are implemented in the future; (2) adopting an extrapolation model (Armstrong 2001; Forbes *et al.* 2011) or probability statistics models (Schulze 1983; Yapa, Shen, and Angammana 1994; Jin 2006; Gong 2006; Meel *et al.* 2007; Liu *et al.* 2008; Tan 2008) based on the results of SQAR and RAR to predict the probabilities/frequency of regional environmental risks from preferred alternative(s); (3) using risk matrix model (Paul, Garvey, and Lansdowne 1998; Zhu, Kuang, and Shen 2003; USNRC 2008) or comprehensive risk index model (Das, Gupta, and Mazumder 2012; Wang *et al.* 2014) combining the expert judgment and public involvements to evaluate and rank regional comprehensive and cumulative risks; and (4) proposing corresponding planning actions against regional environmental risks in SDM level.

2.1.2. Methods

2.1.2.1. An integrated ERA–SDM methodology (Wu, Zhang, and Fang 2014). Based on the integrated ERA–SDM approach, SQAR (Li *et al.* 2005) and RAR (Bejarano, Levine, and Mearns 2013) are usually used to identify the major types, historical frequency, and impact consequences of environmental accidents that have been observed in the study area. It can include for example, *in situ* investigation, statistical analysis, spatial and temporal trend analysis, impact assessment, and analogy analysis, etc. The results obtained by these methods can be used as the basis for the prediction of environmental risk. SQAR and RAR could be effective to minimize the data uncertainty for risks.

Expert judgment (Leung and Verga 2007) is used to assess those issues that are hard to quantify, such as the integrated assessment of every hierarchy, the final results of environmental risk dimension, and the MDDM model for a decision-making process to minimize the data uncertainty and the model uncertainty.

Scenario analysis (Duinker and Greig 2007) is used to identify the specific types of environmental risk from each available alternative based on the results of SQAR and RAR.

The extrapolation model (Armstrong 2001; Forbes *et al.* 2011) and probability statistic models (Schulze 1983; Yapa, Shen, and Angammana 1994; Jin 2006; Gong 2006; Meel *et al.* 2007; Liu *et al.* 2008; Tan 2008) are very popular methods in any ERA process that aims to predict the probabilities/frequency of regional environmental risks.

The comprehensive risk index model (Das, Gupta, and Mazumder 2012; Wang *et al.* 2014) is used as an alternative method to deal with qualitative or semi-quantitative data and to calculate a relative and comprehensive risk value (index) by using the normalization method, the expert judgment, the AHP model, and weighted means.

The risk matrix model (USNRC 2008; Wu, Zhang, and Fang 2014) is used to characterize and rank the regional risk levels based on the relevant judgment criteria of frequency (F) and consequences (C) of incidents (Paul, Garvey, and Lansdowne 1998; Zhu, Kuang, and Shen 2003), the expert judgment, and public involvements (USNRC 2008).

2.1.2.2. MDDM model ([I, C; R] model) (Zhang, Mu, and Zhang 2014). The core model of the MDDM approach is the [I, C; R] model for decision analysis. The terms of I, C, and R in the model represent impact, confidence, and relationship, respectively. This model is used to judge the impacts and relationships between every environmental dimension and each alternative of SDM. In this approach, the [I, C; R] model and the expert judgment is used to support the evaluation/selection of preferred alternative(s) from an environmental risk perspective as a dimension of MDDM. The values of I, C, R can be judged by experts based on the assessment results of the environmental risk dimension.

The formula of [I, C; R] model is as follows (Wu, Zhang, and Fang 2014):

$$S_1 = \frac{\sum_{k=1}^{n} I_{1k} \times C_{1k} \times R_{1k}}{n} \quad (k = 1 \ldots n) \tag{1}$$

$$S_2 = \frac{\sum_{k=1}^{n} I_{2k} \times C_{2k} \times R_{2k}}{n} \quad (k = 1 \ldots n) \tag{2}$$

$$S_3 = S_1 + S_2 , \tag{3}$$

where k is the expert and n is the total number of experts.

