

Ecological status classification of the Taizi River Basin, China: a comparison of integrated risk assessment approaches

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Abstract Integrated risk assessment approaches allow to achieve a sound evaluation of ecological status of river basins and to gain knowledge about the likely causes of impairment, useful for informing and supporting the decision-making process. In this paper, the integrated risk assessment (IRA) methodology developed in the EU MODELKEY project (and implemented in the MODELKEY Decision Support System) is applied to the Taizi River (China), in order to assess its Ecological and Chemical Status according to EU Water Framework Directive (WFD) requirements. The available dataset is derived by an extensive survey carried out in 2009 and 2010 across the Taizi River catchment, including the monitoring of physico-chemical (i.e. DO, EC, NH₃-N, chemical oxygen demand (COD), biological oxygen demand in 5 days

(BOD₅) and TP), chemical (i.e. polycyclic aromatic hydrocarbons (PAHs) and metals), biological (i.e. macroinvertebrates, fish, and algae), and hydromorphological parameters (i.e. water quantity, channel change and morphology diversity). The results show a negative trend in the ecological status from the highland to the lowland of the Taizi River Basin. Organic pollution from agriculture and domestic sources (i.e. COD and BOD₅), unstable hydrological regime (i.e. water quantity shortage) and chemical pollutants from industry (i.e. PAHs and metals) are found to be the main stressors impacting the ecological status of the Taizi River Basin. The comparison between the results of the IRA methodology and those of a previous study (Leigh et al. 2012) indicates that the selection of indicators and integrating methodologies can have a relevant impact on the classification of the ecological status. The IRA methodology, which integrates information from five lines of evidence (i.e., biology, physico-chemistry, chemistry, ecotoxicology and hydromorphology) required by WFD, allows to better identify the biological communities that are potentially at risk and the stressors that are most likely responsible for the observed alterations. This knowledge can be beneficial for a more effective restoration and management of the river basin ecosystem.

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Introduction

Freshwater ecosystems support a huge variety of biological communities and at the same time provide goods and services of critical importance to human societies (Postel and Carpenter 1997; Millennium Ecosystem Assessment 2005).

Ecological risk assessment has been proven to be an effective approach to assess the ecological status of river basins and can support the evaluation of their capability to provide several ecosystem services. Risk-based approaches can identify water bodies characterized by a deteriorated health status and provide relevant information to recognize and evaluate the most likely causes of impairment of ecological conditions. These outputs can guide the decision-making process for river basin management, supporting the prioritization of actions and resources allocation, and help to monitor and evaluate the effectiveness of interventions (Leigh et al. 2012; Brils et al. 2014).

Integrated assessment methods based on the application and integration of multiple indices became in the last decades the mainstream approach for the assessment of river health in North America (Davis et al. 2003; USEPA 2012), European Union (Brils et al. 2014; Von der Ohe et al. 2009) and Australia (Ladson et al. 1999; Bunn et al. 2010). However, the studies conducted in China in the past few years remained focused on the individual evaluation of physico-chemical parameters (Zhang et al. 2009; Wan et al. 2013), chemical parameters (Guo et al. 2009, 2010; Men et al. 2011) or biological conditions (Pei et al. 2010; Geng et al. 2012). Only few studies were based on an integrated assessment of both physico-chemical and biological indicators (Meng et al. 2009; Leigh et al. 2012), which, nevertheless, may not be able to completely reflect the ecological status of rivers and determine an effective improvement to river management measures.

In recent years, significant efforts were devoted to the improvement of the monitoring of Chinese river basins. The Chinese Environmental Quality Standards for Surface Water (General Bureau of China National Environmental Protection 2002) requires a classification of water bodies according to their purpose for use and protecting target into five classes, namely, class I—includes sources of water and national nature protection areas; class II—includes ‘class one protection areas’ for centralized potable water source, protection areas for rare fishes, spawn ground for fishes and shrimps, etc.; class III—includes ‘class two protection areas’ for centralized potable water source, protection areas for general fishes and swimming areas; class IV—includes general industrial water areas and entertainment water areas where there is not direct contact between water and human body; and class V—includes water areas for agricultural demand and scenic water body requirement. Different environmental quality standards for chemicals (i.e. heavy metals and few organic chemicals) and physico-chemical parameters apply depending on the water body’s class.

In 2012, the proportion of water bodies in the ten Chinese river basins (i.e. Yangtze River, Yellow River, Pearl River, Songhua River, Huaihe River, Haihe River, Liaohe River, Rivers in Zhejiang and Fujian Provinces, Southwest Rivers and Northwest Rivers) included in classes from I to III and in classes from IV to V were 68.9 and 20.9 %, respectively,

and 10.2 % did not even satisfy the requirement of class V. The pollution indicators that mostly contributed to lower the quality classification were chemical oxygen demand (COD), biochemical oxygen demand (BOD) and permanganate index (MEP 2013). However, the list of chemicals included in this routine monitoring is very limited and therefore not sufficient to draw a comprehensive picture of chemical contamination, while some river basins (i.e. Liaohe River) are heavily contaminated by chemical pollutants such as polycyclic aromatic hydrocarbons (PAHs) and metals discharged by industries located in these catchments. Meanwhile, since the National 11th Five-Year Plan (for the period from 2006 to 2010), the Chinese government has implemented the control plan for total load of major pollutants by monitoring COD in water, developed the pollution prevention plans for important watersheds, and implemented the China Special Science and Technology Program on Water Pollution Control and Treatment to improve the water quality, and it is planned in the National 12th Five-Year Environment Protection Plan (concerning the period from 2011 to 2015) to reduce the indicators COD and $\text{NH}_3\text{-N}$ by 8 and 10 % in 2015 with respect to 2010 (MEP 2012). However, the inclusion of only these two physico-chemical indicators is not suitable to pursue and monitor the improvement of ecological status of water bodies and could even bias the decisions of policy-makers responsible for water environmental management.

At the same time, and in particular since the enforcement of the Water Framework Directive (WFD) 2000/60/CE (EC 2000), integration concerning different elements and steps to assess the water ecological status has become a key word for the water policy in Europe (EC 2003) and a main goal for decision-makers involved in the process of river basin assessment and management. Integration is seen as a transversal concept, encompassing the definition of multiple environmental goals for water bodies (concerning water quantity, water quality and ecosystem status) as well as the inclusion of socio-economic considerations and the attempt to engage different stakeholder categories in decisional processes (Gottardo et al. 2011b). Several research projects were funded with the aim of developing appropriate and advanced approaches and tools for dealing with and implementing all the requirements of the WFD. In the frame of the EU FP6 project MODELKEY—*Models for Assessing and Forecasting the Impact of Environmental Key Pollutants on Marine and Freshwater Ecosystems and Biodiversity* (Brack et al. 2005), an integrated risk assessment (IRA) methodology was developed for supporting the assessment and classification of water quality by integrating heterogeneous information from different domains such as chemistry and biology. Specifically, the IRA methodology is based on a weight of evidence (WoE) approach to analyze and combine a set of environmental indicators grouped into five lines of evidence (LoE), namely, biology, chemistry, ecotoxicology, physico-chemistry and

hydromorphology. The whole IRA methodology has been implemented as a specific module into a freeware geographic information system (GIS)-based decision support system, named MODELKEY DSS (Gottardo et al. 2009), and has been applied to three European river basins: Llobregat, Elbe and Danube river basins (Gottardo et al. 2011a, 2011b; Semenzin et al. 2012).

In this paper, we present the application of the IRA methodology through the MODELKEY DSS to assess the status of the Taizi River Basin, which forms part of the Liaohe River basin, located in north-east of China. The main objective of the paper is to compare the IRA methodology with the river health assessment (RHA) methodology previously developed and applied to the Taizi River within the project 'River Health and Environmental Flow in China', as described in Leigh et al. (2012). The results of the IRA methodology are presented and discussed in this paper and compared with the outcomes of the RHA methodology with the aim of understanding the differences and identifying possible suggestions for improvement of the current approaches to ecological status assessment of Chinese rivers.

