Preliminary evaluation of ecological risk for the city area from the Pearl River Estuary

Qiuying Chen, KinChung Ho and Jingling Liu

ABSTRACT

It is essential to evaluate the ecological risk for the estuary cities area for the environmental restoration of the estuary. The ecological risk of six city areas from the Pearl River Estuary were evaluated by using the relative risk model. The relative risk assessment method was developed by considering the river network density in the sub-region. The results indicated that Dongguan had the largest ecological risk pressure with total risk scores as high as 10,846.3, and Hong Kong had the lowest ecological risk pressure with total risk scores up to 4,104.6. The greatest source was domestic sewage with total risk scores as high as 1,798.6, followed by urbanization and industry. Oxygen-consuming organic pollutants, organic toxic pollutants and nutrients were the major stressors of the water environment. In terms of habitats, the water environment was enduring the greatest pressure. For the endpoints, water deterioration faced the largest risk pressure.

Key words | city area, ecological risk, model, Pearl River Estuary

Qiuying Chen (corresponding author)
College of Chemistry and Life Science,
Shenyang Normal University,
110034, Shenyang,
China
E-mail: *chanjacy@126.com*

KinChung Ho
School of Science & Technology,
The Open University of Hong Kong,
999077, Hong Kong,
China

Jingling Liu
School of Environment,
Beijing Normal University,
100875, Beijing,
China

INTRODUCTION

An estuary is a concentrated area of land and sea interactions, coupled with a variety of physical, chemical, biological and geological processes, and a complex evolutionary mechanism, which makes the ecological environment of estuary areas sensitive and fragile. An estuary also has an important position in the urban development of coastal areas as the estuaries both attach to the land and attach to the ocean, such as in Shanghai at the Yangtze Delta and Guangzhou at the Pearl River Estuary (PRE) in China (Chen & Chen 2007). In addition, estuarine areas have abundant fresh water resources, land resources, aquatic resources, and shipping resources. Estuary cities are developed regions with better economic development and high density populations. Obviously, estuaries are an important region of the east–west economic and cultural exchange, and play an important role in socio-economic development in coastal areas as well as the entire country. However, estuaries have become one of the regions that face the greatest ecological pressure and environmental risk from industrial development, and few risk assessments have been conducted on the estuary cities which have a unique geographical location in the river basin. Thus, it is essential to evaluate the ecological risk for estuary city areas for environmental management.

To reduce the pollution and other eco-environmental damage to a minimum, ecological risk assessment (EcoRA) aims to generate scientific data and information for environment and ecosystem planning (Suter 1993; US EPA 1998). Regional EcoRA is at a spatial scale that contains multiple habitats with multiple sources of multiple stressors affecting multiple endpoints and the characteristics of the landscape affect the risk estimate (Landis & Wiegers 2005). Therefore, there are many sources, stressors, habitats and endpoints that must be considered (Liu *et al.* 2011; Schäfer *et al.* 2011) at a regional scale. The traditional risk characterization method might not be efficient when evaluating a regional scale risk (Hunt *et al.* 2010; Schmolke *et al.* 2010). The relative risk model (RRM) was developed in order to integrate the impacts due to a variety of stressors at a regional scale (Landis & Wiegers 1997, 2005, 2007; Wiegers *et al.* 1998), and it has been successful in multiple diverse settings, including marine ecosystems (Obery & Landis 2002), aquatic ecosystems (O'Brien & Wepener 2012), tropical rivers (Bartolo *et al.* 2012), and rain forest reserves (Moraes *et al.* 2002).

In the aforementioned studies, we developed the RRM by introducing the concept of 'pressure density' and 'habitat abundance' to reduce the uncertainty, and attempted

doi: 10.2166/wst.2014.399

to apply RRM to assess water ecological risk in Luanhe River Basin (Liu *et al.* 2010) and estuary in China (Chen *et al.* 2012). However, the water environment risk can transfer with the river flow, so this study considered the river network density in the sub-region by introducing river network density as a parameter. One special city area of the PRE was selected as a case study. The purpose of this study was to conduct an initial regional scale risk assessment on PRE. The results will provide a basis for aiding in management prioritization and decision making relating to the environment and restoration in the estuary cities.

