

Risk Assessment of Groundwater and its Application. Part I: Risk Grading Based on the Functional Zoning of Groundwater

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Received: 21 May 2014 / Accepted: 25 February 2015 /
Published online: 12 March 2015
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Abstract The functional zoning of groundwater is the basis for the rational development and utilization, scientific management and effective protection of groundwater. Based on the distribution, type, hydrogeological condition and exploitation status of groundwater in Tianjin, and considering the resource supply, ecological environment maintenance and geological environment stability simultaneously, the function zoning of shallow groundwater has been divided into the non-central water supply area in built-up zones, the fragile marsh zones, the fragile nature reserve zones, the polluted groundwater zones and the salt water zones. And the deep groundwater has been divided into the non-central water supply area in built-up zones, the central supply area in built-up zones, the land subsidence zones, polluted groundwater zones and the salt water descending zones. Firstly, this paper selected dominant factors of groundwater development and utilization risk based on the different groundwater function zoning results, distinguished them into natural factors and human factors, and developed the risk assessment index systems. Secondly, the risk assessment systems for shallow and deep groundwater were built according to the characteristics of respective aquifers, and the weight of each evaluation index was calculated by AHP (Analytic Hierarchy Process) method. Then, each of the unit risk grade was determined by the method of fuzzy synthetic evaluation on basis of these index attributes and the corresponding weights, and results were distributed in space using ArcGIS to obtain the groundwater risk grade map of various aquifers in different groundwater function zones of Tianjin city. Finally, the risk grade in each district of Tianjin was determined by superimposing the district boundaries on these maps. Groundwater development and utilization risk grades based on the functional zoning of groundwater can provide

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a scientific basis for management of groundwater and a method for determining groundwater level.

Keyword Groundwater functional zoning · Risk assessment · AHP · ArcGIS · Tianjin city

1 Introduction

Groundwater system has strong spatial variability, and affected by various factors, such as groundwater occurrence condition, hydrodynamics, water quality and humanity activities, etc. The system of shallow groundwater whose formation and movement is obviously influenced by surface water is open system, and the deep which is not recharged by precipitation and surface water infiltration is mainly semi-closed system (Sheng et al. 2006). So, the management of groundwater should be implemented according to the shallow groundwater and deep groundwater functional zoning respectively (Qureshi et al. 2010). Groundwater is an important source of freshwater throughout the world, especially for surface water resource shortage areas (Moreaux and Reynaud 2006), so it is inevitable to exploit and use it. However, great uncertainty exists in the process of groundwater development and utilization, because each region has its own groundwater condition, different amount of available groundwater, and the economic development, increase in water demand, groundwater development and utilization technology and level in different regions are also different. So the comprehensive risk analysis of groundwater, which can provide more reasonable and reliable plans for groundwater development and utilization, and minimize risk in the process of development and utilization, is necessary.

At present, the studies on risk of groundwater mainly focus on the contamination aspect, especially the groundwater quality. Yang et al. (2010) developed an integrated simulation-assessment approach (ISAA) to systematically tackle multiple uncertainties associated with hydrocarbon contaminant transport in subsurface and assessment of carcinogenic health risk. Milnes (2011) proposed a simulation-based salinisation risk assessment methodology based on the principle of linear superposition of total dissolved solutes in groundwater, calculated the risk index distributions by these simulation results, revealed risk areas requiring remediation or conservation measures with respect to each process by overlaying the risk index distributions with a defined threshold concentration. Wang et al. (2012) described a groundwater contamination risk assessment method that integrated hazards, intrinsic vulnerability and groundwater value, evaluated the hazard harmfulness by quantifying contaminant properties and infiltrating contaminant load, and discriminated the intrinsic aquifer vulnerability using a modified DRAS TIC model. Su et al. (2013) collected groundwater samples for nitrate nitrogen content analysis using the Four Step method developed by the United State Environmental Protection Agency (USEPA) in conjunction with the non-carcinogens health risk model to determine the health risk associated with nitrate pollution of groundwater. The results indicated that agricultural sewage irrigation areas in the study area showed strong health risks, but that those of the city were relatively small. But the reports about the groundwater utilization risk assessment are rare, for instance, Han et al. (2011) developed the risk assessment index system of groundwater development and utilization, and assessed the risks by catastrophe evaluation method, determined the groundwater development risk grades in counties (cities, districts) in west Jilin province and drew the conclusion that the risk of groundwater development here was great. Dong et al. (2013) divided groundwater in Tianjin into seven function areas, built the comprehensive evaluation model of groundwater exploitation and utilization risks to forecast the utilization risks of the third aquifer in years 2015, 2020, and 2030. The above-mentioned

studies involved only part of the underground aquifers, did not study the whole underground aquifers, and the groundwater aquifers have not been divided into shallow groundwater and deep groundwater, while the hydrogeological setting of shallow groundwater and deep groundwater are much more varied. So, it is necessary to carry out the risk assessment of groundwater according to shallow groundwater and deep groundwater function zoning respectively.