Materials and methods

Study area

The Taizi River (40° 30'–41° 40' N, 122° 20'–124° 55' E) is one of the main tributaries of the Liaohe River Basin (separated from Liaohe River since 1958), located in north-east China. Taizi River has a stream length of about 400 km, it receives nine tributaries, and its watershed covers a surface of about $1.39 \times 10^4 \text{ km}^2$ (Fig. 1) (Leigh et al. 2012). The area is characterized by temperate and warm temperate continental climate (CRAES 2010). Taizi River Basin experienced a relevant industrial development within the Liaoning province since the 1950's, and nowadays, the basin constitutes an important area for industry (including metallurgical, petrochemical and equipment manufacturing) and agriculture (dryland and paddy farming). About nine million of inhabitants lived in the river basin in 2009. Taizi waters are used for the domestic, industrial and agricultural needs of the three biggest cities (Benxi, Liaoyang and Anshan) and the surrounding areas. Currently, the land use is dominated by agricultural and forest areas (CRAES 2010). Among the major threats to ecosystem quality in the Taizi River Basin, it is possible to identify urban and industrial point source pollution, as well as diffuse pollution related to agriculture and other activities (road construction, waste disposal, etc.) (Leigh et al. 2012). Moreover, the river basin has been highly modified through the construction of nine reservoirs and several river weir gates, therefore altering its natural flow regime and interfering with solid transport and fish migration. The clearing of riparian vegetation and the

channelling of rivers and streams related to land use changes, as well as the extraction of riverbed materials, represent other processes that can have a significant impact on the ecological quality of Taizi River (CRAES 2010; Leigh et al. 2012).

The available dataset

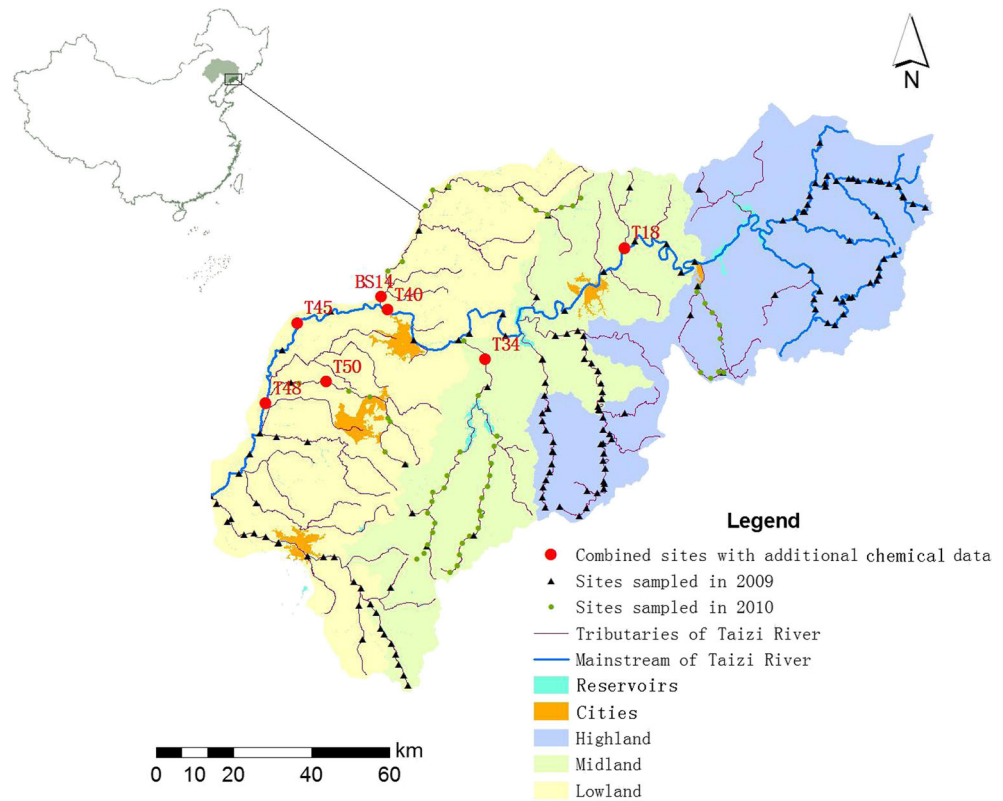
The monitoring dataset for the application of the IRA methodology was obtained from the results of the National Key Science and Technology Special Program of China on Water Pollution Control and Treatment in Taizi River Basin. This programme included 163 sampling sites monitored in 2009 and 60 sites monitored in 2010, along the main channel and tributaries of the Taizi River Basin (Fig. 1) (CRAES 2010; Leigh et al. 2012).

The available dataset includes data on biological communities (i.e. fish, algae and macroinvertebrates), physico-chemistry parameters (i.e. dissolved oxygen, electrical conductivity, $\text{NH}_3\text{-N}$, COD, biological oxygen demand in 5 days (BOD_5), pH, total phosphorus), concentration of chemical contaminants (i.e. As and Hg in surface water) and hydromorphological parameters (i.e. water quantity, channel change and morphology diversity). Fish communities were monitored using electronic fishing and gill net fishing methods, all collected fish were identified, enumerated, and weighed onsite, and rare or unknown species were preserved with 4 % formalin for identification in the laboratory (Ding et al. 2012). Benthic macroinvertebrates collected using a Surber net (30×30 cm, 500 μm mesh) and D-frame dip net (15-cm radius, 500 μm mesh) were identified to the genera level (Zheng et al. 2011). Benthic algae were collected from all available substrates and habitats at each site, and most of the benthic algae were identified to the species level (Yin et al. 2013). Physico-chemistry and chemistry parameters were measured in situ or determined from water samples analyzed in the laboratory, using Chinese water quality standard methods (methods including the measurement and collection of surface water only; Wan et al. 2013). The hydromorphology indicators used in this study are assessed and described by Ding et al. (2012).

Additional chemical data were obtained from other studies in Taizi River Basin for PAHs collected in June 2006 (Guo et al. 2009), nitroaromatic compounds collected in May 2006 (Men et al. 2011), metals collected in 2006 (Lin et al. 2013), and persistent organochlorine residues collected in August 2005 (Wang et al. 2007) in order to enlarge the knowledge on possible chemical pressures in the river. Seven suitable sites were chosen from these studies according to their spatial location to be combined with the sites sampled in 2009 and 2010 (Table 1). These combined sites with additional chemical data are shown in Fig. 1.

For the setting of appropriate reference values, habitat typologies need to be identified within the river basin. This

Fig. 1 Map of the Taizi River Basin with the location of the sampling sites distributed across three habitat typologies



information was also collected from the results of the National Key Science and Technology Special Program of China on Water Pollution Control and Treatment in Taizi River Basin. Altitude (via a digital elevation model), annual precipitation, and normalized difference vegetation index (NDVI) were chosen as the basis of the river classification in Taizi River Basin, which resulted in the identification of three habitat typologies in the catchment, namely, *highlands*, *midlands* and *lowlands* (Fig. 1, Zhang et al. 2013). These three habitat typologies were then used in the process of establishing reference values for the selected indicators.

Description of the methodologies

Integrated risk assessment methodology and selected indicators

The IRA methodology (Gottardo et al. 2011a, b), developed in the EU MODELKEY project, is a risk-based methodology for evaluating the ecological status of surface water bodies. It is proposed as a scientifically sound alternative approach to the ‘One-Out, All-Out’(OOAO) principle that, as suggested by the WFD ECOSTAT working group (EC 2005), is a very conservative approach and can thus lead to an underestimation of the actual ecological status.

