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Assessing Risks from Groundwater Exploitation and Utilization: Case Study of the Shanghai Megacity, China

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Abstract: With rapid economic development, demand for water resources is continuously increasing, which has resulted in common overexploitation of groundwater, particularly in megacities. This overexploitation of groundwater over many years has brought a series of adverse problems, including groundwater level decline, land subsidence and hydrogeological issues. To quantitatively describe these risks, we propose a risk evaluation model for groundwater exploitation and utilization. By deducing and expanding on the cusp catastrophe type, this study breaks through the limitations on the catastrophe assessment method, e.g., the number of indicators, and establishes an improved catastrophe assessment model for groundwater exploitation and utilization risk. In addition, the index system of the risk evaluation is constructed including three criterion layers: groundwater system condition (B1), groundwater exploitation and utilization (B2) and groundwater environmental problems (B3) and is tested for the conditions in Shanghai City, eastern China. The evaluation results show that the comprehensive risk values for groundwater exploitation and utilization in all districts (counties) of Shanghai are between 0.68 and 0.85, which categorizes the city as in the moderate risk zone; therefore, the improved catastrophe model is suitable for assessing groundwater exploitation risk in Shanghai City and should be applicable more broadly for the effective protection and sustainable supply of groundwater.

Keywords: groundwater resources; groundwater exploitation and utilization risk; catastrophe theory; evaluation model

1. Introduction

Groundwater is the most important water resource on Earth and is a major source of water for domestic, industrial and agricultural uses and ecological environments worldwide. However, since the beginning of the 20th century, accelerating urbanization, industrialization and climate changes pose risks to the quantity and quality of groundwater, resulting in regional groundwater dynamic imbalances [1]. In the mid-1980s, global groundwater exploitation was approximately 5500×10^8 m^3/a; of athis total, the exploitation by India, the United States, China, the European Community, Japan, Egypt and Australia was 3631.8×10^8 m^3/a, or 66%. Furthermore, the exploitation of groundwater in different countries was highly variable. By the end of the 20th century, global groundwater exploitation exceeded 7500×10^8 m^3/a, which has led to a series of environmental problems, such as groundwater funnelling, seawater intrusion, land subsidence, soil salinization, desertification, and water pollution, and serious disasters and economic losses [2]. Therefore, the sustainability and management of the groundwater development and utilization require the correct understanding and assessment of these risks and problems caused by unreasonable exploitation and utilization of groundwater resources.

Risk has been defined as the probability of exposure to loss, injury, or other adverse or unwelcome circumstance [3]. Due to the regional importance of groundwater, comprehensive studies on the risks from groundwater usage have been conducted worldwide, including on groundwater environmental, exploitation and utilization risks. Thus far, studies of groundwater risk have mainly focused on aspects of groundwater environmental risk, especially groundwater quality and associated health risks [4–11]. Because groundwater systems are large, open and complex, great uncertainty exists in the process of groundwater development and utilization. Therefore, without scientific and reasonable planning, the exploitation of groundwater can bring great risks and even lead to disasters. Given the consequences, a comprehensive risk analysis of groundwater that can provide reasonable and reliable plans for groundwater exploitation and minimize the risk of exploitation and utilization is necessary [12,13]. At present, there are many methods of groundwater risk assessment, such as fuzzy evaluation [14,15], factor analysis [16], neural network analysis [17–19], analytic hierarchy process [20–23] and so on. Zhang et al. proposed an approach with analysis hierarchy process and fuzzy comprehensive evaluation integrated together to establish a corresponding index system of groundwater risk assessment [15]. Li et al. introduced artificial neural network (ANN) method with learning mechanism containing weights and then evaluated the risk of karst groundwater pollution in Guizhou Province, China. Considering some methods are difficult to solve the problem of determining weight correctly, such as the fuzzy evaluation method; some methods are complicated to calculate and require a large number of samples, such as factor analysis method; it's reasonable to choose the catastrophe theory evaluation method to avoid these problems. The advantage of this method is that the determination of the importance of each index is based on the inherent contradictory position and mechanism of each target in the normalization formula itself, and the weight of the index is not used, thus the evaluation results are objective, accurate and easy to calculate. In recent years, some scholars have introduced catastrophe theory into the field of groundwater, and carried out a lot of basic research on risk assessment in the process of groundwater exploitation and utilization. Du chose Taian County in Liaoning Province as a study area and used catastrophe theory for calculating local groundwater resources exploitation threshold [24]. Wang based on the evaluation results of groundwater development risk, and taking into account the natural situation, development and utilization of the status, socioeconomic status, used a catastrophe evaluation method to assess the risk of groundwater development in Shawan District [25]. The dimensions of control variables of the above-mentioned studies are less than four, when there are more than four indicators corresponding to the criterion layer, the criterion layer needs to be stratified twice, which complicates the evaluation index system [25]. So, it is necessary to extend the type of cusp-like catastrophe and break through the limitation of numbers of the control variables of catastrophe evaluation method.