MATERIALS AND METHODS

The three parts of the risk assessment are problem formulation, risk analysis and risk characterization.

Problem formulation

In this stage, physical, chemical and biological characteristics of the study areas will be summarized, the stressors and endpoints derived from stakeholders' values will be identified, and risk regions included in the conceptual model will be defined.

Study area

As one of the most rapidly growing regions of economic development, the Pearl River Delta has been polluted by heavy metals, inorganic nitrogen, oil and other harmful substances. At present, the increasing water issues, water pollution and aquatic ecosystem damage have become the principal constraint factors for regional sustainable development in the Pearl River Delta. In this study, considering the reliability of data sources, we divided the PRE area into six sub-regions based on the administrative district (Figure 1). They are Hong Kong, Shenzhen, Dongguan, Nansha District of Guangzhou, Zhongshan and Zhuhai.

Sources, stressors, habitats and endpoints

Based on field surveys and datasets, ecological risk sources were divided into six major categories. They were industry, agriculture, domestic sewage, aquaculture, development projects and urbanization. Water and land were selected as the habitats based on the types of habitat in the area and the utility of endpoints. Risk assessment focuses on the aquatic environment, so water quality, water quantity and aquatic ecosystems (water quality deterioration, eco-water shortage, ecosystem damage) were selected as the assessment endpoints.

Conceptual model

The conceptual model is the basis for risk calculations within the RRM (Walker *et al.* 2001). Risk hypotheses were evident through the links among the stressors, habitats and assessment endpoints. The interaction relationships were defined by the exposure and effects pathways (Landis & Wiegers 1997).

Risk analysis

Risk analysis was formed based on the study's assumptions (Landis & Wiegers 1997): (a) the potential for exposure to stressors will be greater if the size or frequency of a source in a sub-region is greater; (b) the type and density of assessment endpoints are relative to available habitat; (c) the sensitivity of receptors to stressors varies between habitats; and (d) the severity of effects in sub-regions depends on relative exposures and characteristics of the organisms present. Source and habitat were classified into ranks by using data segmentation and section assignment methods of ArcGIS software. Exposure and effects coefficients were developed based on the components. The details are referenced in the literature (Chen *et al.* 2012). Data sources were: Statistical Yearbook of Hong Kong, Shenzhen, Guangzhou, Zhongshan, Dongguan, and Zhuhai cities in 2010, Environment Bulletin of cities in Pearl River Delta, Marine Pollution Bulletin and Pearl River Basin land-use type maps in 2004.

Risk calculation

Source and habitat ranks with exposure and effects coefficients are combined to determine the risk score. Calculations were performed for all pathways in the conceptual model. The source rank, habitat rank, exposure coefficients and effects coefficients will be calculated comprehensively in accordance with the four basic hypotheses of the model. The results are a comparative estimate of risk in each sub-region. So each path can be expressed by the equation which is composed of the path and the

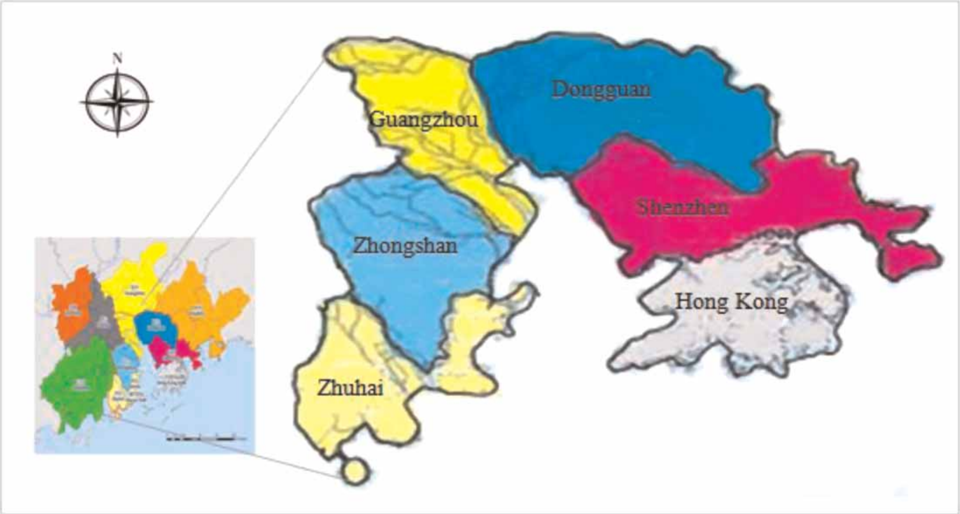

Figure 1 | City locations in the PRE.