The IRA methodology implements a WoE approach (Burton et al. 2002a, b; Linkov et al. 2009, 2011) and a fuzzy

inference system (FIS, Von Altrock 1995) to support the integration of heterogeneous information from different domains to draw conclusions about environmental impacts in river basins. Specifically, monitoring data are used to calculate a set of indicators, which are grouped into five LoEs, namely, biology, physico-chemistry, chemistry, ecotoxicology, and hydromorphology. The LoEs are then integrated according to a specific procedure to establish the ecological status of each sampling site. The biology LoE is referred to as the predominant LoE. Indicators within this LoE are first compared with appropriate benchmarks that are specific for each habitat typology and then aggregated to classify the biological status (according to five quality classes, namely, high, good, moderate, poor and bad). Then, each indicator belonging to the so-called supportive LoEs (i.e. physico-chemistry, chemistry, ecotoxicology and hydromorphology) is compared, for each sampling site within each habitat typology, with its benchmarks (i.e. reference conditions and environmental quality standards) in order to establish the quality conditions of water and sediment (i.e. high, good and not good). The outcomes are integrated with the biological status to confirm or to downgrade its classification, through a dedicated spatially explicit process. Differences between IRA and OOAO as well as examples of applications to a case study are presented by Gottardo et al. (2011a, b).

The environmental module of the MODELKEY DSS v 2.7 (Gottardo et al. 2009) is a freeware GIS-based software

Table 1 Combination of data in sampling sites from different monitoring studies

Additional sites from other studies	Existing sites from 2009 to 2010 monitoring programme	Spatial relationship	Chemicals measured in additional sites	
			In water	In sediment
T1	T18	T1 and T18 are in the same position	As, Hg, Cr, Cu, Cd, Zn, Pb, anthracene, fluorene, naphthalene, phenanthrene, dibenz[ah]anthracene, fluoranthene, pyrene, acenaphthylene, nitrobenzene ^a , 2,4-dinitrotoluol ^a , 2,4,6-trinitrotoluene ^a	As, Hg, Cr, Cu, Cd, Zn, Pb, Ni, anthracene, fluorene, naphthalene, phenanthrene, benz[a]anthracene, benzo[a]pyrene, chrysene, dibenz[ah]anthracene, fluoranthene, pyrene, acenaphthylene, acenaphthene, indeno(1,2,3-c,d)pyrene, benzo[ghi]perylene, nitrobenzene ^a , 2,4-dinitrotoluol ^a , 2,4,6-trinitrotoluene ^a , dieldrin ^b , endrin ^b , heptachlor ^b , aldrin ^b
B5	T34	B5 and T34 are in the same position		
T5	T40	T5 and T40 are in the same position		
B7	BS14	B7 and B14 are in the same position		
T6	T45	T6 is 790 m upstream of T45		
B8	T50	B7 and T50 are in the same position		
T7	T48	T7 and T48 are in the same position		

Source: Lin et al. (2013), Guo et al. (2009), Men et al. (2011) and Wang et al. (2007)

^a Chemicals are only measured in sites T1, T5, T6 and T

^b Chemicals are only measured in sites T1 and T5

system developed in the frame of the EU MODELKEY project (Brack et al. 2005), guiding the users (e.g. experts and decision-makers) in the assessment and management of river basins when implementing the WFD. The ecological status assessment of Taizi River was performed by applying both the IRA methodology and the OOA principle, which are both implemented in the environmental module of the MODELKEY DSS. For its application to the selected case study, the available datasets were processed according to the DSS database requirements (Semenzin et al. 2012).

According to the available monitoring data, a set of indicators were selected for the application of the IRA methodology to the Taizi River Basin. These indicators are reported in Table 2, together with the indication of the typology of impact that they are related to.

Eight biological indicators concerning fish, macroinvertebrates and algae were implemented in the environmental module of the MODELKEY DSS, namely,

Fish species richness (F_S), fish index of biotic integrity (F_IBI) and fish Berger-Parker index (F_BP); these indicators are related to physical, chemical, biological and zoogeographic factors and long-term pressures (Moyle and Cech 1988; Leigh et al. 2012);

Macroinvertebrate families richness (M_S), a measure of diversity of macroinvertebrate families, which reflects the general deterioration of water quality (Flores and Zafaralla 2012);

Biological monitoring working party (M_BMWP), that is a procedure based on macroinvertebrate community

assessment for measuring water quality related to organic pollution (Armitage et al. 1983);

Ephemeroptera, Plecoptera and Trichoptera family richness (M_EPT), displaying the taxa richness within the insect groups, which are considered to be sensitive to pollution (Mandaville 2002);

Algae species richness (A_S) and algae Berger-Parker index (A_BP), both reflecting the water quality deterioration related to eutrophication and organic pollution (Leigh et al. 2012).

For chemistry indicators, two indicators were calculated and implemented in the DSS: the chemical compliance with reference (CCWR; Gottardo et al. 2011b), which confirms high status if no one of the considered substances exceeds its reference value, and the Chemical Status, which considers only priority pollutants according to the Directive 2008/105/EC (EC 2008).

The used physico-chemical indicators were pH, dissolved oxygen (DO), electric conductivity (EC), COD, BOD₅, ammonia nitrogen (NH₃-N), and total phosphorus (TP).

Finally, the following hydromorphology indicators were selected for being included in the DSS application: water quantity (WQ), reflecting river hydrological regime, channel change (CC) related to river continuity, and morphology diversity (MD) reflecting morphological conditions (Ding et al. 2012).

The WFD requires to assess the status of surface water bodies by comparison with reference conditions, which can be defined as the set of conditions to be expected in the

Table 2 List of indicators applied to the Taizi River Basin for the MODELKEY integrated risk assessment and related impact typologies

Indicators for the ecological status		Impact typologies
LoE biology		
Fish	Species richness (F_S) (Moyle and Cech 1988)	General degradation
	Index of biotic integrity (F_IBI) (Leigh et al. 2012)	General degradation
	Berger-Parker index (F_BP) (Leigh et al. 2012)	General degradation
Macroinvertebrate	Families richness (M_S) (Flores and Zafaralla 2012)	General degradation
	Biological monitoring working party score (M_BMWP) (Armitage et al. 1983)	Organic pollution
	Ephemeroptera, Plecoptera and Trichoptera family richness (M_EPT) (Mandaville 2002)	General degradation
Algae	Species richness (A_S) (Leigh et al. 2012)	General degradation
	Berger-Parker index (A_BP) (Leigh et al. 2012)	General degradation
LoE chemistry		
Chemical compliance with reference (CCWR) (Gottardo et al. 2011b)		Toxic pressure
Chemical status (EC 2008)		Toxic pressure
LoE physico-chemistry		
Conductivity (EC)		Salinization
Dissolve oxygen (DO)		Organic pollution
Biological oxygen demand in 5 days (BOD ₅)		Organic pollution
Chemical oxygen demand (COD)		Organic pollution
Ammonia nitrogen (NH ₃ -N)		Eutrophication
Total phosphorus (TP)		Eutrophication
LoE hydromorphology		
Water quantity (WQ) (Ding et al. 2012)		Alteration of hydrological regime
Channel change (CC) (Ding et al. 2012)		Alteration of river continuity
Morphology diversity (MD) (Ding et al. 2012)		Morphological alteration

absence of or under minimal anthropogenic disturbances. For each indicator included in the assessment, there is a need to estimate the deviation from a reference condition (i.e. a control), expressed as a benchmark. Geographical reference sites (i.e. specific locations on a water body that is minimally impaired and is representative of the expected ecological integrity) can constitute the best choice for deriving reference conditions (Semenzin et al. 2012). When such sites do not exist for the river basin of interest, alternatives for setting the reference conditions can include historical or modelled data, established criteria or standards, expert opinion or local knowledge (Leigh et al. 2012). In the present study, the thresholds for the assessment of indicators belonging to the different LoEs were set by choosing appropriate quality standards or by drawing upon expert judgement. Indicators belonging to the LoE biology are considered as predominant and are hierarchically aggregated according to the OOA principle or the dedicated set of fuzzy inference rules in the IRA. The input information is the indicator value, processed according to four thresholds (i.e. high/good, good/moderate, moderate/poor and poor/bad), and expressed as fraction of the reference condition (RC) value. The thresholds used in this application were set as default values at 0.8, 0.6, 0.4 and 0.2 for high/good, good/moderate, moderate/poor and poor/bad, respectively,

on a scale from 0 to 1, where 1 is the best ‘condition’. Since there were no expected reference sites undisturbed by human activity (i.e. in a state of ecological integrity) in the Taizi River Basin, RC values were established case by case by using the values applied in the previous study (Leigh et al. 2012) or expert opinion or the 95th percentile of observed values in May 2009 (see Table 3a).