I (impact) is the mutual impact between the environmental risk and alternatives. I_1 is the impact of current environmental risks on alternative, and I_2 is the impact of alternatives on the environmental risk dimension in the future after preferred alternative (s) are implemented to consider the negative feedback of any final decision. The values of I can be -3, -2, -1, 0, 1, 2, and 3. The positive numbers represent a positive effect, and the negative numbers represent an adverse effect. The numbers 3, 2, 1, and 0 are high, medium, low, and no impact, respectively.

C (confidence) is a subjective probability of I provided by experts to verify their level of uncertainty, on a numerical scale of (0, 1]. C_1 and C_2 represent the confidence for the score of I_1 and I_2, respectively.

R (relationship) is the strength of relationships between alternatives and environmental risk with the possible values {0, 1, 2, or 3}, which represents either no relationship, weak, medium, or strong relationships, respectively. Similarly, R_1 represents the relationship of current environmental risks with alternatives, and R_2 represents the impact of alternatives on the environmental risk dimension after preferred alternative(s) are implemented.

S_1 and S_2 are the summation of the judgment values by all experts of the impacts and relationships between alternatives and the environmental risk dimension in the present and the future, respectively; S_3 is the integrated risk value for decision-making of each alternative. The alternative(s) with relatively low value(s) would be preferred from an environmental risk perspective.

2.2. Study areas

Two coastal areas, Xiamen Bay and Luoyuan Bay, were chosen as case study areas to verify the feasibility of SDM processes because of their large differences in natural situations and socio-economic conditions.

Xiamen Bay (Figure 2), located in the southeast of Fujian Province, China, is semi-enclosed with seven coastal sub-units: Jiulong River Estuary, Western Seas, Southern Seas, Eastern Seas, Tongan Bay, Dadeng Seas, and Weitou Bay. The total coastal area of Xiamen Bay is 6108 km^2, including the land cover of 5623 km^2, and sea area of 485 km^2 (Mu 2013). In 2012, the region had a total population of 4.8 million, and generated a gross domestic production (GDP) of RMB 254 billion (XMNSB 2012), or about \$US42 billion. The coastal area of Xiamen Bay is a very complex natural region with smaller bays, channels and an estuary, and with a high population and a high degree of development.

Luoyuan Bay (Figure 3), located in the northeast of Fujian Province, China, is also semi-enclosed, and is comprised of Luoyuan County in the north and Lianjiang County in

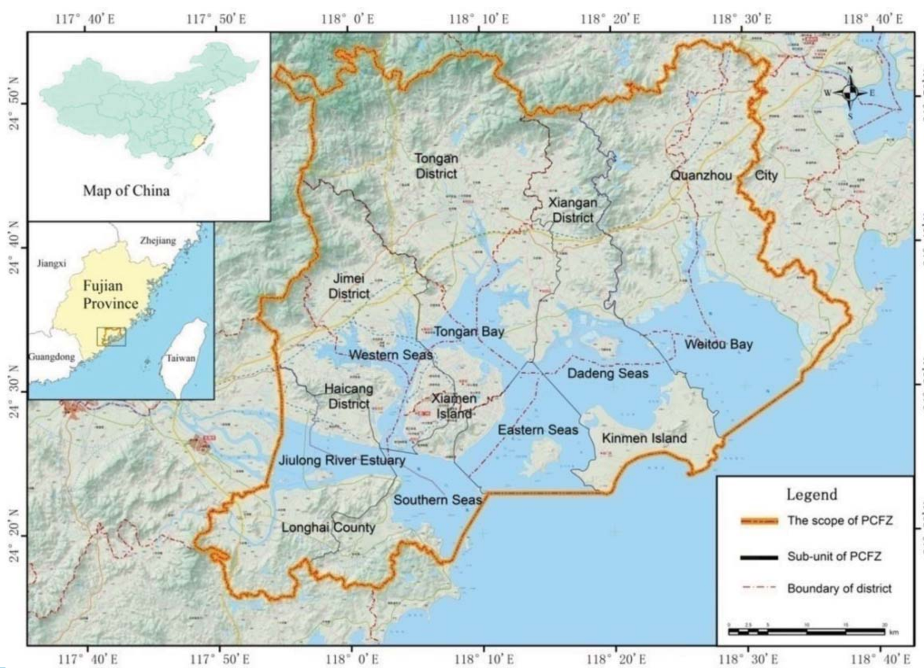

Figure 2. Map of Xiamen Bay for PCFZ. See online colour version for full interpretation.