The paper selected Tianjin city as the typical study area. Tianjin city has completed shallow groundwater and deep groundwater function zoning, which provides the basis for groundwater risk assessment. At the same time, groundwater system in Tianjin has strong spatial variability. In the piedmont plain of north of the salt-fresh boundary line, the shallow groundwater is fresh and exploited seriously. However, in the coastal plain of south of the Salt-fresh boundary line, the shallow groundwater is salt and exploited slightly, so exploitation of groundwater based mainly on deep groundwater. The phenomenon of excessive groundwater exploitation in these areas have been common, which caused a series of environmental geological problems such as ecological environment degradation, earth surface collapse, cone of depression, surface collapse, ground fracture and saline intrusion. So, great uncertainty exists in the process of groundwater development and utilization in Tianjin, which involve in most of risk assessment factors. So, Tianjin city as the study area is suit for the full groundwater risk assessment.

The paper provides the results of shallow groundwater and deep groundwater function zoning, selects dominant factors based on the different groundwater function zoning, develops the risk assessment index system for the two groundwater system respectively, and determines the groundwater utilization risk grades in Tianjin city. The method determining development and utilization risk grades for shallow groundwater and deep groundwater respectively based on the functional zoning of groundwater can also provide a scientific guidance for risk assessment of groundwater in different parts of the world.

2 Groundwater Functional Zoning of Tianjin City

Tianjin City is located in east longitude $116^{\circ}42'05''\sim 118^{\circ}03'31''$ and north latitude $38^{\circ}33'57''\sim 40^{\circ}00'07''$. It extends 172 km from the south to north and 104 km from east to west. Tianjin is bounded by Bohai Sea in the southeast and Yanshan Mountain in the north. The broad plain region from the foothills to the coast is generally divided by the fracture from Baodi to Ninghe, in the north of which the buried depth of bedrock is less than 300 m and with storage of a fourth series of pore groundwater and groundwater in the bedrock, while in the south of which has the thick south of Cenozoic, with pore groundwater.

Based on the distribution type, hydrogeological condition and development status of shallow and deep groundwater in Tianjin city, the shallow groundwater functional zoning has been divided into the non-central water supply area in built-up zones, the fragile marsh zones, the fragile nature reserve zones, the polluted groundwater zones and the salt water zones. And the deep groundwater has been divided into the non-central water supply area in built-up zones, the central supply area in built-up zones, the land subsidence zones, polluted groundwater zones and the salt water descending zones (Hu et al. 2013).

3 The Risk Assessment Index System of Groundwater Functional Zoning

The risk assessment factors of groundwater functional zoning include natural factors and human factors. The natural factors involve climate, water quality, water quantity, aquifer and

geological environment etc. The human factors involve development and utilization condition, social economy, contamination etc.

3.1 The Natural Factors

3.1.1 *Water Quantity*

Although groundwater resource is recoverable, the excessive exploitation can cause various environmental negative effects. To ensure sustainable development, the groundwater resource needs to remain above a safe level. The groundwater exploitation potential is a comprehensive index (Hu et al. 2013). This paper chooses the groundwater exploitation potential as the water quantity index.

3.1.2 *Water Quality*

The deterioration of groundwater quality is a phenomenon that some chemical composition and physical properties of groundwater have changed under the influence of natural or human factors. The problems of groundwater quality caused by natural factors in Tianjin city are mainly the fluorine and salt content to exceed bid. The fluoride concentration of most regions in north of fresh-salt boundary is more than 1 mg/L (GMBGM 2004). This paper chooses fluoride concentration and salinity as the water quality indexes.

3.1.3 *Aquifer*

Aquifer is an index used to describe the properties of groundwater source, including the aquifer thickness, water abundance, permeability coefficient, sand layer thickness, water exchange intensity, buried depth of salt water, water level etc. (Liu et al. 2010). This paper uses the same aquifer indexes as above.

3.1.4 *Geological Environment*

The total area of Tianjin city is about 1×10^4 km² and the land subsidence has happened with area of 7300 km², about 4080 km² is over 1000 mm (Li et al. 2013a, b). The excessive exploitation of groundwater and the poor stability of engineering geological conditions are the main causes of land subsidence. The engineering geological stabilization is a comprehensive index to describe the stability of tectonic movement, soil body and surface (Shao et al. 2010). So this paper chooses it as the assessment index of geological environment safety.

3.1.5 *Climate*

Precipitation is one of the main recharges for groundwater, and it is very important to ecological environment and groundwater in nature reserve and wetland reserve with a weak ecological environment. In addition, it has an effect on groundwater contamination, the precipitation speed up contamination moving downwards on vertical and diffusion on horizontal in aquifers, making the polluted range expanded (Su et al. 2013). So this paper chooses the precipitation as the climate index to assess groundwater risk.