exposure-effects coefficients. The river network density RN_{ij} was calculated by using the number of rivers in each subregion divided by the total number of rivers. The risk value formula is as follows:

$$\mathrm{RS} = \sum (RN_{ij} \times R_{ij} \times \frac{1}{R_{il}} \times SSH_{ijl} \times EH_{iel} \times SE) \qquad (1)$$

where RN_{ij} = the river network density; R_{ij} = the rank of risk source; R_{il} = the rank of habitat; SSH_{ijl} = the exposure coefficient of risk source–stressor–habitat (SSH); EH_{iel} = the exposure coefficient of habitat–endpoint; SE = the effects coefficient of stressor–endpoint.

RESULTS AND DISCUSSION

The interactions were integrated into a conceptual model (Table 1) when the risk components were identified. Thus, the conceptual model is a representation of the predicted relationships among the stressor, exposure pathways, and assessment endpoint responses.

Relative risk of source and stressor

Risk scores are a characterization of regional ecological risk, and are also the integration of the information indicators

Table 1 | Conceptual model from source to stressor, habitat and endpoint

Source-stressor

	Stressor												Habitat	
Source	***a***	***b***	***c***	***d***	***e***	***f***	***g***	***h***	***i***	***j***	***k***	***l***	**Water**	**Land**
Industry	●	●	●	●	●	●	●	○	●	○	○	●	abcdeghil	acdef
Agriculture	○	○	○	●	○	●	○	●	○	○	○	●	dfhjl	dfhl
Domestic sewage	●	●	●	●	●	○	●	●	●	●	●	●	abcdefgl	acdefg
Aquaculture	●	○	○	○	●	●	●	○	○	○	○	●	aefgl	○
Development project	○	○	○	○	○	○	○	●	●	○	●	●	hikl	○
Urbanization	●	●	●	●	●	●	●	●	○	●	●	●	abcdfghjkl	l
Endpoint														
Water quality deterioration													●	●
Eco-water shortage													○	●
Ecosystem damaged													●	○

a = oxygen-consuming organic pollutants; b = suspended solids; c = inorganic toxic pollutants; d = organic toxic pollutants; e = endocrine disruption; f = nutrients; g = pathogens; h = excessive use of water; i = temperature increased; j = surface runoff changed; k = underground runoff changed; l = habitat destruction; '●' = 'exist in'; '○' = 'do not exist in'

(Landis & Wiegers 2005). Source and habitat ranks in each region are shown in Table 2. *SSH* coefficients, exposure coefficients of habitat (*EH*) and effects coefficients of stressor–endpoint (*SE*) are listed in Tables 3 and 4.

The relative risk statuses of six sources in each risk region were calculated. The results are listed in Table 5. According to Table 5, Hong Kong, Dongguan, Guangzhou and Zhongshan were influenced mainly by domestic sewage. Shenzhen was influenced chiefly by urbanization. Zhuhai was influenced principally by aquaculture. As the regional total pressure scores and the assessment results based on the RRM model, the greatest source was domestic sewage with total risk scores as high as 1,798.6, the second was urbanization with total risk scores up to 1,429.2, and the third was the industry with total risk scores as high as 1,178.4.

The relative risk scores of 12 stressors in each risk region were calculated. The results are listed in Table 5. From Table 5, nutrients were the main stress factors for Hong Kong and Zhuhai. Oxygen-consuming organic pollutants were the principal stressors for Shenzhen, Dongguan, Guangzhou and Zhongshan. According to the overall risk position in the study area, the order of the risk scores of each stressor from high level to low level was: oxygen-consuming organic pollutants, organic toxic pollutants, nutrients, pathogens, inorganic toxic pollutants, endocrine disruptions, and surface runoff changed, suspended solids, excessive usage of water, underground runoff changed, habitat destruction and water temperature increased. The results indicated that the largest stressor was oxygen-consuming organic pollutants with risk scores as high as 273.9 for the water environment of PRE, the second was organic toxic pollutants with risk scores of 236.0, and the third was nutrients with risk scores of 235.2, which constituted the main stressors of the region EcoRA.