In regions with frequent water stress and large aquifer systems, groundwater is often used as an additional water source. If groundwater extraction exceeds natural groundwater recharge for extensive areas and long times, overexploitation or persistent groundwater depletion occurs. Wada et al. (2010) provided a global overview of groundwater depletion and noted large extraction rates in China [26]. Shanghai is one of the largest metropolitan areas in China. Like other megacities, Shanghai suffers from overexploitation of groundwater induced by poor water resources management. Since the first deep well was excavated in 1860 in the central city, the number of deep wells and annual exploitation have increased continuously. In 1963, groundwater exploitation reached a historical peak, when total groundwater exploitation for the entire city was 2.03×10^8 m^3/a and the number of deep wells reached 1051. Since 2000, the Shanghai Municipal Government has taken measures to address the exploitation, which has resulted in signs of recovery for the groundwater level of all aquifers in the city and easing of land subsidence. However, overexploitation of groundwater in Shanghai continues to decrease groundwater levels, cause land subsidence and sharply diminish groundwater resources; therefore, risks and challenges remain for sustainable groundwater usage in Shanghai.

Unbalanced development and utilization of groundwater exists all over the world. China is one of the earliest countries in the world to exploit and utilize groundwater. With the rapid development of China in the 1980s, the degree of groundwater development and utilization has increased rapidly, especially in large and medium-sized cities. Taking Shanghai as an example, the exploitation of groundwater in Shanghai has the characteristics of long duration, large intensity and wide scale, and it is a typical representative of regional groundwater development and utilization risk in cities. Objectives of this paper are: (1) to propose a risk assessment model for groundwater exploitation and utilization by deriving and expanding numbers of the control variables of the catastrophe theory, (2) to construct a universal evaluation index system of the groundwater exploitation and utilization risk according the features of groundwater system and its risks, (3) to assess and analyze the risk level of the groundwater exploitation and utilization in the districts and aquifers of Shanghai region.

2. Methodology

The process of continuous, gradual and smooth changes in nature can be solved using calculus. However, natural and social phenomena are subject to sudden changes and transitions, such as rock ruptures, bridge collapses, earthquakes, cell divisions and economic crisis. However, when continuous developments transition from gradual and quantitative change to sudden and qualitative change, they are termed catastrophic phenomena; the sudden jump from one form to another cannot be described and solved by calculus. To address this step-change process, mathematicians use catastrophe theory.

Catastrophe theory is widely applied in academia to many disciplines, and it has been used successfully to solve many problems that are intractable using other methods. Rene Thom [27] pointed out that the application of catastrophe theory can be divided into two levels. The first level is theoretical application, which describes the catastrophe theory model with precise quantitative rules and can quickly give qualitative explanations for global characteristics and singularities of solutions. It is mainly applicable to mathematics [28–30], physics [31] and chemistry [32]. The second level is the practical application of catastrophe theory, which brings observed phenomena, such as jumps and lags, into a mathematical model to simulate data. It has been primarily applied to biological [33], social [34] and environmental sciences [35].