3.2 The Human Factors

3.2.1 Development and Utilization

There are 2749 motor-pumped wells with the average density of 3.8/km² in mountainous areas, and 26,164 wells with the average density of 2.7/km² in plain areas. In Ji county, the north of Baodi and the concentrated exploration areas of major towns, the mining intensity of groundwater ($10 \times 10^4 \sim 15 \times 10^4 \text{ m}^3/\text{a} \cdot \text{km}^2$ in most areas, while over $15 \times 10^4 \text{ m}^3/\text{a} \cdot \text{km}^2$ in some areas, and under $5 \times 10^4 \text{ m}^3/\text{a} \cdot \text{km}^2$ in a few other areas) is high (Shao et al. 2010). The mining intensity reflects the concentrated intensity of groundwater exploitation in time. If it is excessive, the cone of depression will be formed in short time. And the well density is the reflection of groundwater mining intensity to some extent. So this paper chooses the mining intensity and the well density as the assessment indexes of groundwater exploration and utilization.

3.2.2 Contamination

The groundwater contamination is mainly caused by human activities, a great deal of contamination is due to increase in human population, resulting in the deterioration of groundwater (Wang et al. 2012). The contamination degree is not only about content of various pollutants, but also sewage quantity. This paper chooses sewage quantity, SS (suspended solid in water) and COD as the assessment indexes of groundwater contamination.

3.2.3 Social Economy

The groundwater system has close links with human social system. The distribution of groundwater affects the distribution of population, the industrial density, the crops and planting area, in turn these factors also have an impact on groundwater (Nei et al. 2011). So, this paper chooses population density, gross industrial output value and planting area as the assessment indexes of social economy.

Above all, the risk assessment index system of Tianjin groundwater development and utilization is shown in Fig. 1.

The risk assessment indexes exist difference in the shallow and deep groundwater, so the risk assessment index system should be established respectively.

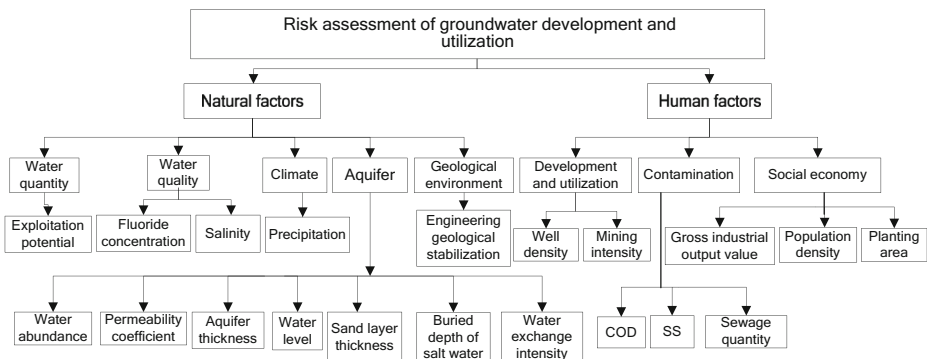


Fig. 1 The risk assessment index system of Tianjin groundwater development and utilization

3.3 The Risk Assessment Index System of Shallow Groundwater

Based on the risk assessment index system of groundwater in Tianjin city and the division result of shallow groundwater functional zoning, the dominant factors are selected and the risk assessment index system of shallow groundwater is developed in each zoning. Because of the land subsidence of Tianjin is mainly caused by deep groundwater exploitation, and salt water in shallow groundwater will affect deep groundwater only when exploiting deep groundwater. So, the risk assessment index system of shallow groundwater excludes engineering geological stabilization, sand layer thickness and buried depth of salt water.

3.3.1 Development Zoning

The shallow groundwater development zoning of Tianjin belongs to non-central water supply area in built-up zones, compared with central water supply area, its safeguard procedures is relatively weak and easily to be contaminated, so groundwater contamination is often considered when assessing the risk of groundwater. In development zoning, the occurrence, supply and exploitation condition of groundwater are good, and the water quality conforms to the National Standard (GB) for Drinking Water. So, the risk assessment in development zoning mainly depend on aquifer (water level), water quantity (exploitation potential) and development and utilization (well density, mining intensity) etc.

3.3.2 Protection Zoning

The protection zoning of Tianjin shallow groundwater is divided into the fragile nature reserve zones, the fragile marsh zones and the polluted groundwater zones.

The fragile nature reserve zones locate mainly in bedrock areas of north part of Ji county, the groundwater is fresh, and uncontaminated, the water quality is good, and precipitation is the major source of groundwater here. There is a great difference between mountain aquifer and plains aquifer, the mountain aquifer structure and water-bearing media are complex and the aquifer index generalization is difficult, so only choose groundwater level as the assessment index of aquifer. The risk assessment mainly depend on natural factors (precipitation, exploitation potential, water level etc.), because the development and utilization of groundwater in fragile nature reserve zones is relatively less.

The fragile marsh zones have a high requirement on water quality. Shallow groundwater is one of the main recharges for marsh, and water quality of marsh is influenced by ions, mineral substance, contaminants in groundwater. Just like the nature reserve zones, it is mainly connected with natural factors (exploitation potential, water level etc.), and little with the development and utilization of groundwater.

The groundwater contamination refers to the chemical composition, physical properties and biological characteristics of groundwater changed because of natural factors and human activities, causing the water quality to deteriorate. Developing the risk assessment index system in the polluted groundwater zones considers the condition of the contamination first, and then the degree that diffusion of contamination which is mainly affected by natural (water alternate intensity) and human factors (well density and mining intensity).

