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A Gis-based system for assessing marine water quality around offshore platforms

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A B S T R A C T

In this study, a GIS-based system (MWQ-FES) is developed for marine water quality assessment around offshore oil platforms. The developed method consists of a fuzzy risk assessment model, a eutrophication assessment module, a heavy metal assessment module, a dynamic database, the ArcGIS Engine, and a graphical user interface (GUI). The developed GIS-based GUI system integrates the fuzzy risk calculation, eutrophication risk assessment and heavy metal risk evaluation and both spatially and visually presents the results in the form of contour maps and color-coded maps that indicate the risk levels. The assessment modules analyze a large amount of data with both spatial and temporal distributions; these data are managed by the developed system. An application of the developed MWQ-FES to a real case study in China is presented in this study. The MWQ-FES produces risk maps that depict the spatial distribution of the integrated water quality index values, the eutrophication risk level and the heavy metal risk level in the study area. The primary factors that affect the water quality are subsequently examined using the visualized results. The results of the fuzzy risk assessment model show that the general water quality status in the study area was good in Oct. 2005, May 2006, and Sept. 2007, while fair water quality occurred in May 2007. For Oct. 2005, May 2006, and Sept. 2007, the eutrophication risk levels were oligotrophic, slightly eutrophic and mesotrophic, respectively. However, the eutrophication risk level at most of the sites in May 2007 was highly eutrophic. These findings agreed with previously reported water quality variations in the study area. The heavy metal risk level in the study area exhibited a slight risk during all four investigations. As for the ecological risk in the mariculture zone near the study area, the heavy metal risk exhibited a slight risk; the eutrophication risk level ranged from eutrophic to slightly mesotrophic. A comparison with previous environmental assessment results for the same study area confirms that the developed MWQ-FES can provide a better understanding of the distribution of the water quality status and ecological risk levels. Moreover, MWQ-FES can be a useful decision-support tool for marine water quality management.

1. Introduction

Adverse effects on water quality arise from the generation of large amounts of gaseous, liquid and solid wastes during offshore oil production, e.g., produced water, drilling fluids and crude oils (Olu-Owolabi et al., 2012). Water quality requires increased attention especially when the offshore facilities are located adjacent to environmentally sensitive regions.

Previous research on surface water quality assessments has proposed various indices to assess the effects of the relevant water quality parameters (Akkoyunlu and Akiner, 2012; MicClelland, 1974; Said et al., 2004). Most of these methods are based on the USEPA Water Quality Index, which was developed by the U.S. National Sanitation Foundation (Said et al., 2004). However, water quality generally cannot be indicated by a simple number or factor (Chen et al., 2010). Particularly, traditional water quality index methods are incapable of handling the uncertainties associated with complex environmental factors, such as physical, chemical, biological interactions and anthropogenic inputs. These problems favor the use of fuzzy logic methods instead of the conventional approaches to handle uncertainties in preference (Ocampo-Duque et al., 2006).

Fuzzy-set based methods have been extensively used to assess surface water quality. To address the additional uncertainty that

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arises from missing data of hydrology variables, an imprecise fuzzy waste load allocation model was developed by Rehana and Mujumdar (2009) for river water quality management. Moreover, Zheng et al. (2007) applied the fuzzy synthetic evaluation method to assess sea water quality in a waste dumping area; the marine water quality level was determined according to the maximum membership principle. The maximum membership principle has a disadvantage due to information loss and may cause deflected results. Therefore, Liu et al. (2010) applied an improved fuzzy synthetic evaluation method to assess the water quality in the Three Gorges region; more credible results were obtained by replacing the maximum membership principle with the weighted average principle. Water quality is spatially distributed; however, the results of fuzzy set-based methods used in previous studies are simply numerical index values without any visually well-displayed forms, which leads to an inadequate representation of the water quality assessment model results. Furthermore, there is a lack of knowledge regarding the interface system that integrates the fuzzy-set based methods and the spatial output in the forms of maps representing the degree of contamination.

Eutrophication is a crucial phenomenon to be included in surface water quality assessment. Eutrophication in the marine environment is a complex problem with adverse effects on the health of the ecosystem and presents one of the major stresses to the marine environment (Meyer-Reil and Köster, 2000). Nutrients, phytoplankton biomass and organic matter are the key variables that should be monitored during eutrophication assessment. Most eutrophication assessment methods integrate physicochemical and biological indicators, such as Chlorophyll a, nutrients, dissolved oxygen, chemical oxygen demand (COD), macro algal abundance, the changes in the distribution of submerged aquatic vegetation, and the increasing occurrence of harmful algal blooms, to provide basic information for management decisions (Herrera-Silveira and Morales-Ojeda, 2009; Pu et al., 2012; USEPA, 2008).

Previous studies regarding heavy metal ecological risk have primarily focused on the sediment environment, corresponding to the region that has been found to contain the highest heavy metal concentrations (Bastami et al., 2014; Liu et al., 2014; Wu et al., 2014; Yi et al., 2011). Although water bodies tend to have the lowest heavy metal concentrations in the aquatic system, the accumulation of heavy metals in fish and other aquatic animals results primarily from surface contact with the water and via the food chain. The uptake amount through these routes depends on the environmental levels of heavy metals in the fish habitat. Thus, heavy metal in the water may cause adverse effects on fisheries. The potential ecological risk index developed by Hakanson (Hakanson, 1980) is a comprehensive method that has been widely used to evaluate the combined heavy metal risk in aquatic systems (Bastami et al., 2014; Pekey et al., 2004; Zhang et al., 2013).

Geographical information system (GIS) provides significant contributions to risk assessment and environmental management systems in virtue of its intrinsic ability to analyze and display large amounts of spatial data. The powerful visualization of data and analysis results are useful in decision-making processes (Debaine and Robin, 2012; Vafai et al., 2013). Existing GIS-based environmental models can be classified into two groups. Models in the first group mainly use GIS to visualize model results over geographical area (Dixon, 2005; Pathak and Hiratsuka, 2011; Reshmidevi et al., 2009; Vafai et al., 2013). In the second group, models are encapsulated into GIS with a shared GIS interface, or the GIS components are embedded into the developed system (Akbar et al., 2011; Giordano and Liersch, 2012; Martin et al., 2004; Vairavamoorthy et al., 2007). The methods in the second group provide a good direction for developing GIS-based environmental assessment systems.

This study aims at developing a GIS-based fuzzy system called MWQ-FES for marine water quality assessment. It is intended to develop a tool that combines the functions of fuzzy-set based environmental risk assessment and GIS. A GUI user interface is further developed to manage the calculation process of the proposed water quality assessment models and to visually present input data and geo-referenced assessment results.

2. Materials and methods

This section presents a brief description of the fuzzy-set theory. A discussion is provided below that address the determination of the membership matrix and the weight vector, and the definition of water quality categories. Moreover, the eutrophication risk level and heavy metal risk level are evaluated. The components and the organization structure of MWQ-FES are also discussed.

2.1. Fuzzy-set based risk assessment model

As one of the commonly used fuzzy-set based methods, the fuzzy synthetic evaluation method is selected to assess the marine water quality in the system. The fuzzy synthetic evaluation consists of four parts: the calculation of the fuzzy membership matrix, the determination of the weight vector, the determination of the final evaluation results and the classification of the water quality.

The fuzzy synthetic evaluation method for assessing marine water quality is developed through the following seven steps:

[i] Select marine water quality parameters to be used in the assessment.
[ii] Establish the evaluation criteria.

Local marine water quality standards are used as the assessment criteria for each indicator in this study.

[iii] Establish membership functions based on the marine water quality assessment criteria.

In fuzzy logic, the membership function represents the degree of truth as an extension of valulation through mapping each point in the input space to a membership value (or degree of membership) between 0 and 1. In this study, on the basis of marine water quality assessment criteria, the membership functions of each water quality parameter at each level can be described by the following set of equations (Icaga, 2007):

$$r_{ij}(x_i) = \begin{cases} 1 & x_i < S_{ij} \\ (S_{i(j+1)} - x_i)/(S_{i(j+1)} - S_{ij}) & S_{ij} \le x_i \le S_{i(j+1)} \\ 0 & \text{otherwise} \end{cases} \quad j = 1, \tag{1}$$

$$r_{ij}(x_i) = \begin{cases} (x_i - S_{i(j-1)})/(S_{ij} - S_{i(j-1)}) & S_{i(j-1)} \le x_i \le S_{ij} \\ (S_{i(j+1)} - x_i)/(S_{i(j+1)} - S_{ij}) & S_{ij} < x_i \le S_{i(j+1)} \\ 0 & \text{otherwise} \end{cases} \quad j = 2, 3, \tag{2}$$

$$r_{ij}(x_i) = \begin{cases} 0 & x_i < S_{i(j-1)} \\ (x_i - S_{i(j-1)})/(S_{ij} - S_{i(j-1)}) & S_{i(j-1)} \le x_i \le S_{ij} \\ 1 & x_i > S_{ij} \end{cases} \quad j = 4, \tag{3}$$

where $r(x)$ is the membership function, i is the number of assessment factors, j is the number of assessment criteria levels, x_i is the observed value of each parameter, $S_{i(j+1)}$,S_{ij}, and $S_{i(j-1)}$ are the assessment thresholds of the ith water quality parameter at levels $j+1$, j and $j-1$, respectively.