The indicators included in the supportive LoEs are then used to confirm or to downgrade the classification as high status and/or good status obtained by the LoE biology. Each indicator from the supportive LoEs is evaluated against one or two thresholds, and a dedicated evaluation process is applied to confirm (in case of full compliance) or reject the high/good status, as represented in the modified flow chart recommended by the CIS working group ECOSTAT (EC 2005) and reported in Gottardo et al. (2011b). For each supportive LoE, a negative response from even a single indicator is considered enough to refuse the classification into high and/or good status derived from the LoE biology.

The two thresholds set for each indicator belonging to the LoE chemistry, physico-chemistry or hydromorphology are reported in Table 3b.

For high/good thresholds, in order to calculate the CCWR indicator, the Canadian Sediment Quality Guidelines for the

Table 3 Thresholds used for biological (a), chemical, physico-chemical, and hydromorphological (b) indicators applied in IRA methodology

Biological indicators		RC value	Highlands	Midlands	Lowlands	Reference
Fish	F_S (scores \geq 0)	\geq 20	\geq 20	\geq 20	\geq 20	Expert opinion
	F_IBI (scores \geq 0)	\geq 63	\geq 63	\geq 63	\geq 63	Expert opinion
	F_BP (scores in 0–1)	\leq 0.15	\leq 0.15	\leq 0.15	\leq 0.15	Leigh et al. (2012)
Macroinvertebrate	M_S (scores \geq 0)	\geq 30	\geq 30	\geq 30	\geq 22	Leigh et al. (2012)
	M_BMWP (scores \geq 0)	\geq 131	\geq 131	\geq 131	\geq 81	Leigh et al. (2012)
	M_EPT (scores \geq 0)	\geq 15	\geq 10	\geq 10	\geq 7	Leigh et al. (2012)
Algae	A_S (scores \geq 0)	\geq 32	\geq 32	\geq 32	\geq 31	Expert opinion and 95th percentile of observed values in May 2009
	A_BP (scores in 0–1)	\leq 0.15	\leq 0.15	\leq 0.15	\leq 0.15	Leigh et al. (2012)
b)						
Supportive LoEs	Indicators	Thresholds	High/Good	Good/Not good	Definition of thresholds	
Chemistry	CCWR with Canada_ISQGs	<1	<1	Not applicable	To confirm the high status, the number of monitored chemicals exceeding the corresponding threshold has to be null. The thresholds for evaluating the compliance of each chemical are set as follows.	
	CCRW with Canada_WQGs	<1	<1		Canada_ISQGs (CCME 2002) and Canada_WQGs (CCME 2007) for organic chemicals: Numerical concentrations recommended as levels that should result in negligible risk to biota, biological functions, or any interactions that are integral to sustaining the health of ecosystems and the designated resource uses that they support.	
	CCRW with China_SWQs_I	<1	<1		China_SWQs_I (General Bureau of China National Environmental Protection 2002) for metals: chemical concentration thresholds not to be exceeded in water bodies used as source of drinking water and to national nature protection areas.	
	Chemical status with WFD_EQS	Not applicable	<1	<1	To confirm the good status, the number of priority pollutants exceeding the corresponding threshold has to be null. Individual thresholds are set as follows.	
	Chemical status with USEPA_ESL				WFD_EQS (EC 2008): concentration of a particular pollutant in surface water used to assess the chemical status of water bodies according to the WFD, defined to ensure that the right environmental conditions are created to support the biology; the EQS Directive (2008) establishes the maximum acceptable concentration and/or annual average concentration for 33 priority substances and 8 other pollutants which, if met, allows the chemical status of the water body to be described as ‘good’.	
	Chemical status with China_SWQs_III			<1	USEPA_ESL (USEPA 1989): conservative screening level values intended to be protective of benthic biota (different thresholds were used for chemicals in water and sediment).	
					China_SWQs_III (General Bureau of China National Environmental Protection 2002): chemical concentration thresholds not to be exceeded in water bodies classified as ‘class two protection areas’ used as centralized potable water source, protection areas for general fishes and swimming areas.	
Physico-chemistry	EC (μ S/cm)	400		766.67	Expert opinion.	

Table 3 (continued)

	DO (mg/L)	7.5	5	China_SWQs_I: thresholds for physico-chemical parameters not to be exceeded in water bodies used as source of drinking water and to national nature protection areas. These thresholds are used to distinguish between high and good status.
	BOD ₅ (mg/L)	3	4	
	COD (mg/L)	15	20	
	NH ₃ -N (mg/L)	0.15	1	
	TP (mg/L)	0.02	0.2	
Hydromorphology	WQ (scores in 0–20)	15	10	China_SWQs_III: thresholds for physico-chemical parameters not to be exceeded in class two protection areas for centralized potable water source, protection areas for general fishes and swimming areas. These thresholds are used to distinguish between good and not good status. For high/good threshold: Water quantity is sufficient to cover the river course (Ding et al. 2012). For good/not good threshold: Water quantity is relatively sufficient to cover about 75 % of the river course (Ding et al. 2012).
	CC (scores in 0–20)	15	10	For high/good threshold: rarely artificial channelization, river maintains its natural channels (Ding et al. 2012). For good/not good threshold: few artificial channelizations with little impact on aquatic organisms (Ding et al. 2012).
	MD (scores in 0–20)	15	10	For high/good threshold: many kinds of small habitats in the river, rich riparian vegetation covering more than 50 % area of the river bank, maintaining its stability. Four types of flow velocity and river depth combination (i.e. slow–deep, slow–shallow, fast–deep and fast–shallow) are evenly distributed in the river (Ding et al. 2012). For good/not good threshold: many kinds of small habitats in the river, riparian vegetation covering 25 to 50 % area of river bank, relatively maintaining its stability (only 5 to 30 % of areas have been eroded). Three types of flow velocity and river depth combination are distributed in the river (Ding et al. 2012).

RC reference condition, LoE line of evidence

Protection of Aquatic Life-Interim freshwater sediment quality guidelines (Canada_ISQGs) and the Canadian Water Quality Guidelines for the Protection of Aquatic Life (Canada_WQGs) were used as the thresholds for organic chemicals and metals in sediment and water, respectively. The Chinese Surface Water Quality Standards class I (China_SWQs_I) were used as thresholds for metals in water in order to compare the results of CCWR derived by different countries' benchmarks. China_SWQs_I were also used as the thresholds for high/good status of physico-chemical indicators. For hydromorphological indicators, the threshold proposed by Ding et al. (2012) for distinguishing between high and good status was used.