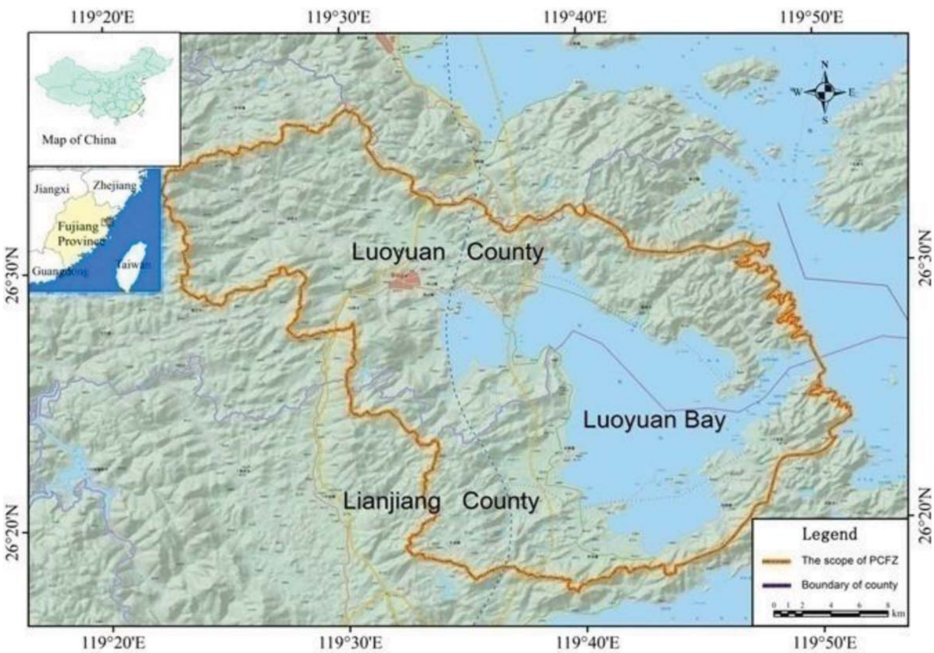

Figure 3. Map of Luoyuan Bay for PCFZ. See online colour version for full interpretation.

the south. The total coastal area of Luoyuan Bay is 1427 km^2, including land cover of 1187 km^2, and sea area of 240 km^2 (Mu 2013). In 2012, the region had a total population of only 386,000 and generated a GDP of RMB 10 billion (LYNSB 2012), or about $US1.7 billion. The coastal area of Luoyuan Bay in comparison with Xiamen Bay is very simple, has low population and is relatively undeveloped.

2.3. Data collection

This study draws on more than 10 years of collected historical data and information related to environmental risks, including accident and natural disaster, in the coastal area of Xiamen Bay and Luoyuan Bay. These data include (1) typhoons and storm tides (PRCSOA 2010; CNMA 2010; FJPDOF 2010), e.g., frequency of typhoon, typhoon damage extent, inundated areas, coastal erosion, and shipping channel sedimentation; (2) maritime traffic accidents (XMUCOMI and IESF 2007; FZMSA 2010; XMNMSA 2010), e.g., frequency of vessel accident and oil spills, the total numbers of vessels, the total numbers of oil tankers, cargo capacity of the harbor, and oil spill volumes; (3) harbor and coastal industrial accidents and other environmental accidents (Gong 2006; Zhang *et al.* 2009); and (4) losses from natural disasters and accidents; related economic, social, and environmental planning (XMUCEE and XMUCOMI 2012).

In addition, other relevant data were used, such as the projected values for cargo capacity, total numbers of vessel, the maritime tourism revenue, shipping industry revenue, aquaculture areas and production, and marine fishery revenue (FJCD 2009; XMUCOMI and IESF 2007; XMNPA 2012; XMNTB 2012; Hong 2008; Zhang *et al.* 2009).

3. Case application and results

The proposed approach and methodology of integrated ERA−SDM was applied to the two case studies of PCFZ in Xiamen Bay and Luoyuan Bay.

3.1. Case 1: Xiamen Bay

3.1.1. Assessment and results of Step 1

Based on the evaluation of natural resources in Xiamen Bay, three potential alternatives of PCFZ, i.e., tourism, shipping and aquaculture/fishery, had been proposed (Mu 2013).