Relative risk of habitat and endpoint

In the aforementioned studies, there was relatively little research and application that considered spatial factors

Table 2 | Source and habitat ranks in each sub-region

		Hong Kong	Shenzhen	Dongguan	Guangzhou	Zhongshan	Zhuhai
Source	Industry	2	6	6	6	4	2
	Agriculture	2	2	2	4	4	2
	Domestic sewage	4	6	4	6	4	4
	Aquaculture	2	4	4	2	4	4
	Development project	4	6	6	4	6	6
	Urbanization	4	6	4	6	4	4
Habitat	Water	6	4	2	4	4	6
	Land	2	6	6	4	6	2

Table 3 | Risk source–stressors–habitat exposure coefficients

		a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*
Hong Kong	Water	1	1	1	1	0.5	0	0.5	1	0.5	0	0	0
	Land	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0	0
Shenzhen	Water	0	0	0	1	0	1	0	0.5	0	0.5	0	0.5
	Land	0	0	1	0.5	0	1	0	0.5	0	0	0	0.5
Dongguan	Water	1	1	1	1	1	1	1	0	0	0	0	0
	Land	0.5	0	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0
Guangzhou	Water	1	0	0	0	1	1	1	0	0	0	0	0.5
	Land	1	0	0	0	1	1	1	0	0	0	0	1
Zhongshan	Water	0	0	0	0	0	0	0	0.5	1	1	1	0
	Land	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5
Zhuhai	Water	0.5	0.5	0.5	0.5	0	0.5	0.5	0.5	0	1	1	0
	Land	0	0	0	0	0	0	0	1	0	0.5	0.5	0.5

Table 4 | *EH* and effects coefficients (*SE*)

	EH		***SE***											
	Water	**Land**	***a***	***b***	***c***	***d***	***e***	***f***	***g***	***h***	***i***	***j***	***k***	***l***
A	1	0.5	1	1	1	1	1	1	1	0.5	0.5	0.5	0	1
B	1	0.5	0	0	0	0	0	0	0	1	0	1	1	0
C	1	0.5	1	1	1	1	1	1	1	0	0.5	0	0	1

A = Water quality deterioration; *B* = Eco-water shortage; *C* = Ecosystem damage.

Table 5 | Risk scores of source, stressor, habitat and endpoint in each sub-region

		Hong Kong	**Shenzhen**	**Dongguan**	**Guangzhou**	**Zhongshan**	**Zhuhai**	**Total**
Source	Industry	90.4	220.9	413.3	235.1	147.3	71.3	1,178.4
	Agriculture	83.2	66.5	116.4	149.6	133.1	83.2	632.0
	Domestic sewage	218.8	342.1	427.6	363.4	228.1	218.8	1,798.6
	Aquaculture	114.1	175.9	304.1	99.8	175.9	228.2	1,097.8
	Development project	147.5	171.0	320.7	121.1	171.0	164.1	1,095.4
	Urbanization	176.0	270.8	337.3	288.6	180.6	176.0	1,429.2
Stressor	*a*	26.3	50.3	78.8	47.3	37.5	33.8	273.9
	b	14.3	36.0	56.3	37.1	24.0	14.3	181.9
	c	23.3	39.8	59.3	42.8	27.0	23.3	215.3
	d	24.0	43.5	67.5	46.1	30.8	24.0	236.0
	e	19.5	34.5	54.0	30.4	27.0	27.0	192.5
	f	28.5	40.5	60.0	37.1	33.0	36.0	235.2
	g	22.5	41.3	63.0	37.1	31.5	30.0	225.5
	h	24.0	29.3	40.5	30.4	22.5	25.5	172.2
	i	10.5	20.3	22.5	15.8	18.0	10.5	97.5
	j	23.3	33.8	39.8	30.4	28.5	27.8	183.5
	k	21.8	31.5	35.3	28.1	26.3	26.3	169.2
	l	16.5	15.0	25.5	15.8	14.3	27.0	114.1
Habitat	Water	46.6	120.0	202.5	113.3	96.8	54.6	633.8
	Land	50.3	19.0	18.5	19.5	17.0	46.5	170.8
Endpoint	Water deterioration	1,461.6	2,501.9	4,051.7	2,487.6	2,168.3	1,786.4	14,457.6
	Eco-water shortage	590.6	272.6	284.9	459.4	284.9	721.9	2,614.4
	Ecosystem damage	871.0	2,173.1	3,766.8	2,028.3	1,883.4	1,064.5	11,787.0
Sub-region	Total risk	4,104.6	6,749.6	**10,846.3**	6,764.1	5,806.8	4,921.0	