For good/not good thresholds, the WFD priority pollutant benchmarks (WFD_EQS), the USEPA Ecological Screening Level benchmarks for a wider list of pollutants in water and sediment (USEPA_ESL), and the Chinese Surface Water Quality Standards class III (China_SWQs_III) were used

to calculate the chemical status of each site. The China_SWQs_III were also used as the thresholds for good/not good status of physico-chemical indicators. For hydromorphological indicators, the threshold proposed by Ding et al. (2012) for distinguishing between good and not good status was used.

River health assessment methodology

The Taizi River has been the subject of a previous assessment undertaken as part of the project 'River Health and Environmental Flow in China' funded under the Australia-China Environment Development Partnership (Leigh et al. 2012). Leigh et al. (2012) assessed the ecological status of Taizi River Basin by applying the RHA methodology, which integrates physico-chemical indicators (i.e. EC, DO, NH₃-N, TP, BOD₅ (used in lowland only), COD (used in lowland only)) and biology indicators (the same used in IRA

application included in Table 3a for macroinvertebrates, fish, and algae) using the data from 69 sites sampled in May 2009.

Three scoring steps are recommended in RHA (Table 4). The first step consists in the calculation of a score for each selected indicator, based on the value monitored in the site for that indicator, the target value (a value representing good health status to be used as water quality objective) and a threshold value (corresponding to the limit between acceptable and unacceptable health status), according to Eq. 1 (Leigh et al. 2012). For each indicator, a score between 0 and 1 is obtained.

$$\text{Site indicator score} = 1 - \left(\frac{\text{target} - \text{observed}}{\text{target} - \text{threshold}} \right) \quad (1)$$

After calculating a score for each indicator at each site, site scores are aggregated into indicator group scores for the following indicator groups: physico-chemistry, nutrients, algae, macroinvertebrates and fish. The indicator group score for nutrients, algae, macroinvertebrates and fish is calculated by averaging the individual indicator scores. For physico-chemistry, the minimum score is taken as indicator group score because most of the physico-chemical indicators can be critically limiting for aquatic biota (Leigh et al. 2012).

For some indicators, a critical value is identified. If the observed value exceeds the critical value, a score equal to 0 is assigned to the indicator (irrespective of the actual score value) and therefore to the indicator group. This rule applies to DO (critical value $\text{DO} \leq 2 \text{ mg/l}$) for the physico-chemical indicator group and to NH_4 (critical value $\text{NH}_4 \geq 2 \text{ mg/l}$) for the nutrient group.

Finally, a whole ecosystem health score is calculated for each site (i.e. site score), based on the five considered indicator groups, following Eq. 2 (Leigh et al. 2012) and applying a decreasing weight moving from fish and macroinvertebrates to physico-chemistry and nutrient groups. This choice is due to the consideration that physico-chemistry and nutrient indicators may be influenced by short-term fluctuations, while the biotic indicators tend to integrate over longer periods of ecosystem health conditions. Similar motivations lead to weight fish and macroinvertebrate indicators more heavily than algal indicators because the former ones are longer lived than algae.

$$\begin{aligned} \text{Site Score} = & (\text{Nutrients score} \times 2/15) + (\text{Physico-chemistry} \times 2/15) \\ & + (\text{Algae} \times 3/15) + (\text{Macroinvertebrates} \times 4/15) \\ & + (\text{Fish} \times 4/15) \end{aligned} \quad (2)$$

Table 4 Main characteristics of the RHA methodology and the IRA methodology

Aggregating level	RHA methodology	IRA methodology	
		Predominant LoE	Supportive LoE
Individual indicator score	$1 - \left(\frac{\text{target} - \text{observed}}{\text{target} - \text{threshold}} \right)^a$	Observed/Target	Observed/Target
Indicator group score	Averaged across each group's individual indicators for nutrients, algae, macroinvertebrates and fish indicator group. The minimum score across all indicators is taken in the case of the physico-chemistry indicator group. Special rule: if $\text{NH}_4 \geq 2 \text{ mg/L}$, the nutrient indicator group fails (score=0).	First, averaged among biological indicators belonging to the same impact typology Second, results are aggregated to the same biological communities (fuzzy inference rules or OOAo principle) Third, results are aggregated to the biological status (fuzzy inference rules or OOAo principle)	For each supportive LoE, one single indicator providing a negative response is enough to reject the inclusion into high and/or good status derived from the LoE biology
Site score	$\text{Site score} = (\text{physico-chemistry score} \times 2/15) + (\text{nutrient score} \times 2/15) + (\text{algae} \times 3/15) + (\text{macroinvertebrates} \times 4/15) + (\text{fish} \times 4/15)$	The site score (ecological status) is determined by biological status; however, if biological status is high or good, the ecological status is determined by the supportive LoE status.	
Final classifications	<0.2 = critical ≤0.4 = poor ≤0.6 = fair >0.6 = good >0.8 = very good	<0.2 = bad ≤0.4 = poor ≤0.6 = moderate >0.6 = good >0.8 = high	

^a‘target’ referred to RC values or thresholds for good/not good status; ‘observed’ referred to observed values of sites; ‘threshold’ referred to represent the ‘worst case scenario’ (i.e. aquatic biota cannot survive and ecosystem functioning collapses resulting in a ‘disaster’ or critical situation)

The cut-off values for the final health status classification scheme are 0.2, 0.4, 0.6 and 0.8, corresponding to critical, poor, fair, good and very good classes, as reported in Table 4.

Comparison of the two methodologies

A summary of the main differences between the RHA methodology applied by Leigh et al. (2012) and the IRA methodology applied in the present paper is reported in Table 4. For the application of the IRA methodology presented in this paper, the same classification of habitat typologies, the same physico-chemical and biology indicators, and the same 69 sites to Leigh et al. (2012) were considered. In order to obtain a more comprehensive understanding of the ecological status and environmental pressures of the Taizi River Basin, the current study incorporates also data on chemical contamination (i.e. concentration of different PAHs and metals in water and sediment) and hydromorphological indicators (i.e. water quantity, channel change and morphology diversity).

Results and discussion

Assessment of IRA methodology results

Ecological status of Taizi River Basin

The spatial distribution of the results for the ecological status classification, as well as for the intermediate LoE classification (i.e. biology, physico-chemistry, hydromorphology and chemistry), for sampling sites in Taizi River Basin according to the IRA methodology is reported in Fig. 2.

The IRA fuzzy output of ecological status and biology LoE (Fig. 2a, b) is represented by the degree of inclusion to one or two adjacent WFD quality classes (high, good, moderate, poor and bad), while the output of physico-chemistry, hydromorphology, and chemistry LoEs (Fig. 2c) is represented as high, good and not good classes. For the limitation of available chemical monitoring data (only As and Hg in surface water were measured in most sites), the chemistry LoE classification results do not reflect the actual situation in the whole Taizi River Basin; that needs to be discussed separately.

As expected, both the IRA results for the ecological status and the intermediate LoEs (i.e. biology, physico-chemistry and hydromorphology) show a consistently negative trend from the highlands to the lowlands of the Taizi River Basin and within the tributaries. This observation is in general confirmed by the OOA ecological status classification (figure not shown).

Furthermore, when applying the OOA methodology, the percentage of sites which obtain a good and moderate

ecological status in the entire basin decrease by 29.6 % (and, accordingly, the percentage of sites in poor and bad ecological status increased by 29.6 %) in comparison with the results obtained from the IRA methodology, as illustrated by the charts in Fig. 3.

The general decreasing trend of river health status deteriorating from the highlands to lowlands in Taizi River Basin reflects the relative intensity of human activity within the catchment, with the highest level of urban and industrial development located in the mid to lower branches. These results confirm the outcomes of previous investigations: River sections located in midlands and highlands prove to have a better ecological status than lowland sections; however, they still turn out to be significantly affected by anthropogenic stress related to agriculture, urbanization, flow alteration and control, and in-stream extractive activities (Leigh et al. 2012).