3.1.1.1. Status quo assessment of risk and retrospective assessment of risk. After all available historical data and information related to ERA in Xiamen Bay were collected; SQAR and RAR were conducted in Step 1. The results showed (1) there were two broad groupings of risk: the natural disaster type (typhoon) and the accidental type, including oil spills from vessels and oil jetties (oil jetties are all located in Western Seas). Other types of risk were very low and thus could be ignored in Xiamen Bay; (2) the average annual cumulative frequency of typhoon was 5 times per year in the last 15 years, with an average loss each time of 6×10^{8} RMB; (3) the vessels types in Xiamen Bay included tanker vessels, containerships, cargo ships, and yachts/cruise ships. The cargo capacity in 2010 was 8.8×10^{7} tons with 250,000 vessels per year in-and-out Xiamen Bay. The average annual cumulative frequency of oil spills from these vessels was 0.55 accidents per year in the last 15 years, with an average loss of 7.3×10^{6} RMB per spill; (4) the average annual cumulative frequency of oil spills from oil jetties was 1.8 accidents per year in the last 15 years, with an average loss of 4.4×10^{5} RMB per spill; and (5) the analysis of historical data (XMNMSA 2010) showed the average annual cumulative frequency of oil spills from vessels was expected to increase linearly with the rise in total numbers of vessels and the development of the shipping industry in Xiamen Bay. However, there will be no expected change in the frequency of oil spills from oil jetties because there was no planned oil jetty development (XMNPA 2012).

3.1.1.2. Integrated assessment of major environmental risks by expert judgment. Based on the results of SQAR and RAR, the expert judgment was chosen to assess every hierarchy and final level of major environmental risks. Seven experts who were familiar with Xiamen Bay were invited to mark risk level, and identify whether there was a catastrophic or high risk in Xiamen Bay. The integrated assessment results (Table 1) showed that the main environmental risks were from typhoons (moderate risk, 2), oil spills from vessels (moderate risk, 2), and oil spills from oil jetties (low risk, 1).

Table 1. Environmental risk level in Xiamen Bay as judged by experts.

Experts' number		1	2	3	4	5	6	7	Average value
Natural disaster risk	Typhoons	2	2	2	2	2	3	2	2
Accident risk	Oil spills from vessels	2	2	2	2	2	2	2	2
	Oil spills from oil jetties	1	1	1	1	1	2	1	1

Note: Number 1, 2, and 3 represent respective level of environmental risk: low, medium, and high, respectively.

3.1.1.3 Identification of available alternatives of PCFZ. According to the results of integrated assessment, there were no catastrophic or high risks in Xiamen Bay. The alternatives of PCFZ, including tourism, shipping and aquaculture/fishery, were all feasible activities for further consideration from an environmental risk perspective.

The alternatives of PCFZ in the coastal area of Xiamen Bay were ultimately determined as being tourism and shipping, based on (1) the integration of natural resource characteristics in Xiamen Bay; (2) assessment results of seven dimensions, including location, economy, society, resource, environment, ecology, and risk; and (3) the results of public involvement by questionnaire survey (Mu 2013).

3.1.2. Assessment and results of Step 2

3.1.2.1. Scenario analysis. Based on the results of Step 1, scenario analysis was used to qualitatively analyze and describe the future risks caused by each available alternative. The results showed that (1) if Xiamen Bay developed tourism, there would be two main environmental risks: the risk from typhoons on maritime tourism and the oil spills from yachts/cruise ships involved in the tourist development; (2) if Xiamen Bay developed shipping, again there were two probable types of environmental risk: oil spills from increased traffic of containerships, tanker vessels, and cargo ships, and the damage to port from typhoons.

3.1.2.2. [I, C; R] model analysis. The same seven experts were also invited to mark the values of I, C, and R by using the [I, C; R] model of the MDDM approach to make the decision analysis of PCFZ. Based on the equation (1), (2), and (3), the results (Table 2) showed that the final values (S_3) of tourism and shipping from the environmental risk dimension was $-0.7-0.5=-1.2$ and $-0.5-2.7=-3.2$, respectively.