[iv] Calculate the fuzzy relationship matrix.

Substituting the data of each water quality parameter and the thresholds for the criteria into the membership functions defined above, the fuzzy matrix R can be expressed as:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}. \tag{4}$$

[v] Determine the weight matrix.

In the fuzzy synthetic evaluation system, each water quality parameter plays a different role when its weighting coefficient is different. The normalized weight for each parameter is defined as:

$$w_{oi} = (x_i/S_{oi}) / \sum_{i=1}^{n} (x_i/S_{oi}) \tag{5}$$

where w_{oi}, x_i, and S_{oi} represent the weight vector, the weight after being normalized, the observed value of the selected water quality parameter, and the average value of all assessment thresholds of the ith parameter, respectively. The weight vector W is subsequently defined as follows:

$$W = \{w_{01}, w_{02}, \cdots, w_{0n}\} \tag{6}$$

This method not only emphasizes the main parameters in environmental assessment, but also considers the difference between the assessment thresholds of the parameters (Zheng et al., 2007).

[vi] Calculate the fuzzy synthetic evaluation vector. The following equation is used for this step:

$$b_j = \sum_{i=1}^{p} (w_{oi} \bullet r_{ij}), \tag{7}$$

where b_j is the weight of the value of the ith assessment parameter at level j and r_{ij} is the membership degree of the ith parameter to the assessment criteria at level j.

The vector can then be expressed as:

$$\begin{aligned} B = W{*}R = [w_{01} \quad w_{02} \quad \cdots \quad w_{0n}] \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \\ = [b_1 \quad b_2 \quad \cdots \quad b_n]. \end{aligned} \tag{8}$$

[vii] Determine the water quality categories.

The maximum membership principle is a commonly used method that is in fuzzy synthetic evaluation. According to this principle, the maximum value of b_j in the vector B is chosen to determine the water quality category, and some information may be lost during this process. Therefore, the weighted average principle is used in this study to improve the maximum membership principle by enhancing retaining the information in the assessment coefficients (Liu et al., 2010). Here,

Table 1
Eutrophication risk levels corresponding to the eutrophication index intervals.

Eutrophication Index	Eutrophication risk level	Color
E < 1.0	Oligotrophic	
1.0 ≤ E < 2.0	Light eutrophic	
2.0 ≤ E < 5.0	Mesotrophic	
5.0 ≤ E < 15.0	High eutrophic	
E ≥ 15.0	Severe eutrophic	

Table 2
Toxic-response factors for selected heavy metals.

Heavy metal	Hg	Cd	As	Pb	Cu	Cr	Zn
T_r^i	40	30	10	5	5	2	1

$$B{*} = \frac{\sum_{j=1}^{m} b_j^k \cdot j}{\sum_{j=1}^{m} b_j^k}, \tag{9}$$

where k is a coefficient to control the importance of the maximum value of b_j. Typically, $k = 1$ or 2. In this study, $k = 1$. Moreover, B* is the fuzzy marine water quality index. The water quality classification is defined according to B* values and local regulations of the study area.

2.2. Eutrophication risk level evaluation

Considering the eutrophication status is one of the key factors for the comprehensive risk assessment of environmentally sensitive areas, e.g., mariculture zones, the eutrophication index is used herein to represent the eutrophication condition in the study area.

Based on the "Specification for Offshore Environmental Monitoring of China" (HJ-442, 2008), three key water parameters are included in the evaluation of eutrophication: the chemical oxygen demand (COD), inorganic nitrogen, and phosphate. The eutrophication index is calculated as follows (HJ-442, 2008):

$$E = \frac{C_{COD} \times C_{\text{Inorganic Nitrogen}} \times C_{\text{Phosphate}}}{4500} \times 10^6, \tag{10}$$

where E is the eutrophication index, C_{COD},$C_{\text{Inorganic Nitrogen}}$, and $C_{\text{Phosphate}}$ are the COD, inorganic nitrogen, and phosphate concentrations in mg/L, respectively.

Table 1 indicates the eutrophication levels that correspond to the eutrophication index intervals.

2.3. Heavy metal risk level evaluation

Hakanson (1980) presented the calculation of heavy metal risk index that is widely used in subsequent research. It is calculated as:

Table 3
Heavy metal risk levels corresponding to RI intervals.

Heavy metal risk index	Heavy metal risk level	Color
RI<110	slight ecological risk	
110 ≤ RI <220	medium ecological risk	
220 ≤ RI <440	high ecological risk	
RI ≥ 440	severe ecological risk	

$$RI = \sum_{i=1}^{n} T_r^i C_s^i \Big/ C_n^i, \qquad (11)$$

where T_r^i is the toxic response factor for a given substance to the aquatic system (Pu et al., 2012) and C_s^i represents a metal's concentration in the water samples. The values of C_n^i correspond to the reference concentration of heavy metals to which the risk is considered.

The toxic response factors for heavy metals are listed in Table 2 (Hakanson, 1980).

The heavy metal risk levels corresponding to individual RI intervals are listed in Table 3.

The assessment modules described above are integrated within the developed GIS-based interface system that is described in the following section.

2.4. Development of a GIS based marine water quality assessment system

This GIS-based water quality assessment system is developed using the C sharp programing language and is integrated with the fuzzy synthetic evaluation model, the eutrophication risk and heavy metal risk evaluation modules, ArcGIS Engine 9.3, and the Microsoft Access database software. The primary components and working processes of the MWQ-FES are shown in Fig. 1.

The six primary components of MWQ-FES support the following functions: data entry and input analysis, risk assessment model (including fuzzy synthetic water quality assessment), eutrophication risk and heavy metal risk evaluation, data storage and management, producing risk maps with the retrieved data, displaying the database and the risk maps, and export of the results.

2.4.1. Data processing and management

The database is designed to achieve three main functions: data acquisition, data processing, and data management. Data acquisitions are achieved by capturing the input of the user through the interface. The acquired data are processed using the risk assessment model. The input data and model results are subsequently stored in the database and displayed in the data table tab in the user interface.

Database management is conducted using the Microsoft Access software. Some basic management options are linked to the interface by considering the convenience, including the sorting of columns and the deletion of selected rows. To avoid unintentional data alteration and deletion, the modification of data and the direct removal of rows or columns in the data table are unavailable. The data are exported to an Excel file for further reorganization and calculations.

Data in the database are grouped by survey date, which can be extracted from the corresponding column. All of the survey dates and water quality parameters in the input module are added to the drop-down menus in the “Create Maps” module that is described in the following section. Using this menu, users can obtain the resulting contour maps for different water quality parameters in each investigation and produce color-coded maps for eutrophication risk and heavy metal risk.