Stress identification

A detailed analysis of the intermediate results obtained for the individual LoE shows that the biology LoE is classified mainly in the moderate class (41.7 % sites) and in the poor class (25.3 % sites).

The macroinvertebrate fauna is significantly impaired (60.6 % sites fall in bad and poor quality classes), while the fish community is less impaired. The algae community receives the best evaluation if compared to other communities (Fig. 4a).

Moreover, both physico-chemistry and hydromorphology LoEs seems to play a major role in contributing to the biological impairment, if compared to the chemistry pressure (Fig. 4b). However, it is worth noting that there are only two chemical indicators (i.e. As and Hg in surface water) which were measured in most sites, while the seven combined sites (BS14, T18, T34, T40, T45, T48 and T50) with additional chemical data (i.e. PAHs and metals both in surface water and sediment) are all in not good chemical status. It can be concluded that the chemistry pressure needs to be further analyzed by considering additional contaminants in a larger number of sites.

The analysis at indicator level identifies the BOD₅ and COD as the physico-chemical indicators reaching the lowest values (Fig. 4c), which indicates that the organic pollution plays the greatest influence on the biological communities' conditions. Moreover, WQ is the responsible for 61 % of sites in a not good condition. This result indicates that the hydrological regime is an important factor affecting the ecological status of the Taizi River Basin (Fig. 4d).

A further analysis at the seven combined sites characterized by the largest set of chemical contamination data shows that there is also a general decreasing trend of river health status from upstream to downstream areas. Sites T18 and T40 are in good biological status,

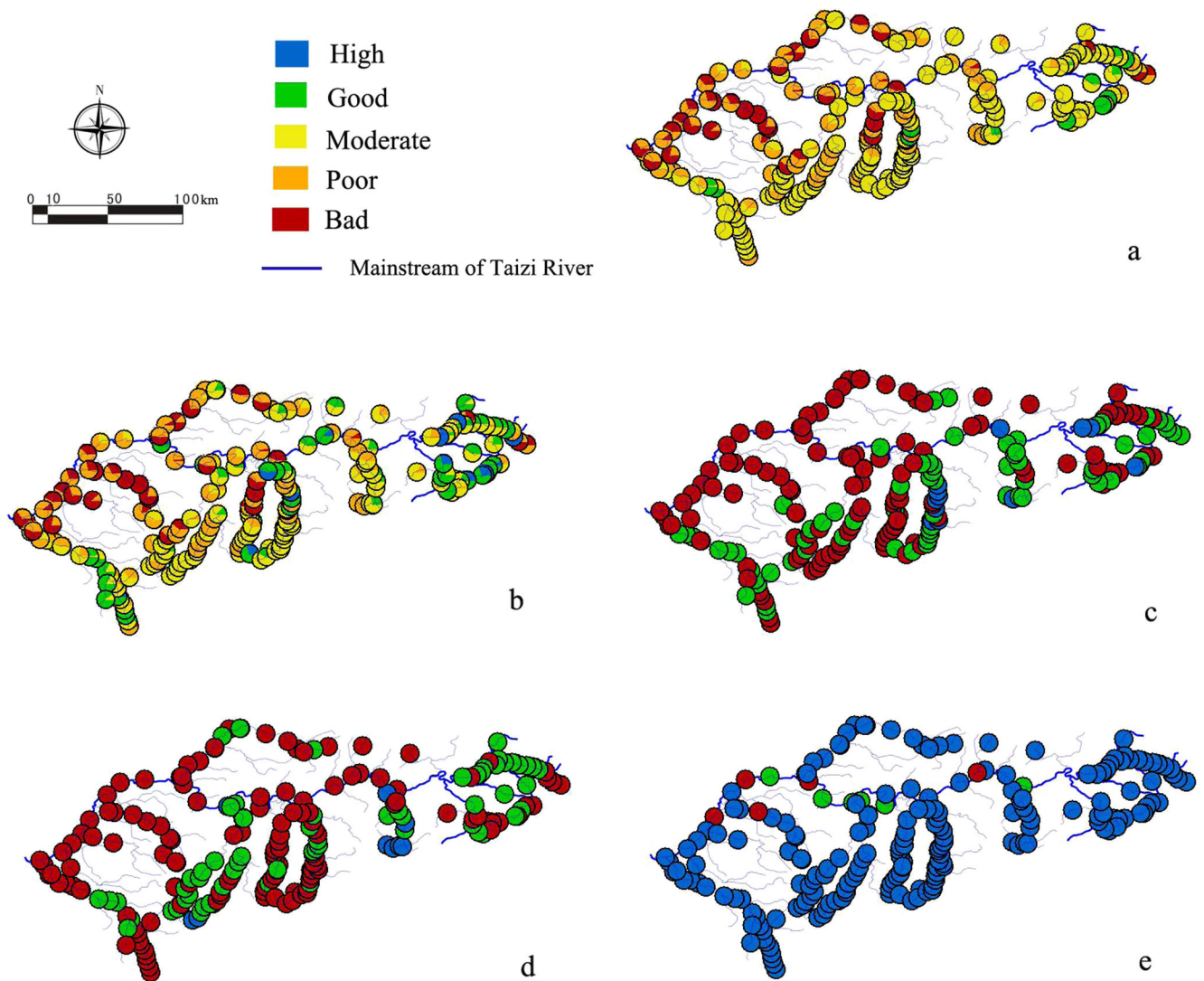


Fig. 2 Spatial distribution of the ecological status classification (a), biology LoE classification (b), physico-chemistry classification LoE (c), hydromorphology classification LoE (d) and chemistry classification LoE (e) for the sampling sites in Taizi River Basin according to IRA methodology

T34 and T45 are in poor biological status, and BS14, T48 and T50 are in bad biology status (Table 5). However, the classification of physico-chemistry,

hydromorphology and chemistry LoEs for all these seven sites results to be ‘not good’, which decreases the final classification of their overall ecological status.

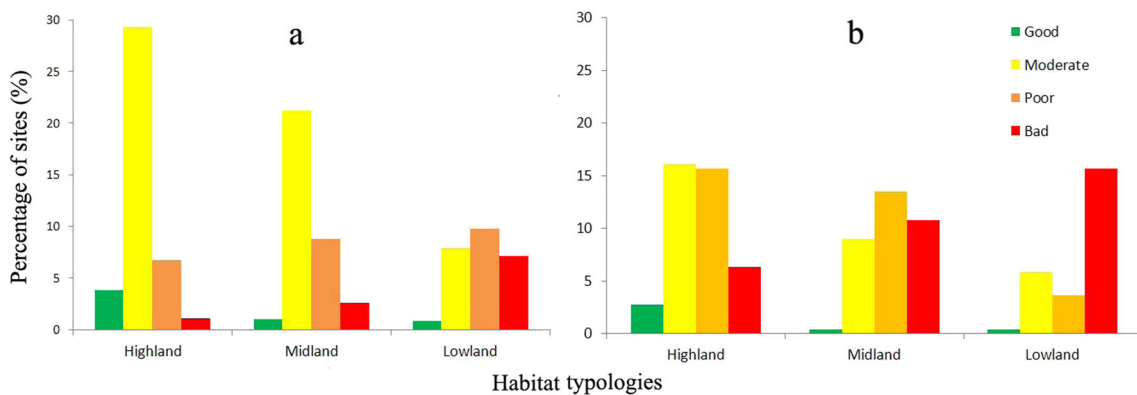


Fig. 3 Percentage of sites classified into the five WFD Ecological Status classes according to IRA (a) and OAO methodologies (b) in the Taizi River Basin