Catastrophe theory classifies the critical points of the system using the potential function and studies the characteristics of discontinuous change states near various critical points. According to their geometric shapes, there are seven primary catastrophe types [36], which are shown in Table 1.

Table 1. The seven primary catastrophe types.

Catastrophe Type	Control Variable Dimension	State Variable Dimension	Potential Function
Fold	1	1	$V(x) = x^3 + ax$
Cusp	2	1	$V(x) = x^4 + ax^2 + bx$
Swallow Tail	3	1	$V(x) = x^5 + ax^3 + bx^2 + cx$
Butterfly	4	1	$V(x) = x^6 + ax^4 + bx^3 + cx^2 + dx$
Hyperbolic Umbilical Point	3	2	$V(x) = x^3 + y^3 + axy - bx - cy$
Elliptic Umbilical Point	3	2	$V(x) = x^3 - xy^2 + a\left(x^2 + y^2\right) - bx + cy$
Parabolic Umbilical Point	4	2	$V(x) = y^4 + x^2y + ax^2 + by^2 - cx - dy$

Note: $V(x)$ represents the potential function and there are two types of variables in the potential function: (1) state variables x and y represent the behaviour state of the system and (2) control variables a, b, c and d, which can be regarded as factors affecting the behaviour state of the system.

As shown in Table 1, the dimensions of these seven primary control variables are not greater than four. In practice, the research object is more complex, and the dimension of control variables (the number of evaluation indicators) is far more than four in most cases, which limits the application of catastrophe theory. Therefore, it is necessary to expand the type of primary catastrophe.

2.1. Extension of the Catastrophe Theory Evaluation Method

A catastrophe with one-dimensional state variables is called a cusp-like catastrophe. Because the state variables involved in this study are all one-dimensional, we apply and extend the cusp-like catastrophe, and the control variable dimension is extended from four to n. For a research object whose state variable is one-dimension, the dimension of control variable is no longer restricted, thus the application condition and range of catastrophe theory are expanded.

When $\eta(x)$ is a finite function, ε_i is the coefficient and $g(x)$ is a polynomial close to $\eta(x)$, $g(x)$ can be written as:

$$g(x) = \eta(x) = \sum_i \varepsilon_i x^i \tag{1}$$

Considering infinitesimal diffeomorphism:

$$\Phi : x| \rightarrow x + \varphi(x) \text{ (where, } \varphi(x) \text{ is a polynomial)} \tag{2}$$

The effect of $\varphi(x)$ on $\eta(x)$ is given by the formula:

$$\Phi : \eta(x)| \rightarrow \widetilde{g}(x) = \eta(x) + \varphi(x)\frac{d\eta}{dx} \tag{3}$$

In the case of only one substantive variable, the singularities all belong to the form x^n. According to the above deduction method, a diffeomorphism can be found to eliminate all terms that are multiples of $\frac{d\eta}{dx}$ (x^{n-1}). Thus, the universal unfolding of the cusp-like point is:

$$x^n + a_1x^{n-2} + a_2x^{n-3} + \cdots + a_ix^{n-i-1} + \cdots + a_{n-2}, \quad n \geq 3 \tag{4}$$

Therefore, the cusp-like catastrophe potential function is:

$$V(x) = x^n + a_1x^{n-2} + a_2x^{n-3} + \cdots + a_ix^{n-i-1} + \cdots + a_{n-2}x, \quad n \geq 3 \tag{5}$$

When n = 3, 4, 5, 6, the corresponding catastrophe types are folded, cusp, swallow tail and butterfly. When n = 7, it is termed an Indian cottage due to its similar geometry. When $n > 7$ the geometry is more complex. The extended cusp catastrophic types are shown in Table 2.

Based on the potential function, the equilibrium surface, singular point set and bifurcation point of different catastrophe models are analysed, and the normalized formula of control variables are obtained (Table 2). The normalization formula is the basic formula for evaluating using catastrophe theory. The total catastrophe membership value can be obtained using a recursion operation with the normalization formula, which is the basis for the final comprehensive evaluation.