2.4.2. Development of a GIS-based user interface system

By integrating ArcGIS Engine 9.3 into the system, GIS was used as a post-processor of the risk assessment model. The ArcGIS Engine component was linked to the database, which is the data source for creating risk level maps. This component processes the retrieved data and creates and displays risk maps. Moreover, this component also contains some common GIS functions that are

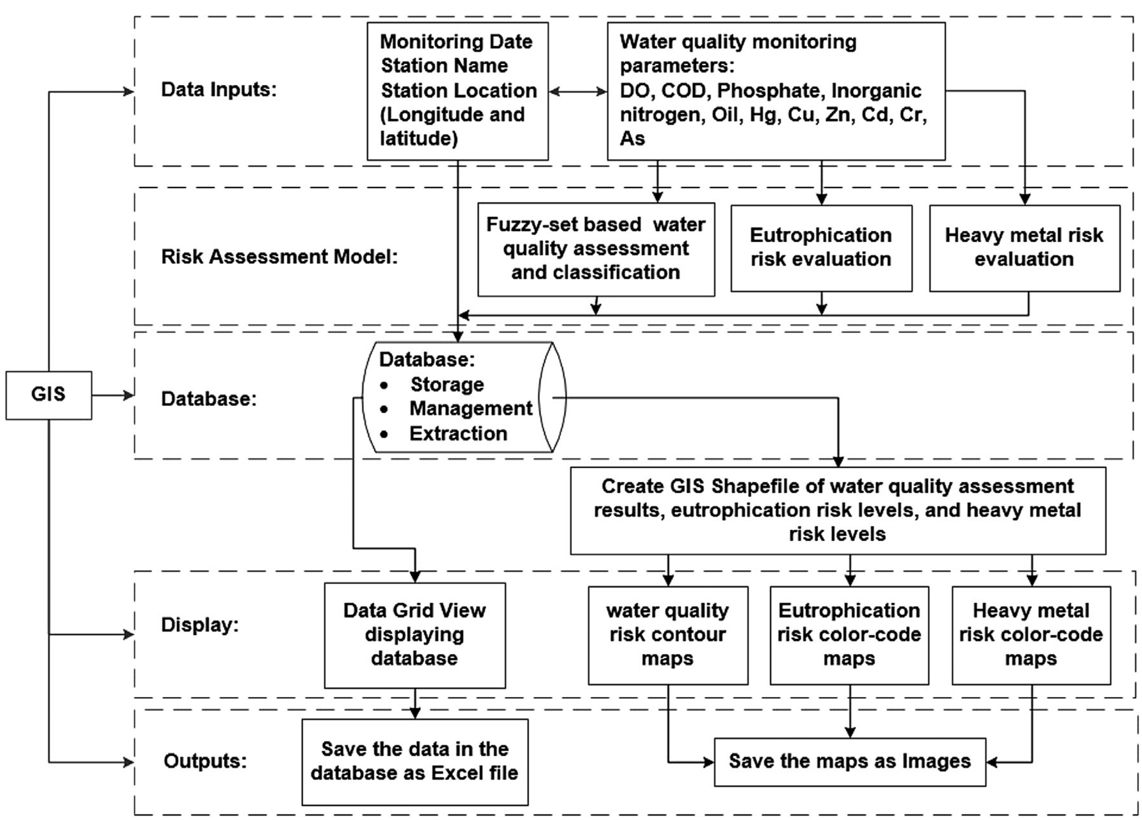

Fig. 1. The primary components and working process of the MWQ-FES.

listed in the toolbox at the top of the map window. The main interface of the system is shown in Fig. 2.

The developed system facilitates calculations of the fuzzy synthetic evaluation model and intuitively demonstrates the results by integrating with GIS-based visualization. The implementation of the system functions can be achieved as follows (Fig. 2):

[I] Enter investigation data, including the information of the monitoring station, the investigation time and observed values of parameters involved in the assessment, in the "Parameter Input" module.

[II] Click the "Run FSE Model", "Calculate Eutrophication Index" and "Calculate Heavy Metal Risk Index" buttons to obtain the fuzzy synthetic evaluation result and the water quality classification, the eutrophication index and eutrophication risk level, and the heavy metal risk index and heavy metal risk level, respectively.

[III] Save all input data and results in a database, which can be displayed using the data table tab in the interface.

[IV] Refresh the data source, select the date of investigation and parameter and set the interval of the contours in the map. By clicking the "Create Contour Map" button, the contour map is automatically produced and added to the base map. The user can choose to display a contour map or a filled contour map by clicking the checkbox in front of the layer. The contour map includes contour lines with the corresponding fuzzy water quality index labels adjacent to each line. The filled contour map uses black, white and shades of grey to depict the corresponding fuzzy water quality index, with a legend shows the corresponding colors. Then, click the "Create

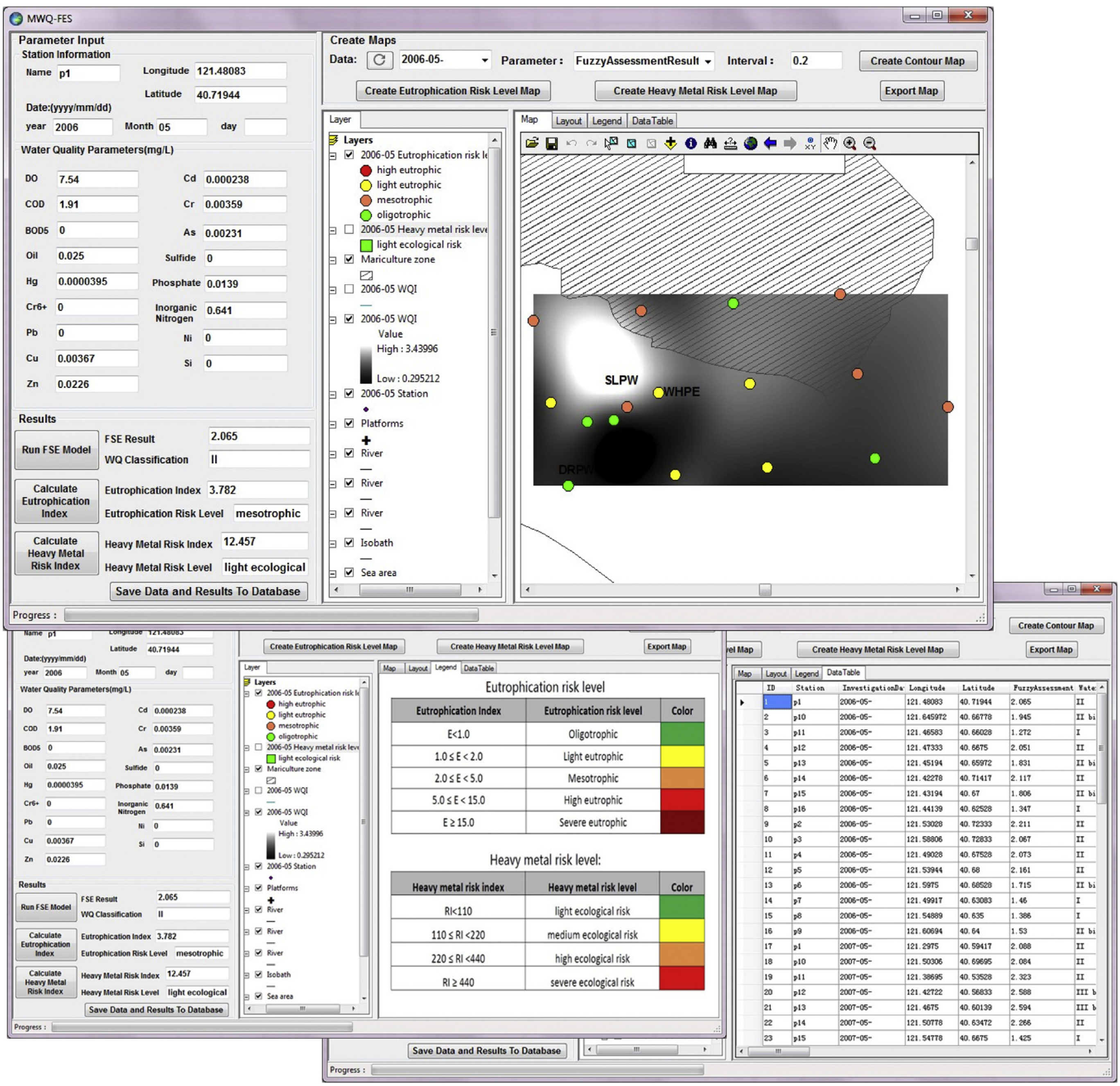

Fig. 2. The main user interface of MWQ-FES.

Eutrophication Risk Level Map" and "Create Heavy Metal Risk Level Map" buttons to obtain the respective color-coded maps of risk level. The legend for these color-coded maps is located in the legend tab in the interface.

[V] The layout tab in the interface presents the produced maps from the system with longitude and latitude axes, a north arrow, and a plotting scale. To export the produced maps, users can use the "Export Map" button to export the selected maps as images. By right clicking on the selected line in the data table and selecting the export item, the data can be saved as Microsoft Excel files.

For example, input the information for station P1 and the 11 water quality parameters in the input module (Fig. 2). Then, click the "Run FSE Model" button to obtain the fuzzy synthetic evaluation result and the water quality classification, which is 2.065 and class II, respectively. The eutrophication and heavy metal indices and risk levels can be acquired by clicking the corresponding buttons. By clicking the "Save Data and Results to Database" button, the information and assessment results for station P1 are saved to the database and displayed in the data table. After completing the calculations for all of the stations in one survey, the user can proceed to step 4, choosing the survey date and parameter, setting the contour interval, and subsequently creating contour maps and risk level maps, then exporting the maps and data.