3.3.3 Reserve Zoning

The reserve zoning of Tianjin shallow groundwater belongs to salt water zones, it is located in the south of Baodi fracture zone, and widely distributes salt water with high salt content. The

high salt content is the main reason of groundwater function loss. The risk assessment in the salt water zones mainly depend on aquifer (water level), water quantity (exploitation potential) and water quality (salinity) etc.

3.4 The Risk Assessment Index System of Deep Groundwater

The characteristic of shallow and deep groundwater is different. The shallow groundwater is mainly recharged by precipitation, the annual mean recharge volume and exploitable volume is almost equal, the main problem in the process of development and utilization is groundwater contamination. However, the deep groundwater is long time over-exploited, and results in significant issues such as groundwater cross strata pollution, land subsidence and salt water downwards.

Not only the assessment indexes of shallow and deep groundwater have difference, but also do each aquifer in deep groundwater. The main exploitation layers of deep groundwater are II, III and IV aquifer groups, only where the groundwater risk assessment of development and utilization is affected by water abundance. So, the water abundance of aquifer is not looked as the assessment index in V and VI aquifers.

3.4.1 Development Zoning

The development zoning of Tianjin deep groundwater is divided into the non-central water supply area in built-up zones and the central supply area in built-up zones. The central supply areas mainly include Xiacang, Xiawuqi and Ninghebei, where have a strict monitoring, supervision management system and completed infrastructural facilities to protect it from pollution, ecosystem degradation and geological disasters. So, the risk assessment in the central supply area in built-up zones mainly depend on aquifer (water level), water quantity (exploitation potential) and development and utilization (mining intensity, well density).

The risk assessment indexes of the non-central water supply area in built-up zones in shallow and deep groundwater are fundamentally the same, except the contaminant. SS mainly distributes in shallow groundwater. So, the risk assessment indexes in both shallow and deep groundwater are the same except for SS.

3.4.2 Protection Zoning

The protection zoning of Tianjin deep groundwater is divided into the land subsidence zones, the polluted groundwater zones and the salt water descending zones.

The land subsidence zones are mainly located in Urban area, Tanggu, Hangu, Dagang, Jinghai, where the industry is relatively developed. Land subsidence is caused by long-term over-exploited groundwater. So, the risk assessment in the land subsidence zones mainly depend on aquifer (water level, sand layer thickness), development and utilization (mining intensity, well density), geological environment (engineering geological stabilization) and social economy (gross industrial output value).

The polluted groundwater zones are located in the south of Ji county hilly region to north of Baodi fracture zone. The deep groundwater contamination is the result of that shallow contaminated groundwater enters into through the uneven clay aquiclude on the top of II aquifer. So, the risk indices of polluted groundwater zones mainly depend on water quantity (exploitation potential), contamination (sewage quantity) and aquifer (water alternate intensity).

The salt water descending zones are located in alluvial plain and sea-alluvial plain in the south of Baodi fracture zone. The upper salt water can enter into fresh water aquifer if there is a

hydraulic connection between them. In nature, the deep groundwater is supplied little by shallow groundwater leakage recharge. But, deep groundwater is in long-term over-exploited condition, leading to the groundwater level lowering, the recharge from shallow salt water increasing, and finally the deep groundwater salty. The motor-pumped wells used to exploit groundwater in Tianjin were built in the 1970s or 1980s and have been seriously damaged, which constituted the deep groundwater pollution channels, making the shallow contamination and salt water flow into deep groundwater. So, the risk assessment in the salt water descending zones mainly depend on aquifer (water level, buried depth of salt water), water quantity (exploitation potential) and development and utilization (mining intensity, well density).

4 Risk Assessment Methods of Groundwater Function Zoning

4.1 The Determination of Index Weights

Based on the risk assessment index system of shallow and deep groundwater in Tianjin city (Tables 1, 2), the weights of each level index are calculated by a suitable method. At present, there are many methods to calculate weights of synthetic assessment indexes, among them AHP (Analytic Hierarchy Process) method is widely used. In this paper, the AHP method is selected and combined with spatial information based on expert advice to make comprehensive and quantitative decisions based on a multi-criteria system. According to expert advice, the comparison matrix is constructed reflecting relative importance of factors. The weight of each evaluation index in the different levels is shown in Tables 1 and 2.

4.2 The Risk Assessment Model

The risk values of groundwater development and utilization are calculated by raster overlay algorithm. So, the study area is divided into 514,848 rectangular units having cell size of 500×500 m, decomposed into 6 floors having 346 lines and 248 columns. Because different index has different dimension and there are significant differences of values among them, the normalized processing for original index values need to be carried out according to the larger the better or the smaller the better.

Based on the normalized factor values $(x_1, x_2, x_3, \dots, x_n)$ and the weights of functional zoning indexes, the risk values (represented by Z) of I、 II、 III、 IV、 V and VI aquifer and bedrock aquifer are calculated by raster calculator of ArcGIS. The formula (1) is as following.

$$Z = f(x_1, x_2, x_3, \dots, x_n) = \sum_{i=1}^n w_i x_i \quad (1)$$

Where x_i is the i th factor, and w_i is the corresponding weight of the i th factor.