such as the different types of habitat distribution. In this study, a comparative analysis of the risk pressure of the water and land habitat in each risk region was carried out. The results are shown in Table 5. It was shown that water habitats were enduring the largest risk pressure in every sub-region except Hong Kong. Water habitats overall have higher risks with a total risk score as high as 633.8, which is possibly because more sources discharged into the water habitats and more endpoints utilized the water habitats. The relative risk pressure scores of three endpoints in each risk region were calculated (Table 5). Overall, for all risk regions, water deterioration was the largest risk pressure in the five regions with a total risks score of 14,457.6, followed by ecosystem damage and eco-water shortage.

Total risk of the sub-region

Finally, the ecological risk scores of the six regions were calculated and the results are shown in Table 5. According to Table 5, we have an intuitive understanding of the ecological risk distribution status of the water environment in the study area. Dongguan had the largest ecological risk pressure with total risk scores as high as 10,846.3. The second was Guangzhou, and the third was Shenzhen. Shenzhen, Dongguan and Guangzhou are located in the centre portion of

PRE, which receives a large number of contaminants from upstream and from inner city industry. Heavy industrial development, fast urbanization and large-scale domestic sewage have caused higher risk scores than in other regions. According to an analysis and comparison of the risk scores of each region, we divided the study area into three ecological risk status levels based on the region's integrated risk scores: 4,104–4,921 for low-risk areas; 4,922–6,765 for medium risk areas; and 6,766–10,847 for high-risk areas. The results showed (Figure 2) that there were two low-risk regions (Hong Kong and Zhuhai), three medium-risk regions (Shenzhen, Guangzhou and Zhongshan) and one high-risk region (Dongguan) in the study area.

Over the past decade, environment and ecosystems have been subjected to unprecedented pressures with the rapid socio-economic growth of China, as well as the depletion of natural resources and pollutant emissions. With the runoff of rivers, large quantities of pollutants are transported into the coastal waters, air and land, which causes degradation or fundamental damage to the habitat of part of the 1.8 million km of coastline. However, as the last barrier of the basin's water environment, the estuary can provide fresh water, control floods and drainage, protect ecological security, provide unique habitats and ensure watershed biodiversity (Bai *et al.* 2011). From this study, although the estuary has important ecological value as a sensitive symbol of ecosystem health at the end of the basin, the assessment results indicated that this area was facing a certain degree of risk. The estuary is long-neglected and suffers from continuously destructive interference from various human activities. For example, as the regional aggregate pressure status and the assessment results show, domestic sewage was the largest source, which meant this area had high density population. Therefore, municipal water pollutant emissions should be controlled strictly, and industrial pollution reduction should be promoted by low-polluting industrialization, especially for Shenzhen and Dongguan. For Shenzhen, Guangzhou and Zhongshan, comprehensive management of the water environment should be carried out so as to promote recovery of the river ecosystem function. However, the results are only theoretical risks with no actual measures of the extent of the impact included. For example, one 'unit' of exposure to pesticides may have a higher or lower impact than one 'unit' of domestic sewage. Hence the 'potency' of each stressor should be considered when allocating the resource for remediation. After all, owing to the enormous risks and challenges for water quality and ecosystem security in the estuary cities, it is necessary to establish a set of ecosystem risk evaluation systems for the estuary in a timely manner. This will not only provide early warning to part of the estuarine ecosystem, but also prevent estuarine ecosystem degradation and tidal erosion.