3.1.2.3. Selection of preferred alternative(s). From the integrative risk value of tourism ($S_3=-1.2$) and shipping ($S_3=-3.2$), it could be concluded that Xiamen Bay would experience much less environmental risk by developing tourism than by developing shipping. Thus, the preferred alternative of PCFZ in Xiamen Bay should be tourism from the perspective of the environmental risk dimension.

By integrating these results with other dimensions and public involvement, tourism was found to be the preferred alternative of principal coastal functions in Xiamen Bay, and shipping was a compatible function (Mu 2013).

3.1.3. Assessment and results of Step 3

3.1.3.1. Risk identification. The results of risk identification based on expert judgments showed that there would be four main specific types of environmental risks caused by the principal function, tourism, and compatible function, shipping, in Xiamen Bay. They were (1) the risk to maritime tourism from typhoons, (2) the oil spills from vessels due to the development of tourism and shipping, (3) the oil spills from oil jetties, and (4) the damage to port from typhoons.

3.1.3.2. Predicted risk analysis.

3.1.3.2.1. The risk to maritime tourism or damage to port from typhoons. Based on the results of SQAR and RAR in Step 1, the predicted annual cumulative frequency (F) of typhoon occurrence would be $F=5.8$ times per year, using the probabilistic model of

Table 2. The experts' scores of risk-dimension in Xiamen Bay.

	Risks→alternatives [I_1, C_1; R_1]					Alternatives→risks [I_2,C_2;R_2]				
Alternatives	Experts	I	C	R	I^*C^*R	Experts	I	C	R	$I \times C \times R$
Tourism	Expert 1	−1	0.7	2	−1.4	Expert 1	0	0.6	1	0
	Expert 2	1	0.8	2	1.6	Expert 2	0	0.6	1	0
	Expert 3	−1	0.7	2	−1.4	Expert 3	−1	0.6	1	−0.6
	Expert 4	−1	0.7	2	−1.4	Expert 4	−2	0.6	1	−1.2
	Expert 5	−1	0.7	2	−1.4	Expert 5	−1	0.6	1	−0.6
	Expert 6	1	0.5	1	0.5	Expert 6	0	0.8	0	0
	Expert 7	−2	0.6	1	−1.3	Expert 7	−2	0.6	1	−1.2
	Average value of S_1 (tourism)				**−0.7**	Average value of S_2 (tourism)				**−0.5**
Shipping	Expert 1	−1	0.7	1	−0.7	Expert 1	−2	0.6	2	−2.4
	Expert 2	1	0.7	1	0.7	Expert 2	−1	0.6	1	−0.6
	Expert 3	−2	0.8	1	−1.6	Expert 3	−2	0.6	2	−2.4
	Expert 4	−1	0.6	1	−0.6	Expert 4	−2	0.7	2	−2.8
	Expert 5	−1	0.7	1	−0.7	Expert 5	−2	0.6	2	−2.4
	Expert 6	0	0.8	1	0	Expert 6	−3	0.8	3	−7.2
	Expert 7	−1	0.6	1	−0.6	Expert 7	−1	0.6	2	−1.2
	Average value of S_1 (shipping)				**−0.5**	Average value of S_2 (shipping)				**−2.7**

Note: I, C, and R are the impact, confidence, and relationship in the MDDM model mentioned in 2.1.2, respectively; and the values of $I \times C \times R$ are the product of I, C, and R judgment values by expert. The S_1 and S_2 are the summation of the judgment values by all experts of the impacts and relationships between alternatives of PCFZ and the environmental risk dimension in the present (risks→alternatives) and future (alternatives→risks), respectively (The average value of S1 and S2 are shown in bold values).

typhoon occurrence (Liu *et al.* 2008; Tan 2008). The average loss (C) in maritime tourism from typhoons was 9.3×10^6 RMB per time, and the average loss in port damage from typhoons was1.0×10^7 RMB per time.

3.1.3.2.2. Oil spill risk from vessels. The Port Planning for Xiamen Bay (XMNPA 2012) showed that the total number of vessels would grow from 250,000 in 2010 to 500,000 in 2020. There was a near linear relationship between annual cumulative frequency of oil spills from vessels and the increase in total numbers of vessels in Xiamen Bay from the results of SQAR and RAR. Thus, the annual cumulative frequency of oil spills from vessels in 2020 is expected to be approximately twice that of the present annual cumulative frequency ($F = 0.55$), i.e., $F = 1.1$ accidents per year by extrapolation model (Forbes *et al.* 2011). Meanwhile, the predicted probability of oil spills per vessel would be $P = 1.1/500{,}000 = 2.2 \times 10^{-6}$, and the average loss would be 7.3×10^6 RMB per accident from RAR in Step I.