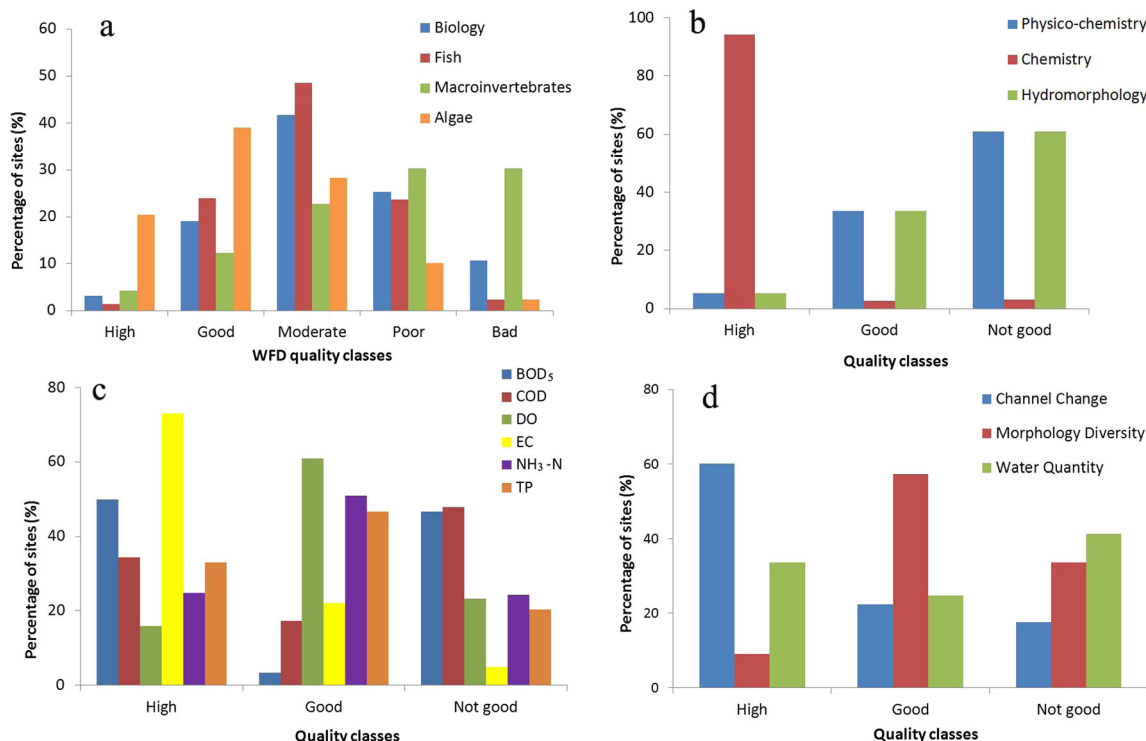


Fig. 4 Overview of intermediate results (percentage of sites) obtained by the application of the IRA methodology for the Taizi River Basin: **a** biological quality elements, classification of LoE biology as well as fish, macroinvertebrate, and algae communities according to WFD

classes; **b** classification of LoE chemistry, LoE physico-chemistry and LoE hydromorphology according to three classes (i.e. high, good, not good); **c** physico-chemical indicators; **d** hydromorphological indicators

The biological community that mostly determines the lowering of the class for the biological LoE is the macroinvertebrate fauna, while COD and BOD₅ are the physico-chemical indicators which most often exceed the threshold in the seven sites. MD (representing the alteration of morphological condition) and WQ (representing the alteration of hydrological regime) are the hydromorphology indicators which most often exceeded the threshold.

The chemicals exceeding the thresholds for the WFD priority pollutant benchmarks (WFD_EQS), the USEPA ecological screening level benchmarks (USEPA_ESL, ‘S’ referred to sediment guideline, ‘W’ referred to water guideline), and the China_SWQs_III are also reported in Table 4. For site BS14, there are no chemicals exceeding the thresholds for WFD_EQS and China_SWQs_III, but three chemicals exceeding the USEPA_ESL, the DSS automatically considers the worst situation to classify the chemical status, that is not good.

The results show that fluoranthene, polyaromatic hydrocarbons, anthracene, benzo[a]pyrene, Hg and Cd are the chemicals most responsible for not reaching the good status in surface water, while in sediment these are acenaphthylene, naphthalene, 2,4-dinitrotoluol, As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn. The results indicate that the chemical pollution from industry in midlands and

lowlands is likely to be an important factor affecting the health of river ecosystems. The results also show that the China_SWQs have the poorest capability to identify the chemicals which have potential impacts on aquatic organisms, and neither China_SWQs nor WFD_EQS allow to properly identify the chemical pressure from sediment contamination (Table 5).

Comparison of results between IRA and RHA methodologies

The comparison of the results for the ecological status classification for the same 69 sites assessed through the RHA (Leigh et al. 2012) and IRA methodologies (Fig. 5a) shows that the OOA methodology provides the most strict ecological status classification of Taizi River Basin. It is also relevant to highlight that in both OOA and IRA results, there are no sites assigned to the high ecological status.

The most ‘optimistic’ assessment results were obtained by Leigh et al. (2012) with two sites assigned to the high (excellent) ecological status and only 7.2 % of the sites assigned to the bad (critical) ecological status. The comparison of the classification results of LoE biology (considering fish, macroinvertebrate, and algae communities) between IRA and RHA applications confirms that

Table 5 Ecological status classification, classification of individual LoEs, and indicators/chemicals exceeding the thresholds for the seven combined sites according to the IRA methodology

Sites and habitat typologies	T18	T34	T40	BS14	T45	T50	T48
Results	Upstream → downstream						
	Midland						
Ecological status	Moderate	Poor	Moderate	Bad	Poor	Bad	Bad
Biology	Good	Poor	Good	Bad	Poor	Bad	Bad
Impaired fauna	No exceedance	Macroinvertebrate	No exceedance	Macroinvertebrate	Macroinvertebrate	Macroinvertebrate	Fish, macroinvertebrate
Physico-chemistry	Not good	Not good	Not good	Not good	Not good	Not good	Not good
Exceeding indicators	COD	DO, BOD ₅ , COD	DO, COD	BOD ₅ , NH ₃ -N	DO, BOD ₅ , TP, NH ₃ -N, COD	EC, DO, BOD ₅ , TP, NH ₃ -N, COD	BOD ₅ , TP, NH ₃ -N, COD
Hydromorphology	Not good	Not good	Not good	Not good	Not good	Not good	Not good
Exceeding indicators	MD	MD, WQ	MD	MD	MD, WQ	MD, CC	MD
Chemistry	Not good	Not good	Not good	Not good	Not good	Not good	Not good
Exceeding chemicals	Fluoranthene, Hg	Polyaromatic hydrocarbons, Hg	No exceedance	Polyaromatic hydrocarbons, Hg	Cd	Fluoranthene, Hg	Anthracene, Cd, Hg
USEPA_ESL_S	Acenaphthylene, Cr, Cu, Ni	Acenaphthylene, Naphthalene, Cr, Cd, Ni	Acenaphthylene, Naphthalene	Acenaphthylene, Cr	Acenaphthylene, Naphthalene	Acenaphthylene, Naphthalene, 2,4-dinitrotoluol, Cr	Acenaphthylene, Cr
USEPA_ESL_W	No exceedance	Benzo[a]pyrene, Hg	Benzo[a]pyrene	Benzo[a]pyrene	Benzo[a]pyrene	Benzo[a]pyrene, Hg	Benzo[a]pyrene
China_SWQs_III	Hg	Hg	No exceedance	Hg	No exceedance	Hg	Hg