Uncertainty

Uncertainty exists in the procedures for objective EcoRA. As a major tool for uncertainty analysis, conceptual models can communicate the full range of assumptions and uncertainties for risk assessment. Each method can introduce a level of uncertainty to the results. Based on the existing data, we selected major risk source categories through the traditional macro method. Source rank was classed by using data segmentation methods of the software, which introduced uncertainty in the numerical boundary of the risk rank. For example, it will produce different results if

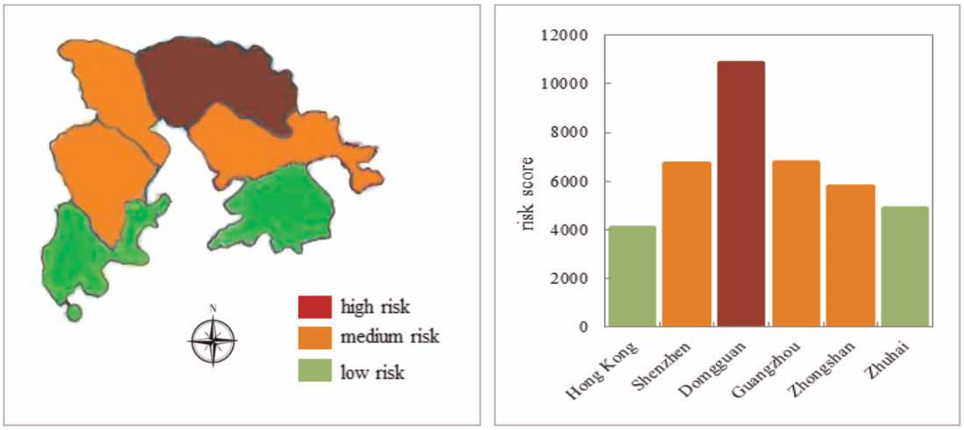

Figure 2 | Risk scores of the water environment by sub-region.

source strength is close to two or four boundaries. Similarly, the stressor rank also experiences uncertainty when it is close to the boundary. Additionally, water and land were selected as representative habitats, which might not necessarily be typical of all types of habitat in the area. This might introduce a bias in the data collected. With the mixing of water in the transversal and longitudinal directions in the compound channels (Besio *et al*. 2012) and the horizontal mixing of quasi-uniform straight compound channel flows (Stocchino & Brocchini 2010), the risk can be conducted with the flow. However, uncertainty is also introduced in the risk rank classification and result calculation. Even so, it may not give an accurate measurement with some model modifications. At the same time, insufficient datasets in the study area also contribute to the uncertainty. Therefore, further modification and uncertainty analysis are still to be developed.

CONCLUSION

The city area of the PRE was chosen for study with its developed economy and high density population. The relative risk assessment method was developed by considering the river network density in the sub-region and introducing the 'river network' parameter. According to the model method, Dongguan had the largest ecological risk pressure, and Hong Kong had the lowest ecological risk pressure. The main stressors of the water environment were oxygen-consuming organic pollutants, organic toxic pollutants, and nutrients. For the habitats, the water endured the larger pressure and should be given considerable attention. Still, further modification and uncertainty analysis should be developed for the method. Thus, water pollution control was identified as the major orientation for reducing the ecological risk.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (grant no. 41301573) and the Croucher Foundation of Hong Kong (2010–2011).

REFERENCES

Bai, J. H., Cui, B. S., Chen, B., Zhang, K. J., Deng, W., Gao, H. F. & Xiao, R. 2011 Spatial distribution and ecological risk assessment of heavy metals in surface sediments from a typical plateau lake wetland. *China. Ecol. Model.* **222** (2), 301–306.

Bartolo, R. E., van Dam, R. A. & Bayliss, P. 2012 Regional ecological risk assessment for Australia's tropical rivers: application of the relative risk model. *Hum. Ecol. Risk. Assess.* **18**, 16–46.

Besio, G., Stocchino, A., Angiolani, S. & Brocchini, M. 2012 Transversal and longitudinal mixing in compound channels. *Water Resour. Res.* **48**, W12517, 1–15.