3.1.3.2.3 Oil spill risk from oil jetties. Given there are no plans for oil jetties' development (XMNPA 2012), the predicted annual cumulative frequency of oil spills from oil jetties can be assumed to remain at $F = 1.8$ accidents per year, and the average loss would be 4.4×10^5 RMB per accident in Step 1.

3.1.3.3. Risk evaluation and ranking. The annual cumulative risk values (R) caused by the final principal coastal functions, and the risk levels and their ranking in Xiamen Bay

Table 3. Environmental risk values and risk levels for the principal coastal functions in Xiamen Bay and Luoyuan Bay.

Risk types	Risk value ($R = F \times C$) (RMB per year)	Risk level
Xiamen Bay		
—Damage to port from typhoons	5.8×10^7	Moderate risk
—Maritime tourism from typhoons	5.4×10^7	Moderate risk
—Oil spills from vessels	8.0×10^6	Moderate risk
—Oil spills from oil jetties	7.9×10^5	Low risk
Luoyuan Bay		
—Damage to aquaculture/fishery from typhoons	3.4×10^7	Moderate risk
—Damage to port from typhoons	1.7×10^7	Moderate risk
—Oil spills from vessels	6.5×10^5	Moderate risk
—Accident from petrochemical industry	600	Low risk

Note: The cumulative risk values (R) is the product of annually cumulative frequency of risk (F) and the average loss (C) of each accident. The risk levels were determined by the expert judgment according to the risk values to select preferred alternative(s).

were derived using the risk matrix model (Paul, Garvey, and Lansdowne 1998; Zhu, Kuang, and Shen 2003; USNRC 2008) and the expert judgment (see Table 3).

3.1.3.4. Risk-based planning (management and actions of SDM). The corresponding measures of risk management for principal coastal functions in the coastal area of Xiamen Bay were proposed according to the risks with relatively high value and level (Table 3). These include formulating port planning, conducting strategic environmental assessment for each sectoral planning, enhancing the ability to counteract the impact of typhoon, and establishing contingency plans of oil spills from vessels to help the formulation of the coastal risk-based planning and management measurements.

3.2 Case 2: Luoyuan Bay

Based on the evaluation of natural resource in Luoyuan Bay, three alternatives of PCFZ were identified, i.e., tourism, shipping, and aquaculture/fishery (Mu 2013).

3.2.1. Assessment and results of Step 1

All available historical data and information on Luoyuan Bay were collected, and then assessed using SQAR and RAR. Results showed that (1) there were mainly two broad groupings of environmental risks: the natural disaster risk (typhoons) and the accident risk, including oil spills from vessels and accidents from petrochemical industry; (2) the average annual cumulative frequency of typhoon was 3.4 times per year in the last 15 years, with average loss each time of 1.0×10^8 RMB; (3) the vessel types included tanker vessels, containerships, cargo ships, and fishing boats, but there was only one oil spill from a vessel from 1995–2010; and (4) there is lack of data on the petrochemical industry accidents for this region. However, data for the Sinopec Group from 1986 to 2005 (Gong 2006) showed that the annual cumulative frequency of petrochemical industry accidents had decreased, due to an improvement in production and safety technology, from 3.7 to 0.5 accidents per year for an annual production of 10 million tons; (5) the results of integrated assessment by the expert judgment showed that the current level of risks from typhoons and oil spills from vessels were both at moderate levels, and the risk level of the petrochemical industry was low in Luoyuan Bay; and (6) there were no catastrophic or high risks in Luoyuan Bay. The alternatives of PCFZ including tourism, shipping, and aquaculture/fishery were all feasible for further consideration from an environmental risk perspective.

According to the integrated assessment results of seven dimensions, including ERA and public involvement, the available alternatives of PCFZ in the coastal area of Luoyuan Bay were finally determined as shipping and aquaculture/fishery (Mu 2013).