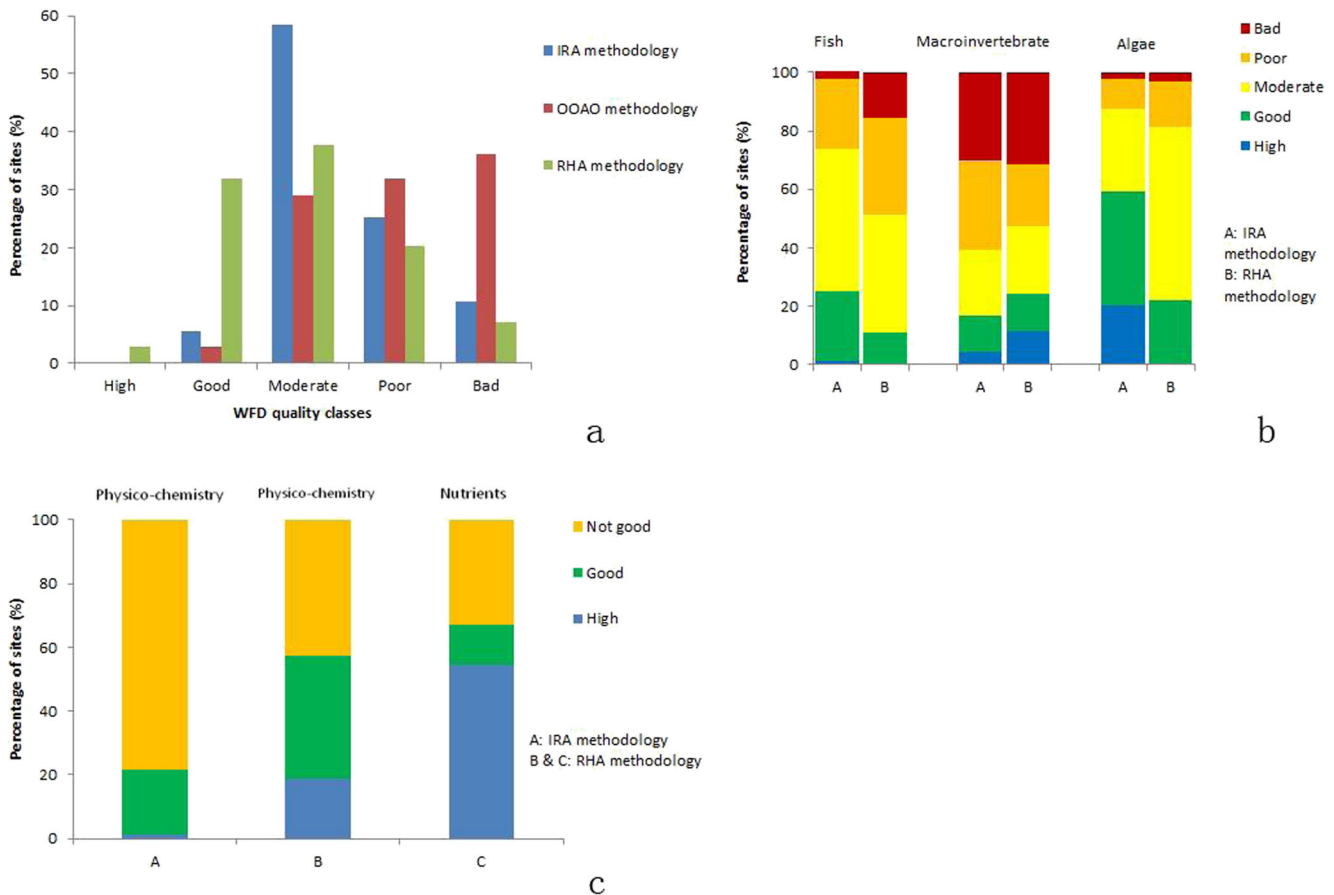


Fig. 5 Comparison of the ecological status classification according to IRA, OOA and RHA methodologies (a); comparison of the classification of LoE biology fish, macroinvertebrate, and algae communities according to IRA and RHA methodology (b) and LoE

physico-chemistry (c) according to IRA methodology and RHA methodology (all the comparisons consider the results for the same set of sampling sites)

the macroinvertebrates represent the most impaired fauna group (Fig. 5b). The fish and algae communities receive a relatively better classification from the IRA methodology if compared to the previous study, which indicates that the degradation of ecological status from the IRA methodology can be mainly attributed to the inclusion of the supportive LoEs, in particular the physico-chemistry LoE (Fig. 5c).

The differences in the results between the IRA and the RHA methodology application can be associated to the following factors:

1. The numbers of indicators included in the evaluation process: In the IRA methodology application, COD (LoE physico-chemistry); water quantity, channel change, and morphology diversity (LoE hydromorphology); and PAHs and metal concentrations (chemistry LoE) are included in the assessment, which means that more factors potentially influencing the ecological status are taken into consideration in the IRA application;
2. Threshold refinement: Some thresholds (namely, the thresholds for the indicator “fish species richness”) were refined according to expert opinion in the IRA application, which could be further improved when more historical or field data are available. A rigorous and transparent process has always to be followed in setting reference conditions or target values because, as previously discussed in Semenzin et al. (2012), this is a sensitive step in the integrated risk assessment process that could lead to significantly different results irrespective of the algorithms included in the adopted methodologies;
3. The methodologies used for the integration of data from different domains: The IRA implements three hierarchical aggregation steps based on fuzzy inference system for the LoE biology (predominant LoE), and it applies the OOA principle for physico-chemistry, hydromorphology and chemistry (supportive LoE); these approaches lead to more stricter results with respect to the RHA methodology proposed by Leigh et al. (2012) (Table 3).

Conclusions

The MODELKEY IRA methodology considering data from biology, physico-chemistry, hydromorphology and chemistry domains was applied to evaluate the ecological status of the Taizi River Basin in north-east China, in order to compare this approach with the RHA methodology proposed by Leigh et al. (2012), previously applied to the same case study.

The results of the IRA methodology show that there is a negative trend in the ecological status from the highlands to the lowlands of the Taizi River Basin and within the tributaries, reflecting the relative intensity of human activity within the catchment, with the highest level of urban and industrial development located in the mid to lower reaches.

At the level of individual indicators, BOD₅ and COD (reflecting the organic pollution from industry and agriculture), water quantity (reflecting the hydrological regime which strongly impacted the river health in northern China), PAHs and metal concentrations (associated to the industrial pollution caused by the steel and iron factories and petroleum and chemical factories located in the big cities in the mid and low lands such as Benxi, Anshan and Liaoyang) are the indicators which mostly contribute to lower the ecological status of the Taizi River Basin.

The results indicated that the detrimental impacts of chemical pollution on the biological communities and the overall ecological status, which was not considered in the previous studies (Meng et al. 2009; Leigh et al. 2012), cannot be ignored in Taizi River Basin. The chemical analysis also indicated that the present guidelines for river health assessment in China cannot effectively support the identification of the effects of potential chemical pollution. Thus, guidelines for river monitoring and associated quality standards are recommended to be developed in the future, including the requirement for a detailed assessment of chemical contamination status both in water and sediment compartments.

The comparison between IRA and RHA methodology results provides a better understanding of the identification of the biological communities (i.e. macroinvertebrates) that are potentially at risk and the description of stressors (e.g. organic pollution, chemicals discharged by industry and flow shortage) that are most likely responsible for the observed alterations in Taizi River Basin. The previous study by Leigh et al. (2012) provided a simpler integration methodology and more readable classification results for assessors, while the IRA methodology implemented in MODELKEY DSS considers more factors (as required by WFD) and consists of a more refined approach which can provide more information on the identification of stressors. The IRA methodology requires much more investment on the data collection but can effectively support the development of appropriate management actions for rivers affected by chemical or hydromorphological

alterations, focusing on the most critical areas, as well as help in the definition and implementation of future cost-effective monitoring plans. The most appropriate integrated risk assessment methodology should be selected case by case considering management objectives, local experts' opinion, and available capital budget.

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