Chen, J. Y. & Chen, S. L. 2007 Estuarine research a five years in China. *Retrospect Prospect [M]*. **38** (6), 481–486 (in Chinese).

Chen, Q. Y., Liu, J. L., HO, K. C. & Yang, Z. F. 2012 Development of a relative risk model for evaluating ecological risk of water environment in the Haihe River Basin estuary area. *Sci. Total. Environ.* **420**, 79–89.

Hunt, J., Birch, G. & Warne, M. S. J. 2010 Site-specific probabilistic ecological risk assessment of a volatile chlorinated hydrocarbon–contaminated tidal estuary. *Environ. Toxicol. Chem.* **29**, (5), 1172–1181.

Landis, W. G. & Wiegers, J. K. 1997 Design considerations and a suggested approach for regional and comparative ecological risk assessment. *Hum. Ecol. Risk. Assess.* **3**, 287–297.

Landis, W. G. & Wiegers, J. K. 2005 Chapter 2: Introduction to the regional risk assessment using the relative risk model. In: *Regional Scale Ecological Risk Assessment Using the Relative Risk Model* (W. G. Landis, ed.). CRC Press, Boca Raton, FL, pp. 11–36.

Landis, W. G. & Wiegers, J. K. 2007 Ten years of the relative risk model and regional scale ecological risk assessment. *Hum. Ecol. Risk. Assess.* **13**, 25–38.

Liu, J. L., Chen, Q. Y. & Li, Y. L. 2010 Ecological risk assessment of water environment for Luanhe River Basin based on relative risk model. *Ecotoxicology* **19**, 4000–4015.

Liu, J. L., Chen, Q. Y., Li, Y. L. & Yang, Z. F. 2011 Fuzzy synthetic model for risk assessment on Haihe River Basin. *Ecotoxicology* **20**, 1131–1140.

Moraes, R., Landis, W. G. & Molander, S. 2002 Regional risk assessment of a Brazilian rain forest reserve. *Hum. Ecol. Risk. Assess.* **8**, 1779–1804.

Obery, A. M. & Landis, W. G. 2002 A regional multiple stressor risk assessment of the Codorus Creek watershed applying the relative risk model. *Hum. Ecol. Risk. Assess.* **8**, 405–428.

O'Brien, G. C. & Wepener, V. 2012 Regional-scale risk assessment methodology using the relative risk model (RRM) for surface freshwater aquatic ecosystems in South Africa. *Water SA* **38** (2), 153–166.

Schäfer, R. B., Kefford, B. J., Metzeling, L., Liess, M., Burgert, S., Marchant, R., Pettigrove, V., Goonan, P. & Nugegoda, D. 2011 A trait database of stream invertebrates for the ecological risk assessment of single and combined effects of salinity and pesticides in South-East Australia. *Sci. Total. Environ.* **409** (11), 2055–2063.

Schmolke, A., Thorbek, P., Chapman, P. & Grimm, V. 2010 Ecological models and pesticide risk assessment: current modeling practice. *Environ. Toxicol. Chem.* **29** (4), 1006–1012.

Stocchino, A. & Brocchini, M. 2010 Horizontal mixing of quasi-uniform, straight, compound channel flows. *J. Fluid Mech.* **643**, 425–435.

Suter II, G. W. 1993 *Ecological Risk Assessment*. Lewis Publishers, Boca Raton, FL.

US EPA 1998 *Guidelines for Ecological Risk Assessment*. EPA/630/R-95/002F. Risk Assessment Forum, Washington, DC, Environmental Protection Agency.

Walker, R., Landis, W. G. & Brown, P. 2001 Developing a regional ecological risk assessment: a case study of a Tasmanian agricultural catchment. *Hum. Ecol. Risk. Assess.* **7**, 417–439.

Wiegers, J. K., Feder, H. M., Mortensen, L. S., Shaw, D. G., Wilsona, V. J. & Landis, W. G. 1998 A regional multiple-stressor rank-based ecological risk assessment for the fjord of Port Valdez, Alaska. *Hum. Ecol. Risk. Assess.* **4**, 1125–1173.

First received 13 March 2014; accepted in revised form 5 September 2014. Available online 18 October 2014