5 Results and Discussion

Data from Tianjin city including precipitation, well density, exploitation potential, mining intensity, water exchange intensity, buried depth of salt water, sewage quantity, COD, SS, gross industrial output value, planting area, population density, engineering geological stabilization, aquifer salinity, aquifer fluoride concentration, aquifer thickness, aquifer permeability coefficient, aquifer sand layer thickness, aquifer water level, aquifer water abundance can be

Table 1 Index weights of shallow groundwater development and utilization risk

First level indexes	Second level indexes	Third level indexes	Fourth level indexes	Weight		
Non-central water supply area in built-up zones	Natural factors	Water quantity	Exploitation potential	0.2500		
			Aquifer	Water abundance	0.0247	
		Human factors	Development and utilization	permeability coefficient	0.0175	
				Aquifer thickness	0.0208	
	Contamination		Water level	0.1870		
			Well density	0.0917		
			Mining intensity	0.0917		
	Social economy	COD	SS	0.0225		
			Sewage quantity	0.0225		
		Gross industrial output value	Population density	0.0830		
			Planting area	0.0830		
	Fragile nature reserve zones	Natural factors	Water quantity	Exploitation potential	0.1128	
				Climate	Precipitation	0.2956
Aquifer			Water level	0.2582		
Human factors		Development and utilization	Well density	0.0833		
			Mining intensity	0.0833		
		Social economy	Gross industrial output value	Population density	0.0282	
Planting area				0.0739		
Fragile marsh zones			Natural factors	Water quantity	Exploitation potential	0.1538
		Water quality			Fluoride concentration	0.0171
	Aquifer	Salinity		0.0342		
		Water abundance		0.0321		
		Permeability coefficient	0.0540			
	Human factors	Development and utilization	Aquifer thickness	0.0321		
			Water level	0.3434		
		Contamination	Well density	0.0917		
			Mining intensity	0.0917		
COD			0.0233			
Social economy	SS	Sewage quantity	0.0233			
		Gross industrial output value	0.0135			
	Population density	Planting area	0.0310			
		Polluted ground water zones	Natural factors	Water quantity	Planting area	0.0355
					Climate	Exploitation potential
Water quality	Precipitation		0.1232			
	Aquifer	Fluoride concentration	0.0134			
Salinity		0.0134				
Water abundance		0.0188				
Permeability coefficient	Aquifer thickness	Permeability coefficient	0.0188			
		Aquifer thickness	0.0097			

Table 1 (continued)

First level indexes	Second level indexes	Third level indexes	Fourth level indexes	Weight		
	Human factors	Development and utilization	Water level	0.1176		
			Water exchange intensity	0.1085		
			Well density	0.1083		
			Mining intensity	0.1083		
			Contamination	COD	0.0560	
				SS	0.0489	
		Social economy	Sewage quantity	0.1283		
			Gross industrial output value	0.0167		
			Population density	0.0167		
		Salt water zones	Natural factors	Water quantity	Planting area	0.0167
					Exploitation potential	0.1538
				Water quality	Fluoride concentration	0.0171
					Salinity	0.0742
Aquifer	Water abundance			0.0321		
	Permeability coefficient			0.0540		
	Aquifer thickness		0.0321			
	Water level		0.3034			
Human factors	Development and utilization		Well density	0.0917		
			Mining intensity	0.0917		
	Contamination		COD	0.0233		
			SS	0.0233		
			Sewage quantity	0.0233		
	Social economy	Gross industrial output value	0.0135			
		Population density	0.0310			
		Planting area	0.0355			

obtained in Tianjin atlas of geological environment (GMBGMR 2004). After vectorization and normalized processing of raw data, the normalized factors ($x_1, x_2, x_3, \dots, x_n$) are derived.

The risk value of each cell is calculated according to the Eq. (1). Based on range of risk values, the risk grade of aquifer is divided into five (1~5) according to the principle of equipartition, corresponding risk grades are potential, slight, light, medium and heavy. The groundwater management zones in Tianjin were divided into thirteen areas by administrative districts. So, based on the risk grades of aquifers, adding the district boundaries on the risk maps of function zoning, the risk grade in each district of Tianjin is determined, as shown in Fig. 2. The different risk grades area of each aquifer in districts of Tianjin city can be found in Table 3, the area proportion of risk grade 4 and 5 of each aquifer in districts of Tianjin city is shown in Table 4.