3.2.2. *Assessment and results of Step 2*

The assessment results of scenario analysis of ERA in Luoyuan Bay showed that if aquaculture/fishery were developed further, there would be two main types of environmental risk: damage to aquaculture/fishery from typhoons, and oil spills from fishing boats. If Luoyuan Bay developed shipping, two types of environmental risks would be likely: oil spills from tanker vessels, containerships, and cargo ships, and the damage to port from typhoons.

The results from MDDM model by the expert judgment showed that the risk values of aquaculture/fishery and shipping from the environmental risk dimension were $-2.1-0.2 = -2.3$ and $-0.4-4.5 = -4.9$, respectively.

Thus, the preferred alternative for PCFZ in Luoyuan Bay should be aquaculture/fishery from an environmental risk perspective. After integrating the results from seven dimensions and public involvement, the preferred alternative of principal coastal functions in Luoyuan Bay was found to be aquaculture/fishery as a principal function, and shipping as a compatible function.

3.2.3. *Assessment and results of Step 3*

3.2.3.1. Risk identification. Risk identification based on expert judgments highlighted four types of environmental risk caused by the aquaculture/fishery and shipping as the principal coastal functions in Luoyuan Bay. These risks were damage caused by (1) typhoons to aquaculture/fishery; (2) typhoons to ports; (3) oil spills from vessels due to the development of aquaculture/fishery and shipping; and (4) accidents from the petrochemical industry.

3.2.3.2. Predicted risk analysis.

3.2.3.2.1. The risk of damage to aquaculture/fishery or port from typhoons. Using the typhoon model of Liu *et al.* (2008) and Tan (2008) shows the predicted annual cumulative frequency (F) of typhoons in Luoyuan Bay would be $F = 4$ times per year. The average loss (C) of the damage to aquaculture/fishery from typhoons was 1.0×10^7 RMB per time, and the average loss (C) of the damage to ports from typhoons was 5.0×10^6 RMB per time.

3.2.3.2.2. Oil spills from vessels. The Port Planning of Luoyuan Bay (XMUCOMI and IESF 2007) showed that the total number of vessels in Luoyuan Bay would grow to 8300 in 2020. Due to lack of historical data of oil spills from vessels in Luoyuan Bay, the probabilistic model of oil spills (Schulze, 1983; Yapa, Shen, and Angammana 1994; Jin 2006; Hong 2008) was adopted to predict the probability. The results showed that the predicted probability (P) and annual cumulative frequency (F) of oil spills from vessels would be $P = 1.6 \times 10^{-6}$ per vessel, and $F = 1.6 \times 10^{-6} \times 8{,}300 = 0.13$ accidents per year. The average loss of oil spills from vessels would be 5.0×10^{6} RMB per accident in Luoyuan Bay, based on the relevant data (FZMSA 2010) of oil spills from vessels in Fuzhou Seas (Luoyuan Bay belongs to Fuzhou Municipality).

3.2.3.2.3. Petrochemical industry accidents. The annual cumulative frequency (F) of accidents from the petrochemical industry was estimated as $F = 0.04$ accident per year in Luoyuan Bay, with an average loss of 1.5×10^{4} RMB per accident. These estimates are based on a probability statistic model of chemical industries (Meel *et al.* 2007) and accident statistics data for the Chinese petrochemical industry company (Gong 2006) mentioned in Step 1.

3.2.3.3. Risk evaluation and ranking. Adopting the same approach and methods used on Xiamen Bay, the cumulative risk values, risk levels, and their ranking in Luoyuan Bay were estimated (Table 3).

3.2.3.4. Risk-based planning (management and actions of SDM). The corresponding measures of risk management for principal coastal functions in the coastal area of Luoyuan Bay were proposed according to the level of risks. These measures might include formulating port planning and conducting its strategic environmental assessment, enhancing the ability to counteract the impact of typhoons, and establishing contingency plans for oil spills from vessels to help the formulation of coastal risk-based planning and management.

4. Discussion

4.1. The effects of the application of integrated ERA-SDM approach

From the two case studies (Xiamen and Luoyuan Bays), it could be found that the integrated ERA−SDM approach could effectively support the generation of a set of alternatives for PCFZ by identifying the possible catastrophic or high risk(s). The approach could evaluate the preferred alternatives by using the MDDM approach to support the decision-making process. It could also assist with the risk management and actions of PCFZ by identifying regionally comprehensive and cumulative impacts to help with the regional risk-based planning and management. In summary, the integrated ERA−SDM approach is able to integrate ERA into the overall process of PCFZ to avoid or mitigate dire environmental risk, especially in the very beginning of SDM processes.