3. Case study

3.1. Study area

The location of the study area is presented in Fig. 3. The minimum distance from the selected platforms to the coastline is 15 km. Water depths in this area range from 6.5 to 10.5 m. The tide is regular semi-diurnal with a high slack tide of 10 m and a low tide of

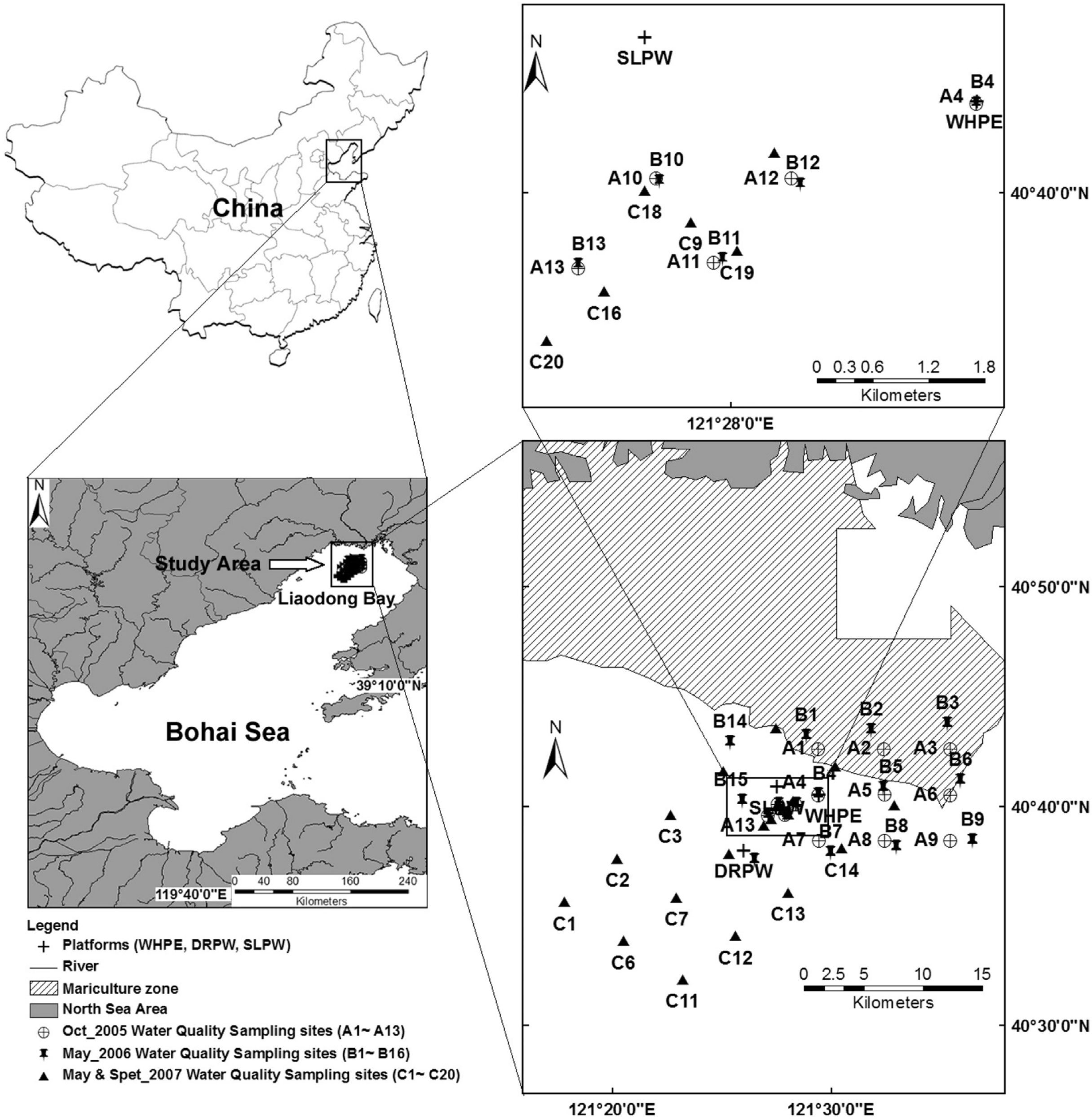

Fig. 3. Study area and the sampling sites for the four field investigations between 2005 and 2007.

Table 4
Marine water quality criteria.

Factors	Criteria for water quality grades (mg/L)			
	Grade S_1	Grade S_2	Grade S_3	Grade S_4
Dissolved oxygen (DO)	6	5	4	3
COD	2	3	4	5
Phosphate (p)	0.015	0.03	0.03	0.045
Inorganic nitrogen (IN)	0.2	0.3	0.4	0.5
Oil	0.05	0.3	0.3	0.5
Mercury (Hg)	0.00005	0.0002	0.0002	0.0005
Copper (Cu)	0.005	0.01	0.05	0.05
Zinc (Zn)	0.02	0.05	0.1	0.5
Cadmium (Cd)	0.001	0.005	0.01	0.01
Chromium (Cr)	0.05	0.1	0.2	0.5
Arsenic (As)	0.02	0.03	0.05	0.05

Table 5
Water quality classifications based on B* values.

Range of B* Values	Water quality classification	Water quality status
0~1.5	Class I	Very good
1.5–2.0	Class II biased toward I	Good
2.0~2.5	Class II	Fair
2.5~3.0	Class III biased toward II	Bad
3.0~3.5	Class III	Very bad
3.5~4.0	Class IV biased toward III	Poor
>4.0	Class IV	Very poor

6 m. The Liao, Shuang-Tai-Xi, Dalinghe and Xiaolinghe Rivers flow into the northern area of Liaodong Bay. Some significant environmentally sensitive areas are located adjacent to the study area, e.g., the mariculture zones. Hence, water quality in this area is of crucial importance to the protection and development of these sensitive areas.

3.2. Data collection

The data were provided by the North China Sea Monitoring Center. As displayed in Fig. 3, water samples were collected from 13 sites in October 2005, 16 sites in May 2006, and 20 sites in May and Sept. 2007. The samples were collected at two depths when the water depth exceeded 10 m, i.e., at approximately 0.5 m from the surface and 2 m above the bottom, corresponding to the surface and bottom levels, respectively. If the water depth was less than 10 m, only the surface water samples were collected. Water samples were collected using CTD and properly stored until laboratory analysis. Water quality parameters, including concentrations of DO, COD, phosphate, inorganic nitrogen, oil, Hg, Cu, Zn, Cd, Cr and As, were determined by laboratory analysis following standard procedures (GB3097, 1997). Only the analysis of the surface water samples is presented herein.

3.3. System implementation

Using the data collected during each survey, the MWQ-FES can be applied according to the five steps introduced in Section 2 to obtain the water quality assessment, eutrophication risk and heavy metal risk evaluation results.

Standard values based on the marine water quality standards of China (GB3097, 1997) were used as the criteria for water quality classification in the developed system.

According to the values of the fuzzy marine water quality index (B*), seven water quality classes were derived; the corresponding water quality statuses are defined in Table 4. The classification "Class II biased toward I" means that the water quality was determined to be close to class II but still better than class II; the other biased classifications have similar meanings.

Seven parameters were considered for the heavy metal risk evaluation in this study, e.g., the concentrations of Hg, Cd, As, Pb, Cu, Cr, and Zn. The selection of reference concentrations for heavy metals was based on the heavy metal concentrations in the water quality standard for fisheries and grade S_2 of sea water quality standard (GB3097, 1997; GB11607-89, 1989; Pu et al., 2012) (Table 4).

3.4. Results

The monitoring data and the fuzzy risk assessment results were exported from the database to Microsoft Excel file. Data re-arrange was performed to obtain the average values of each parameter in all the investigations. The monitoring data and assessment results are listed in the following tables.

3.4.1. Monitoring results

By comparing the monitoring data of the 11 water quality parameters listed in Table 6 with the marine water quality criteria in Table 4, the phosphate (P) concentrations exceeded grade S_3 of the marine water quality criteria at all sampling sites in Oct. 2005. In May 2006, the P concentrations were significantly lower, i.e., between grade S_1 and grade S_2 at 25% of the stations; the P concentrations at the other stations met the grade S_1 criteria. In May and Sept. 2007, the P concentrations increased significantly over the previous survey. The P concentrations in September 2007 met the criteria of grade S_2 at all stations with higher concentrations than that were measured in May 2006. The situation was more serious in

Table 6
Marine water quality monitoring results.