The Table 4 shows that the higher risk of aquifer I is located in Urban area, Dagang, Xiqing; the higher risk of aquifer II is located in Urban area, Jinghai, Dagang, Hanggu, Beichen, Jinnan, Wuqing; the higher risk of aquifer III is located in Urban area, Dagang; the higher risk of aquifer IV is located in Urban area, Dagang, Jinnan, Jinghai; the higher risk of aquifer V is located in Urban area, Jinnan, Dongli, Dagang, Jinghai, Xiqing; the higher risk of aquifer VI is

Table 2 Index weights of deep groundwater development and utilization risk

First level indexes	Second level indexes	Third level indexes	Fourth level indexes	Weight II, III, IV	Weight V, VI		
Central supply area in built-up zones	Natural factors	Water quantity	Exploitation potential	0.2500	0.3333		
			Aquifer	Water abundance	0.1192	–	
		Permeability coefficient	0.0151	0.0156			
			Aquifer thickness	0.0155	0.0162		
			Water level	0.1002	0.1349		
	Human factors	Development and utilization	Well density	0.1667	0.1667		
			Mining intensity	0.1667	0.1667		
		Social economy	Gross industrial output value	0.0546	0.0546		
			Population density	0.0433	0.0688		
			Planting area	0.0688	0.0433		
Non-central water supply area in built-up zones and	Natural factors	Water quantity	Exploitation potential	0.1667	0.2500		
			Aquifer	Water abundance	0.1562	–	
		Permeability coefficient	0.0210	0.0180			
			Aquifer thickness	0.0210	0.0285		
			Water level	0.1352	0.2036		
	Human factors	Development and utilization	Well density	0.1083	0.1083		
			Mining intensity	0.1083	0.1083		
		Contamination	COD	0.0251	0.0251		
			Sewage quantity	0.0251	0.0251		
			Social economy	Gross industrial output value	0.0777	0.0777	
		Population density	0.0777	0.0777			
		Planting area	0.0777	0.0777			
		Polluted groundwater zones	Natural factors	Water quantity	Exploitation potential	0.1051	0.1148
					Water quality	Fluoride concentration	0.0239
Salinity	0.0239			0.0305			
	Aquifer			Water abundance	0.0639	–	
Permeability coefficient	0.0463			0.0221			
	Aquifer thickness			0.0156	0.0200		
Human factors	Development and utilization		Water level	0.0844	0.1623		
			Well density	0.0819	0.0819		
	Mining intensity		0.0819	0.0819			
			Contamination	COD	0.0688	0.0688	
	Sewage quantity			0.1375	0.1375		
	Social economy		Gross industrial output value	0.0536	0.0536		
Population density		0.0426	0.0426				
Planting area		0.0338	0.0338				
Land subsidence zones		Natural factors	Water quantity	Exploitation potential	0.0630	0.0630	
	Aquifer			Water abundance	0.0713	–	
	Permeability coefficient		0.0151	0.0327			
		Aquifer thickness	0.0151	0.0327			
	Water level	0.1275	0.1635				
		Sand layer thickness	0.1040	0.1040			

Table 2 (continued)

First level indexes	Second level indexes	Third level indexes	Fourth level indexes	Weight II, III, IV	Weight V, VI
		Geological environment	Engineering geological stabilization	0.1040	0.1040
	Human factors	Development and utilization	Well density	0.1667	0.1667
			Mining intensity	0.1667	0.1667
		Social economy	Gross industrial output value	0.1151	0.1151
			Population density	0.0267	0.0267
Salt water descending zones	Natural factors	Water quantity	Planting area	0.0248	0.0248
			Exploitation potential	0.1163	0.1163
		Water quality	Fluoride concentration	0.0219	0.0219
			Salinity	0.0658	0.0658
			Aquifer	Water abundance	0.0755
			Permeability coefficient	0.0528	0.0634
			Aquifer thickness	0.0200	0.0251
		Water level	0.1972	0.2219	
		Buried depth of salt water	0.1172	0.1523	
	Human factors	Development and utilization	Well density	0.0833	0.0833
			Mining intensity	0.0833	0.0833
		Social economy	Gross industrial output value	0.0556	0.0556
			Population density	0.0556	0.0556
			Planting area	0.0556	0.0556

located in Urban area, Jinghai, Dagang, Xiqing, Jinnan; while 59.29 % of bedrock area in Ji has the higher risk grade.

In general, the risk grades of Urban area, Danggang, Jinnan, Hangu, Tanggu, Xiqing, Jinghai, Dongli are highest, the assessment conclusion is in agreement with actual situation of groundwater development and utilization in various regions and the function assessment in Tianjin (Li et al. 2013a, b), which can be used as the basis of decision-making about groundwater. If the exploitations of groundwater in these areas are maintained or increased, the risk grades will be further increased. But, after the south-to-north water transfer project has transported, the structure of water-supply sources would change in Tianjin, reducing the overdependence on groundwater, the risk grades of these areas would continue to reduce.

6 Conclusions

- Based on the function zoning of shallow groundwater and deep groundwater in Tianjin, the risk assessment systems for shallow and deep groundwater are built up according to natural and human factors.
- The weights of each assessment index are calculated by AHP method. The original index values are normalized according to the larger the better or the smaller the better. Based on the normalized factor values and the weights of functional zoning indexes, the risk values of I, II, III, IV, V and VI aquifer and bedrock aquifer are calculated by raster calculator of ArcGIS.