Taking cusp catastrophe as an example, from $V'(x) = 0$, the equation of equilibrium surface is obtained as follows:

$$4x^3 + 2ax + b = 0 \tag{6}$$

From $V''(x) = 0$, we can know that the equation of singular point set is:

$$12x^2 + 2a = 0 \tag{7}$$

By eliminating x, the bifurcation equation is obtained as follows:

$$8a^3 + 27b^2 = 0 \tag{8}$$

The bifurcation equation written in the form of decomposition is as follows:

$$\begin{aligned} a &= -6x^2 \\ b &= 8x^3 \end{aligned} \tag{9}$$

The bifurcation equation can be further rewritten as follows:

$$x_a = \sqrt{\frac{a}{-6}},\ x_b = \sqrt[3]{\frac{b}{8}} \tag{10}$$

If $|x| = 1$, then $a = -6$, $b = 8$, which determines the range of state variables x and control variables a, b. That is to say, $0 \leq |x| \leq 1$, $0 \leq |a| \leq 6$, $0 \leq |b| \leq 8$, the values of these three variables are not uniform. In order to operate conveniently, the range of state variables and control variables is usually limited to 0–1. For this reason, we should reduce a by 6 times and b by 8 times, the method of reducing the relative range does not affect the properties of catastrophe model.

The normalization formula of cusp catastrophe type is as follows:

$$x_a = \sqrt{a},\ x_b = \sqrt[3]{b} \tag{11}$$

Similarly, it can be concluded that the normalization formula of swallow tail catastrophe type is as follows:

$$x_a = \sqrt{a},\ x_b = \sqrt[3]{b},\ x_c = \sqrt[4]{c} \tag{12}$$

The normalization formula of butterfly catastrophe type is as follows:

$$x_a = \sqrt{a},\ x_b = \sqrt[3]{b},\ x_c = \sqrt[4]{c},\ x_d = \sqrt[5]{d} \tag{13}$$

The normalization formula of Indian cottage type is as follows:

$$x_a = \sqrt{a},\ x_b = \sqrt[3]{b},\ x_c = \sqrt[4]{c},\ x_d = \sqrt[5]{d},\ x_e = \sqrt[6]{e} \tag{14}$$

According to the requirements of evaluation content and index selection, the dimension of control variables can be properly expanded to meet the requirement of evaluation (Table 2).

2.2. Risk Assessment Model for Groundwater Exploitation and Utilization Based on Catastrophe Theory

2.2.1. Construction of the Risk Evaluation Index System

Groundwater exploitation and utilization risk is the result of interactions between natural, social, economic and ecological factors, which can also be used to measure the risk and losses from the groundwater system. At present, progress has been made in generating a water resources risk evaluation index system, but there are many differences in index systems established by different scholars because the evaluation purposes are different. Because the groundwater system is characterized by non-linearity, openness and dynamic behavior, the established evaluation index system must include the main components of groundwater exploitation and utilization risk.

Generally, indicators should be selected to achieve two purposes: (1) the index system established can fully and accurately reflect the current groundwater exploitation and utilization risk evaluation status; (2) the index system should be simple and minimal. Considering groundwater recharge, allowable exploitation, population, society, economy and negative effects of ecological environment, we proposed the following risk evaluation index system for groundwater exploitation and utilization. The index consists of three levels: target, criterion and index (Table 3).

Table 2. Expanded cusp catastrophic types.