Parameters	October 2005		May 2006		May 2007		September 2007	
	Range (mg/L)	Average (mg/L)	Range (mg/L)	Average (mg/L)	Range (mg/L)	Average (mg/L)	Range (mg/L)	Average (mg/L)
DO	6.74~9.07	8.361	7.54~8.76	7.873	8.26~9.34	8.95	6.90~7.58	7.02
COD	0.32~1.36	0.945	0.472~1.91	1.194	1.00~1.84	1.355	0.688~1.29	0.973
Phosphate	0.0336~0.0455	0.0403	0.00463~0.0171	0.0118	0.0194~0.0338	0.0257	0.00572~0.02	0.0168
Inorganic Nitrogen	0.162~0.231	0.208	0.315~0.687	0.515	0.36~1.069	0.709	0.213~0.594	0.433
Oil	0.0155~0.0278	0.0222	0.0172~0.0688	0.0328	0.0299~0.0747	0.0436	0.0116~0.0263	0.0177
Hg	4.15E-05~8.65E-05	5.67E-05	3.64E-05~4.57E-05	3.97E-05	2.86E-05~5E-05	4.06E-05	3.31E-05~5.26E-05	4.09E-05
Cu	2.74E-03~3.58E-03	3.03E-03	2.50E-03~3.88E-03	3.19E-03	2.41E-03~3.31E-03	2.88E-03	2.53E-03~3.42E-03	3.07E-03
Zn	0.0152~0.0178	0.0165	0.0153~0.0229	0.0196	0.0148~0.0204	0.0175	0.0144~0.0277	0.0225
Cd	1.46E-04~1.92E-04	1.65E-04	1.49E-04~2.38E-04	1.97E-04	1.3E-04~1.8E-04	1.50E-04	1.3E-04~1.9E-04	1.57E-04
Cr	2.26E-03~3.27E-03	2.89E-03	2.73E-03~3.67E-03	3.17E-03	2.49E-03~3.29E-03	2.94E-03	2.8E-03~4.14E-03	3.36E-03
As	2.36E-03~4.06E-03	3.08E-03	1.63E-03~2.31E-03	1.20E-03	1.118E-03~1.26E-03	1.21E-03	6.65E-04~3.38E-03	1.60E-03

Table 7
Marine water quality assessment results.

Station	Oct. 2005			May 2006			May 2007			Sept. 2007		
	B*[a]	WQC[b]	WQS[c]	B*	WQC	WQS[c]	B*	WQC	WQS[c]	B*	WQC	WQS[c]
p1	1.728	II biased toward I	Good	2.065	II	Fair	2.088	II	Fair	1.289	I	Very Good
p2	1.744	II biased toward I	Good	2.211	II	Fair	1.980	II biased toward I	Good	1.337	I	Very Good
p3	1.748	II biased toward I	Good	2.067	II	Fair	2.097	II	Fair	1.337	I	Very Good
p4	1.656	II biased toward I	Good	2.073	II	Fair	2.123	II	Fair	1.680	II biased toward I	Good
p5	1.941	II biased toward I	Good	2.161	II	Fair	2.101	II	Fair	1.761	II biased toward I	Good
p6	1.875	II biased toward I	Good	1.715	II biased toward I	Good	2.464	II	Bad	1.025	I	Very Good
p7	1.937	II biased toward I	Good	1.460	I	Very Good	2.007	II	Fair	1.502	II biased toward I	Good
p8	1.984	II biased toward I	Good	1.386	I	Very Good	2.014	II	Fair	1.986	II biased toward I	Good
p9	1.889	II biased toward I	Good	1.530	II biased toward I	Good	2.098	II	Fair	1.966	II biased toward I	Good
p10	1.638	II biased toward I	Good	1.945	II biased toward I	Good	2.084	II	Fair	2.012	II	Fair
p11	1.773	II biased toward I	Good	1.272	I	Very Good	2.323	II	Fair	1.429	I	Very Good
p12	1.709	II biased toward I	Good	2.051	II	Fair	2.588	III biased toward II	Bad	2.053	II	Fair
p13	1.624	II biased toward I	Good	1.831	II biased toward I	Good	2.594	III biased toward II	Bad	1.601	II biased toward I	Good
p14	–	–		2.117	II	Fair	2.266	II	Fair	1.940	II biased toward I	Good
p15	–	–		1.806	II biased toward I	Good	1.425	I	Very Good	2.116	II	Fair
p16	–	–		1.347	I	Very Good	1.990	II biased toward I	Good	2.053	II	Fair
p17	–	–		–	–		2.163	II	Fair	1.774	II biased toward I	Good
p18	–	–		–	–		2.097	II	Fair	2.028	II	Fair
p19	–	–		–	–		2.122	II	Fair	1.967	II biased toward I	Good
p20	–	–		–	–		2.403	II	Bad	1.968	II biased toward I	Good
Average	1.785	II biased toward I	Good	1.815	II biased toward I	Good	2.151	II	Fair	1.741	II biased toward I	Good

[a] B*: Fuzzy marine water quality index.
[b] WQC: Water Quality Classification.
[c] WQS: Water Quality Status.

May 2007 with the P concentrations at 20% of the sampling stations failed to meet the criteria of grade S_3.

The inorganic nitrogen (IN) concentrations in Oct. 2005 were the lowest of the four investigations; the values were lower than the grade S_2 criteria at all sites. However, the concentrations were particularly high in May 2006 and May 2007, failing to meet the criteria of grade S_3 at 69% of the sampling sites in May 2006 and at 95% of the sites in May 2007. The IN concentrations were measured

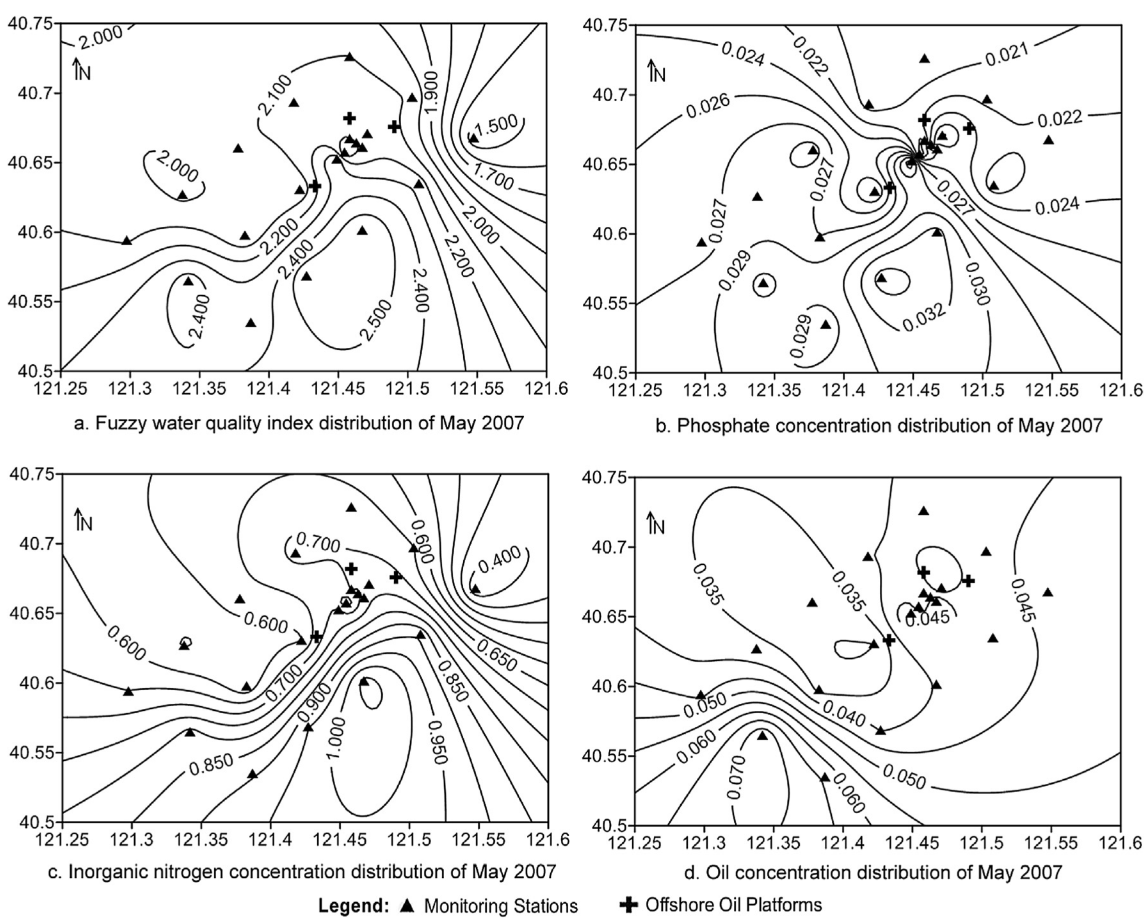

Fig. 4. Contour map of the fuzzy marine water quality index and the phosphate, inorganic nitrogen and oil concentrations in May 2007.