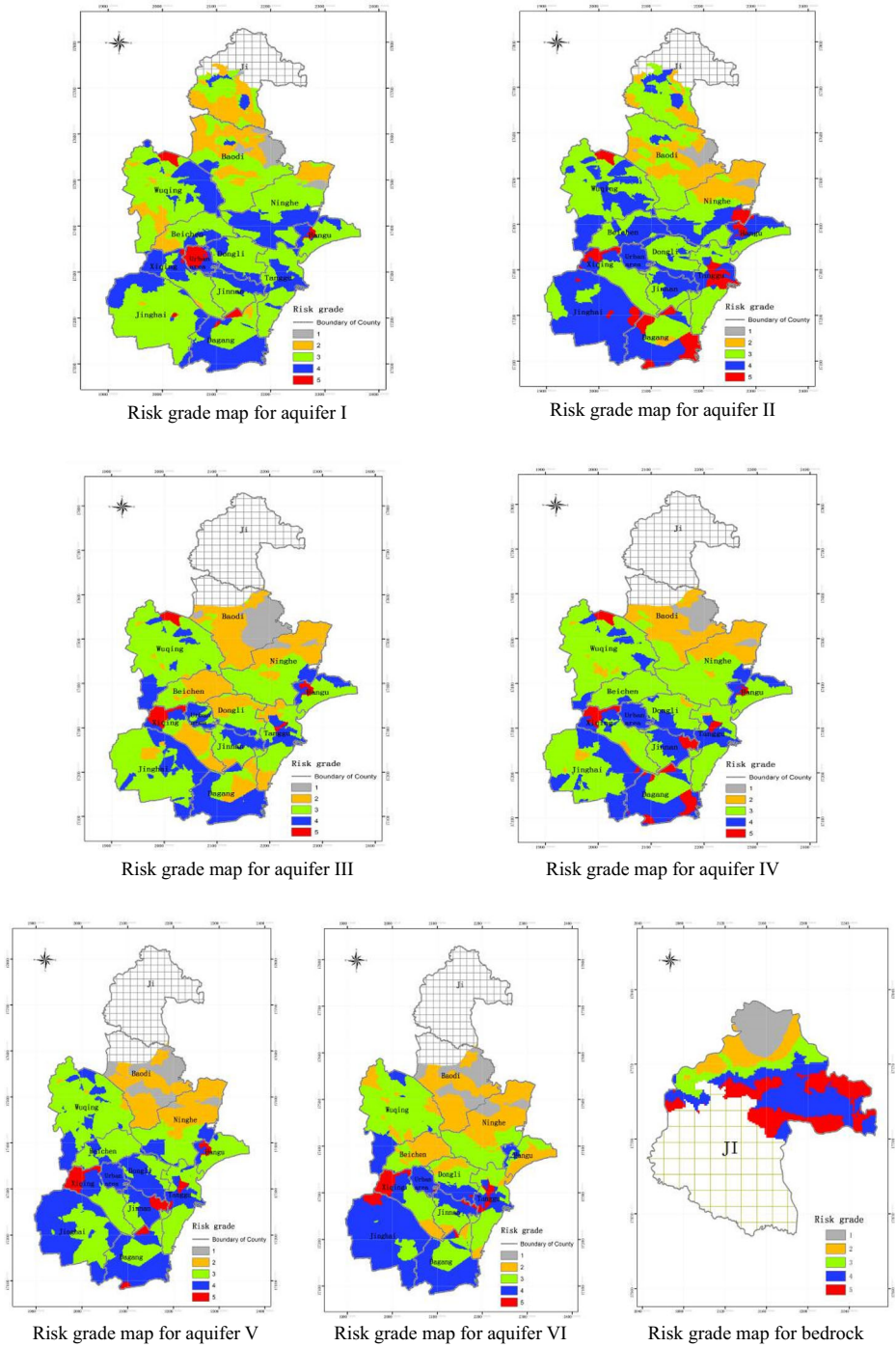


Fig. 2 Risk grades of groundwater development and utilization in Tianjin city

Table 3 The different risk grades area of each aquifer in districts of Tianjin city (unit:km²)