Comparative analysis of the case studies reveals that Luoyuan Bay is a very simple, undeveloped coastal area with a lack of relevant data; whereas Xiamen Bay is a very complicated coastal area, highly developed with a high population density, and with considerable long-term monitoring data. Our evaluations of these very different locations indicate that the integrated ERA−SDM approach could be used to support SDM processes in situations with simple or complicated natural and socio-economic conditions. And the approach has proved to be flexible by using MDDM and the expert judgment to overcome any lack of data or high uncertainty in non-structured SDM processes.

4.2. Necessity and features of the integrated ERA–SDM approach

All current ERAs for project or sectoral decision-making or management are passive–active processes (Wu and Zhang 2014) because their predictions are generally made after the conclusion of SDM processes. This made the predictability of environmental consequences become weaker at strategic levels compared with project or sectoral decision-making levels (Nilsson and Dalkmann, 2001). It could not integrate an ERA into the entire SDM process, especially in early stages of it, and could not adequately assess the regional, comprehensive, and cumulative risk impacts of SDM. Due to these limits, we consider it necessary to adopt the integrated ERA–SDM approach in order to remedy the deficiencies of current ERAs to SDM.

The results of two case studies indicated that the integrated ERA–SDM approach could be an intrinsic element of SDM, and integrated into the overall SDM processes (alternatives generation, alternatives evaluation and selection, and management and actions), and consider the regional, comprehensive, and cumulative risks in SDM processes.

4.3. Features of the methodology of integrated ERA–SDM

The methodology of integrated ERA–SDM in the case studies could resolve problems related to high uncertainty, lack of data, unquantifiable results, and the regional, comprehensive, and complex features of SDM processes.

From the two case studies, it is evident that the integrated ERA–SDM methodology would be flexible, and could be selected according to the actual situation of any study area. For instance, when a regional interrelated risk value could be quantified completely in both Xiamen Bay and Luoyuan Bay, a comprehensive risk indexes model in Step 3 is not needed. The historical data of oil spills in Xiamen Bay was evaluated to be sufficient to predict the trend of oil spill risk from vessels, and thus the probabilistic model is not needed. On the contrary, the probabilistic model of oil spills has to be used in Luoyuan Bay due to lack of relevant historical data for trend analysis.

Furthermore, some methods are not limited to only one step in the integrated ERA–SDM approach. For example, the methods of the expert judgment, SQAR and RAR could be used in Step 1, 2, or 3. In particular, the expert judgment is a method that could be applied in any of the three steps, should there be a lack of data, high uncertainty, or unquantifiable SDM processes.

Uncertainty is always the key and the most difficult issue for ERA, especially for any SDM with high uncertainty. Our proposed methodology of integrated ERA–SDM decreases the various types of uncertainty that may be encountered. For example, it minimizes data uncertainty by using SQAR and RAR, model uncertainty by using the expert judgment, and expert uncertainty by using the confidence (C) of the expert judgment in the MDDM model and the group decision method of experts.

5. Conclusions

ERA has been used to support decision-making processes over the last two decades (Linkov *et al.* 2006; USNRC 2009). However, most applications of ERA were applied to individual sectors of decision-making processes, and there has been no interrelated systematic research and application of ERA to support SDM processes (Wu and Zhang 2014). We propose an integrated ERA–SDM approach and methodology, in which ERA supports (1) the process of available alternative generation; (2) the process of evaluation/selection of available alternatives; and (3) the process of management and actions for the regional risk-based planning and management. We have then applied this in two case studies of PCFZ in China.

The applications demonstrated several beneficial outcomes. First, this integrated ERA−SDM approach could be an intrinsic element of SDM, and integrate ERA into the overall processes of PCFZ so as to avoid, or mitigate dire environmental risk from the PCFZ process. Second, it can be used in a range of natural and socio-economic conditions to support SDM processes. Moreover, it could be applied to support highly uncertain and non-structured SDM processes, assess regional cumulative risks, fully consider the negative feedback of a final decision, and ensure sustainable coastal development.

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