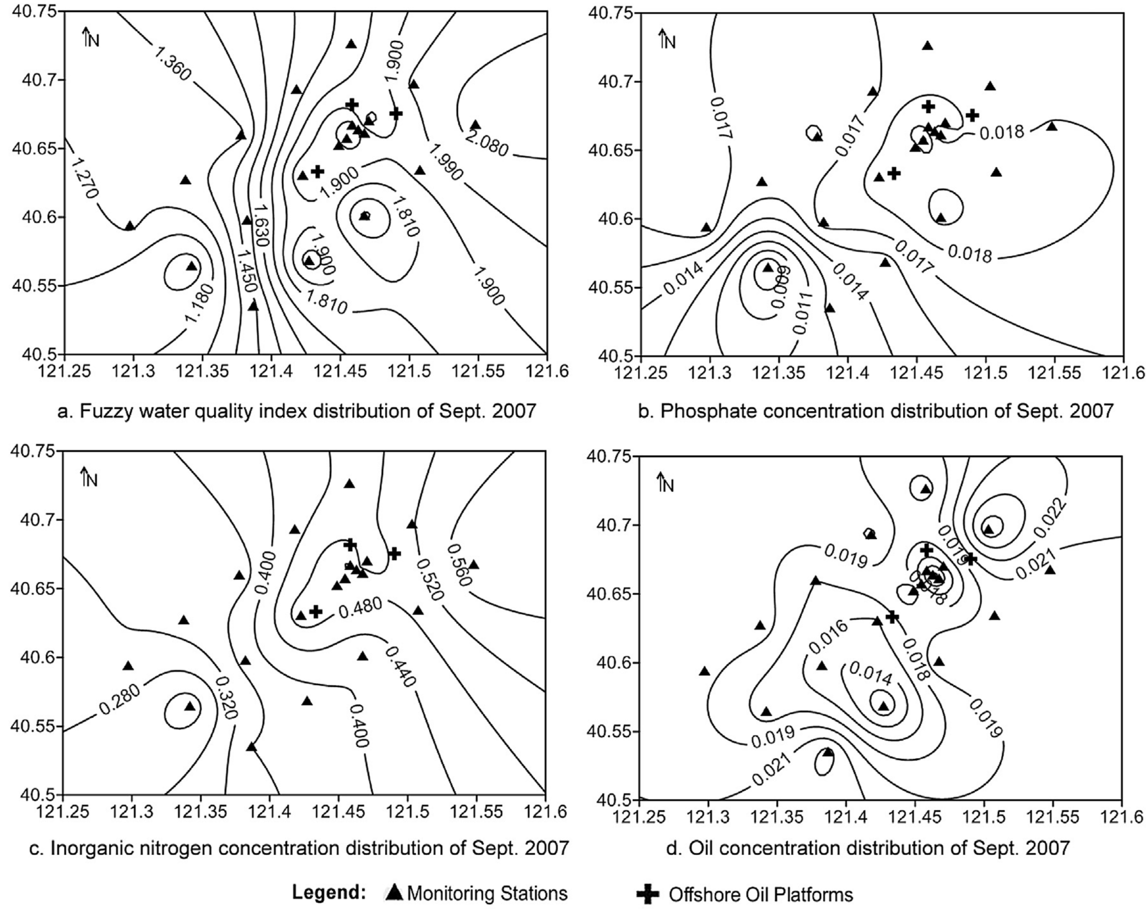

Fig. 5. Contour map of the fuzzy marine water quality index and the phosphate, inorganic nitrogen and oil concentrations in Sept. 2007.

in Sept. 2007 with lower values than that were measured during May 2007; and the concentrations exceeded the grade S_3 criteria at 65% of the sites. Additionally, the zinc (Zn) concentrations measured in Oct. 2005 met the criteria of grade S_1; and the concentrations were generally higher than the grade S_1 criteria at 37% of the sites in May 2006, 15% of the sites in May 2007, and 65% of the sites in Sept. 2007. The measured mercury concentrations met the criteria of grade S_1 at all stations in May 2006 and May 2007, while the concentrations exceeded the criteria of grade S_1 at 69% of the sites in Oct. 2005 and 10% of the sites in Sep. 2007. The concentrations of the other parameters met the criteria of grade S_1 in all four investigations.

In summary, the main contaminants in the study area were phosphate, inorganic nitrogen, zinc, and mercury.

Table 8
The eutrophication index and heavy metal risk index values for the four investigations.

Station	Oct. 2005		May-06		May-07		Sept. 2007	
	EI[a]	HMRI[b]	EI	HMRI	EI	HMRI	EI	HMRI
P1	1.976	14.355	3.782	12.457	3.813	12.47	0.993	11.416
P2	2.353	14.666	0.667	13.346	4.534	12.669	1.321	14.14
P3	2.441	12.923	2.498	12.149	4.902	10.901	0.839	11.652
P4	2.318	16.393	1.168	11.278	5.257	8.933	1.397	10.247
P5	0.676	14.584	1.851	13.308	4.448	9.628	1.998	11.012
P6	2.605	13.663	2.171	10.751	5.545	13.127	0.251	10.914
P7	1.616	13.356	1.044	11.216	4.118	10.666	1.471	10.81
P8	0.926	12.171	1.093	10.614	3.598	11.593	2.352	10.828
P9	0.748	13.999	0.942	11.089	6.724	10.683	2.421	9.809
P10	1.464	15.105	2.44	11.305	4.875	11.165	1.627	10.405
P11	2.133	15.711	0.493	12.325	7.148	13.043	0.906	13.695
P12	1.993	20.292	3.013	11.423	7.983	10.249	1.212	12.237
P13	1.113	21.143	0.85	11.64	13.227	11.199	1.806	12.083
P14	–	–	2.433	11.789	7.879	11.925	2.29	10.804
P15	–	–	1.742	11.985	3.387	12.783	1.643	13.088
P16	–	–	0.802	12.689	4.159	11.628	2.024	11.067
P17	–	–	–	–	7.321	10.653	1.656	13.466
P18	–	–	–	–	5.229	10.705	2.348	12.89
P19	–	–	–	–	6.833	9.877	2.149	10.87
P20	–	–	–	–	8.338	11.663	1.979	12.659
Average	1.720	15.259	1.687	11.835	5.966	11.278	1.634	11.705

[a] EI: Eutrophication index.
[b] HMRI: Heavy metal risk index.

3.4.2. Fuzzy synthetic water quality assessment results

According to the water quality classification and fuzzy assessment results (B*) calculated using MWQ-FES, the assessment results are listed in Table 7. Overall, the water quality in the study area was good (class II biased toward I) in the investigations during Oct. 2005, May 2006, and Sept. 2007. The water quality in May 2007 was fair mainly due to that the water quality of two sampling locations were class III and the average water quality was class II. This finding can also be demonstrated based on the single parameter analysis, since the inorganic nitrogen and oil concentrations in May 2007 were the highest among the four investigations.

3.4.3. Water quality distribution

The MWQ-FES is capable of generating distribution contour maps of all parameters included in the assessment. In conjunction with the water quality index, the distribution of phosphate, inorganic nitrogen, and oil concentrations were selected to perform assessment and comparison analysis; this selection is based that the phosphate and inorganic nitrogen concentrations were often at high levels to significantly affect the water quality in the study area and the oil concentration is selected as water in the offshore platform was affected by oil leaking or spill. The contour map for the water quality index in May 2006 is shown in Fig. 2 as an example to illustrate the system interface. The water quality index ranged from 1.272 to 2.211; the corresponding overall water quality was good (class II biased toward I). Contour maps of the four selected parameters in 2007 are presented in Fig. 4 and Fig. 5. Among these contour maps, the distribution of water quality index indicates that the range of water quality index in May 2007 was 1.425–2.594; the overall water quality was fair (class II). Moreover, the overall water quality was good (class II biased toward I) in Sept. 2007 with water quality index in the range of 1.025–2.116.

3.4.4. Eutrophication risk and heavy metal risk evaluations

The eutrophication index and heavy metal risk index for the four investigations were calculated using MWQ-FES and the results are provided in Table 8. The risk levels of eutrophication and heavy metal are presented as color-coded risk maps (Fig. 6 and Fig. 7, respectively).