Risk grade	Ji	Baodi	Wuqing	Ninghe	Beichen	Urban area	Jinnan	Xiqing	Dongli	Jinghai	Hangu	Tanggu	Dagang
I	1	9.00	184.92	0.00	42.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	428.63	515.67	164.39	135.56	91.69	0.00	10.27	0.00	5.34	0.00	0.00	23.34
	3	273.38	755.44	975.94	663.05	310.36	0.00	307.83	333.42	1116.70	243.56	486.28	338.48
	4	55.69	52.45	382.64	451.97	79.17	77.91	230.48	141.19	339.47	103.08	193.64	532.97
	5	0.00	0.00	48.52	0.00	0.00	95.63	11.53	0.00	0.00	5.20	17.86	0.00
II	1	0.00	144.84	0.00	39.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	203.34	576.00	0.28	448.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	38.11
	3	440.72	756.70	908.58	450.14	231.47	0.00	384.61	321.61	196.88	150.33	416.25	287.44
	4	122.63	30.94	614.11	298.69	249.75	172.69	100.41	153.00	1213.03	175.64	139.08	377.44
	5	0.00	0.00	48.52	56.67	0.00	0.84	75.09	0.00	0.00	56.81	38.53	124.59
III	1	-	463.64	0.00	67.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	-	678.23	27.14	530.16	303.47	0.00	257.34	202.36	60.47	0.00	153.42	179.16
	3	-	346.36	1236.80	630.42	177.75	56.11	126.28	223.17	957.23	224.58	365.63	187.45
	4	-	20.11	259.03	65.39	0.00	117.42	68.91	49.08	449.02	109.27	148.64	560.67
	5	-	0.00	48.52	0.00	0.00	0.00	107.58	0.00	0.00	30.66	12.23	0.00
IV	1	-	254.67	0.00	35.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	-	717.61	45.70	473.48	1.55	0.00	22.92	17.72	36.98	0.00	8.16	0.00
	3	-	515.95	1268.86	721.97	458.16	2.25	338.06	311.77	825.75	225.42	467.58	325.55
	4	-	20.11	208.41	62.72	21.52	171.28	110.25	145.13	597.80	122.20	182.67	459.56
	5	-	0.00	48.52	0.00	0.00	0.00	88.88	0.00	0.00	16.88	21.52	142.17
V	1	-	474.61	0.00	64.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	-	714.66	35.44	610.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	-	298.97	1214.86	454.92	405.00	0.00	295.73	152.72	514.83	277.88	463.64	310.22
	4	-	20.11	321.19	163.41	76.22	173.53	128.39	321.89	951.89	55.97	183.66	575.30
	5	-	0.00	0.00	0.00	0.00	0.00	135.98	0.00	0.00	30.66	32.63	41.77
VI	1	-	459.00	0.00	126.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3 (continued)

Risk grade	Ji	Baodi	Wuqing	Ninghe	Beichen	Urban area	Jinnan	Xiqing	Dongli	Jinghai	Hangu	Tanggu	Dagang
2	-	737.16	210.94	667.97	315.42	0.00	33.33	86.48	90.70	0.00	184.22	58.22	28.55
3	-	292.08	1087.59	499.50	164.25	8.86	189.00	228.52	242.02	102.52	118.97	413.86	314.16
4	-	20.11	272.95	0.00	1.55	159.05	145.83	110.39	139.08	1308.66	61.31	157.78	576.14
5	-	0.00	0.00	0.00	0.00	5.63	16.88	134.72	2.81	55.55	0.00	50.06	8.44
Bedrock	1	125.16	-	-	-	-	-	-	-	-	-	-	-
	2	105.05	-	-	-	-	-	-	-	-	-	-	-
	3	106.17	-	-	-	-	-	-	-	-	-	-	-
	4	271.69	-	-	-	-	-	-	-	-	-	-	-
	5	218.25	-	-	-	-	-	-	-	-	-	-	-

Table 4 The area proportion of risk grade 4 and 5 of each aquifer in districts of Tianjin city (unit:%)

Aquifer	Ji	Baodi	Wuqing	Ninghe	Beichen	Urban area	Jinnan	Xiqing	Dongli	Jinghai	Hangu	Tanggu	Dagang
I	7.26	3.48	27.44	34.94	16.45	100.00	38.64	43.21	29.75	23.50	33.18	28.48	60.98
II	15.99	2.05	42.17	27.47	51.90	100.00	49.20	31.33	32.24	86.58	58.76	38.78	64.89
III		1.33	19.57	5.06	0.00	67.67	33.56	31.51	10.34	30.61	38.39	23.66	60.46
IV		1.33	16.35	4.85	4.47	98.70	62.89	35.55	30.58	41.18	38.16	30.03	64.89
V		1.33	20.44	12.63	15.84	100.00	68.22	47.20	67.82	64.90	23.77	31.81	66.55
VI		1.33	17.37	0.00	0.32	94.89	42.26	43.76	29.90	93.01	16.82	30.57	63.04
Bedrock	59.29												

- (c) The higher risk of aquifer I is located in Urban area, Dagang, Xiqing; the higher risk of aquifer II is located in Urban area, Jinghai, Dagang, Hanggu, Beichen, Jinnan, Wuqing; the higher risk of aquifer III is located in Urban area, Dagang; the higher risk of aquifer IV is located in Urban area, Dagang, Jinnan, Jinghai; the higher risk of aquifer V is located in Urban area, Jinnan, Dongli, Dagang, Jinghai, Xiqing; the higher risk of aquifer VI is located in Urban area, Jinghai, Dagang, Xiqing, Jinnan; while 59.29 % of bedrock area in Ji has the higher risk grade.
- (d) In general, the risk grades of Urban area, Danggang, Jinnan, Hangu, Tanggu, Xiqing, Jinghai, Dongli are highest.

Acknowledgments The authors would like to acknowledge the financial support for this work provided by the Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research) (Grant no.IWHR-SKL-201312), the Science Fund for Creative Research Groups of the National Natural Science Foundation of China (Grant no.51321065), Ministry of Water Resources Special Funds for Scientific Research on Public Causes (201401041) and Tianjin Research Program of Application Foundation and Advanced Technology (Grant no. 12JCQNJC05200).

Conflict of Interest The authors declared that they have no financial conflicts of interest to this work.

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