According to the risk levels and colors in Tables 1 and 5, the ecological risk level of heavy metals in the study area was slight during the four investigations; the eutrophication risk level in Oct. 2005, May 2006 and Sept. 2007 corresponded to oligotrophic, light eutrophic and mesotrophic conditions, respectively, while the mesotrophic and high eutrophic conditions occurred in May 2007.

3.5. Discussion

3.5.1. Comparison with results from previous studies

Previous studies have suggested that domestic sewage and industrial wastewater are the main contaminant sources in Liaodong Bay (Li, et al., 2001). High concentrations of nutrients were presented in this study, and similar results were reported in previous studies and in coastal environmental reports, indicating that the

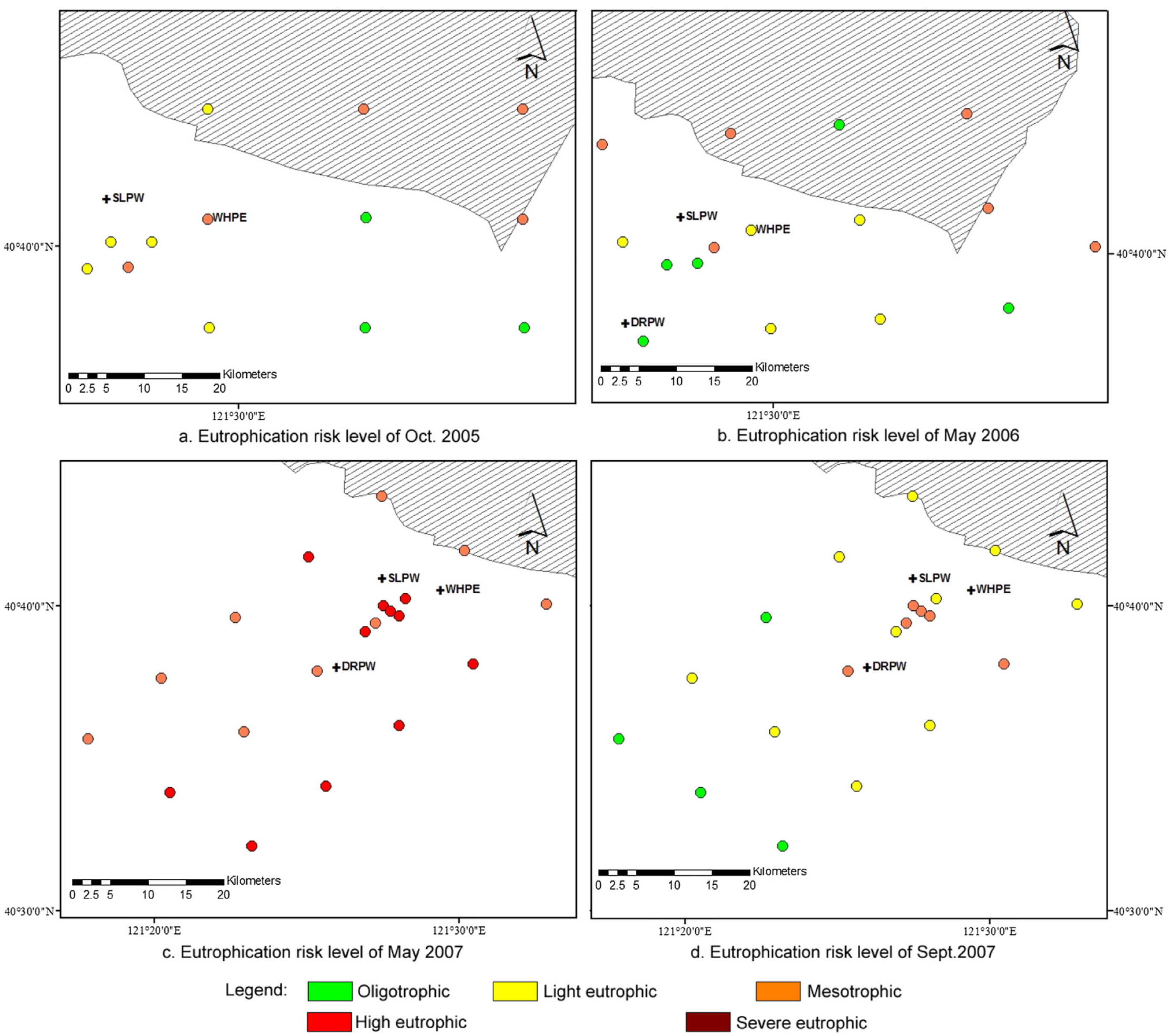

Fig. 6. Eutrophication risk levels for the four investigations.

water quality in the northern portion of Liaodong Bay is primarily affected by inorganic nitrogen and phosphate (Li et al., 2001; Wan et al., 2008). Moreover, the main pollutants in the wastewater discharged into coastal water include large amounts of nutrients (SOA, 2007).

The fuzzy risk assessment results showed that the overall water quality in the study area was class II biased toward class I.Wan (2008) assessed the water quality in the north portion of Liaodong Bay in 2004 using fuzzy mathematics and indicated that the water quality in this region was generally class I with some sites near the estuaries exhibiting worse water quality (class II). The water quality determined in the current study was worse than proposed in previous studies. This difference is probably due to the following two reasons. First, the weighted average principle method was applied in this research to replace the maximum principle method that was used in Wan's study. Because the nutrient concentrations were particularly high in the study area, the results of weighted average principle method correspond more closely to the actual situations. Second, the data in Wan's study were collected few years ahead of the current study and the water quality probably declined in this area.

3.5.2. Single parameter analysis

The contour maps generated from the MWQ-FES system in Fig. 4 indicated close relevance between the fuzzy water quality index and the concentrations of the three selected pollutants in May and Sept. 2007. The contour maps of the fuzzy water quality index reflected the synthetic effects of these parameters on the ambient water quality, i.e., the distribution of the areas with high concentration were similar to the distribution of high water quality index values, which correspond to worse water quality. This finding supports the foregoing analysis that the water quality in the study area is primarily affected by nutrients. Chemical analysis showed that water-based drilling mud also contains phosphate (Zhang, 2003). Thus, the leaking of drilling mud related to the operation of the oil platforms may have partially affected the water quality in

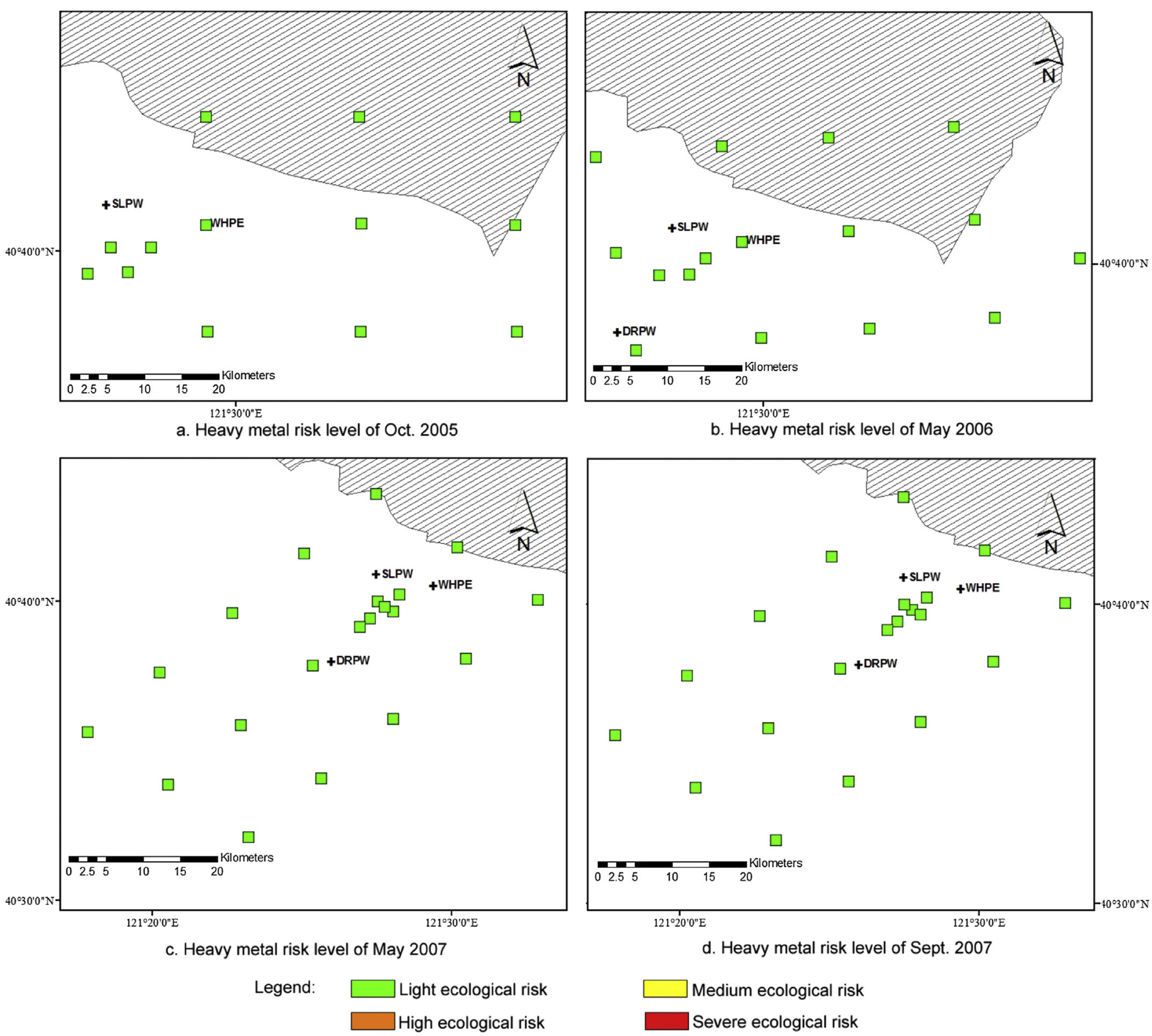

Fig. 7. Heavy metal risk levels for the four investigations.

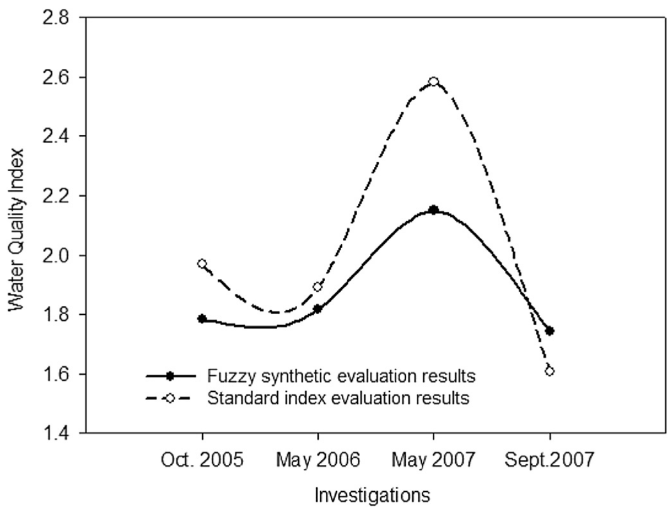

Fig. 8. Comparisons between the results of the fuzzy synthetic evaluation and the standard index evaluation methods.

the surrounding area. The effect of oil exploitation on water quality was reflected by the elevated concentrations of oil distributed near the platforms. The results of other investigations are analogous to the situation discussed above for the 2007 surveys.

According to studies regarding the current in the northern part of Liaodong Bay (Hu, 2007), the mean current in the study area exhibits a SE to NW flow in summer and a NW to SE flow in winter. According to the contour maps, the parameter distributions did not exactly follow the same trend due to the complex effects of shorelines and offshore facilities on the current in the study area. Consequently, the transport of pollutants will also be affected.

3.5.3. Eutrophication risk and heavy metal risk in the mariculture zone

The eutrophication risk level in May 2007 was significantly higher than during the other three investigations, agreeing well with the fuzzy water quality index and nutrient concentrations determined in this investigation.

According to Fig. 3, some sampling sites are located within the mariculture zone close to the study area. The eutrophication risk level and heavy metal risk level at these sites are displayed in the color-coded maps generated by MWQ-FES in Fig. 6 and 7. There was only a slight heavy metal risk in the mariculture zone during the four investigations. The eutrophication risk level for most of the sites located within the mariculture zone was mesotrophic in Oct. 2005, May 2006 and May 2007; light eutrophic conditions prevailed in Sept. 2007. It is well accepted that the probability of having toxic algal blooms and red tides is much higher in eutrophic waters. Blooming and the ultimate collapse of algae blooms may lead to hypoxia or anoxia and cause mass mortality of benthos and fish over large areas. There have been reports of economic losses as fishery was affected by red tides and toxic blooms (Feng et al., 2004; Wu, 1999). Thus, management personnel should pay close attention to the nutrient discharges in this area and take effective measures to reduce the eutrophication risk in the mariculture zone.

3.5.4. Comparison between the fuzzy synthetic evaluation and the standard index evaluation

The standard index evaluation method is commonly used in surface water quality assessments in China. This method can be represented by the following equation:

$$I_i = C_i/S_i, \tag{12}$$

where I_i is the standard index of each parameter, C_i is the measured concentration of each parameter, and S_i is the evaluation criteria of each parameter.

For the dissolved oxygen evaluation,

$$\begin{aligned} I_i(DO) &= \left|DO_f - DO\right| \Big/ (DO_f - DO_s) \quad DO \geq DO_s \\ I_i(DO) &= 10 - 9DO/DO_s \quad DO < DO_s, \end{aligned} \tag{13}$$

where DO_f is the saturated concentration of dissolved oxygen in water and DO_s is the dissolved oxygen criteria. Moreover,

$$DO_f = 468/(31.6 + t), \tag{14}$$

where t is the water temperature in °C.

The standard indices of all parameters included in the analysis are synthesized to obtain the water quality index using the following equation:

$$\mathrm{WQI} = \sqrt{\frac{I_{\max}^2 + I_j^2}{2}}, \tag{15}$$

where $I_{\max}$ and I_j are the maximum and the average values of all standard indices, respectively.

The results of the fuzzy synthetic evaluation and the standard index evaluation are provided in Fig. 8.

According to Fig. 8, the results of the two methods were comparable. Moreover, the water quality variation trend over the studied period was the same, indicating that the results obtained from the developed system were accurate. It was also evident that most of the fuzzy water quality indexes were smaller than suggested by the standard index method. This difference was probably because the standard index method primarily focused on the parameters with severely high concentrations that exceeded the criteria, which demonstrated the decisive effect of these parameters in the water quality assessment. While the fuzzy synthetic evaluation method sufficiently considered the contribution of each parameter in the assessment process, the contributions were assigned based on the individual weight of each parameter, which can provide a better understanding of the water pollution resulting from multiple factors.

3.5.5. Other uncertainties

Other uncertainties may be associated with the following factors: (i) the uncertainty in the platform and/or land-based discharges, which make it challenging to identify the precise correlation between the water quality variations and offshore oil production, and (ii) the four surveys that were performed in different months and at a distinct interval may not be able to accurately constrain temporal water quality variations. Continuous monitoring is needed in the future to obtain sufficient data to support related studies regarding the water quality in this area. Moreover, the developed MWQ-FES system can be further customized for automatic data processing and for verifying results.

4. Conclusions

This paper presents a newly developed MWQ-FES system, which integrates a risk assessment model that includes fuzzy synthetic water quality evaluation, eutrophication risk assessment and heavy metal risk evaluation. The developed system enables engineers and decision makers to better understand the spatial distribution of water quality risks. A user-friendly GUI was further developed to manage input information, process data, and visually present the results. The MWQ-FES system was developed using the C sharp programing language and was integrated with ArcGIS Engine and the Microsoft Access database software. The MWQ-FES system was applied to assess the marine water quality near offshore platforms in the northern part of Liaodong Bay, China. The system results indicated that the overall water quality of the study area was good in Oct. 2005, May 2006, and Sept. 2007 and fair in May 2007. The water quality risk contour maps generated by the system depicted the distribution of the integrated water quality conditions in the study area. It was concluded that the high nutrient concentrations was the main reason that contributed to the water quality deterioration. The ecological risk of eutrophication and heavy metal contamination was also analyzed. The eutrophication risk level in Oct. 2005, May 2006, and Sept. 2007 corresponded to oligotrophic, light eutrophic and mesotrophic conditions, while mesotrophic and high eutrophic conditions occurred in May 2007. Only a slight heavy metal risk was identified for the four investigations. Compared with the results of previous environmental assessments in the same area and with the standard index method, the developed MWQ-FES system provides reliable and intuitive results regarding the water quality distribution and offers an efficient tool for engineers and decision makers.

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