Catastrophe Type	Control Variable Dimension	State Variable Dimension	Potential Function	Normalization Formula for the Control Variable
Fold	1	1	$V(x) = x^3 + ax$	
Cusp	2	1	$V(x) = x^4 + ax^2 + bx$	$x_a = \sqrt{a}, x_b = \sqrt[3]{b}$
Swallow Tail	3	1	$V(x) = x^5 + ax^3 + bx^2 + cx$	$x_a = \sqrt{a}, x_b = \sqrt[3]{b}, x_c = \sqrt[4]{c}$
Butterfly	4	1	$V(x) = x^6 + ax^4 + bx^3 + cx^2 + dx$	$x_a = \sqrt{a}, x_b = \sqrt[3]{b}, x_c = \sqrt[4]{c}, x_d = \sqrt[5]{d}$
Indian Cottage	5	1	$V(x) = x^7 + ax^5 + bx^4 + cx^3 + dx^2 + ex$	$x_a = \sqrt{a}, x_b = \sqrt[3]{b}, x_c = \sqrt[4]{c}, x_d = \sqrt[5]{d}, x_e = \sqrt[6]{e}$
	$n > 7$	1	$V(x) = x^n + a_1x^{n-2} + a_2x^{n-3} + \cdots + a_ix^{n-i-1} + \cdots + a_{n-2}x$	

Table 3. Risk evaluation index system for groundwater exploitation and utilization.

Target Layer	Criterion Layer	Index Layer	Unit
Comprehensive Risk Situation of Groundwater Exploitation and Utilization (A)	groundwater system condition (B1)	hydraulic conductivity (C1)	m/day
		specific yield (C2)	-
		storage coefficient (C3)	-
		aquifer thickness (C4)	m
		aquitard thickness (C5)	m
		groundwater depth (C6)	m
		water abundance (C7)	m^3/day
		phreatic evaporation (C8)	mm
		groundwater supply (C9)	m^3/a
		groundwater resources (C10)	m^3/a
		groundwater quantity exploitable (C11)	m^3/a
	groundwater exploitation and utilization (B2)	groundwater exploitation (C12)	m^3/a
		artificial recharge (C13)	m^3/a
		degree of groundwater exploitation (C14)	%
		groundwater supply guarantee ratio (C15)	%
	groundwater environmental problems (B3)	area of groundwater overexploitation (C16)	km^2
		groundwater level change rate (C17)	m/a
		accumulative land subsidence (C18)	mm
		land subsidence rate (C19)	mm/a
		TDS (C20)	g/L
		pH (C21)	-
		soil salinization area (C22)	km^2
		land desertification area (C23)	km^2
		soil erosion area (C24)	km^2
	socio-economic level condition (B4)	population growth rate (C25)	‰
		GDP growth rate (C26)	%
		urbanization rate (C27)	%
		ratio of industrial groundwater use (C28)	%
		ratio of irrigated groundwater use (C29)	%
		ratio of domestic groundwater use (C30)	%
		repetitive use rate of water (C31)	-

2.2.2. The Proposed Catastrophic Risk Assessment Model

In this study, the catastrophe theory evaluation method was used to evaluate the risk of groundwater development and utilization [37]. The specific steps are as follows:

Step 1: Construct the risk evaluation index system. Using the described risk assessment of groundwater development and utilization and inherent relationship between risk factors, we decompose the risk assessment objectives into many layers.

Step 2: Calculate the fuzzy membership value of the index. The scores of the underlying evaluation indices are determined and the values of the indices (control variables) are unified. The data are not comparable when the original data values and measurement units of each index are different. Therefore, before using the Catastrophe Normalization Formula, a multi-dimensional fuzzy membership function with values between [0, 1] is generated using fuzzy mathematics [38].

For positive indices, larger values are considered better and the fuzzy membership value of the index value is calculated from:

$$Y = \begin{cases} 1 & 0 \le X \le a_1 \\ (a_2 - X)/(a_2 - a_1) & a_1 < X < a_2 \\ 0 & a_2 \le X \end{cases} \tag{15}$$

For negative indices, smaller values are considered better and the fuzzy membership value of the index value is calculated from:

$$Y = \begin{cases} 1 & X \ge a_2 \\ (X - a_1)/(a_2 - a_1) & a_1 < X < a_2 \\ 0 & 0 \le X \le a_1 \end{cases} \tag{16}$$

For moderate indices, the fuzzy membership value of the index value is:

$$Y = \begin{cases} 2(X - a_2)/(a_2 - a_1) & a_1 \le X \le a_1 + (a_2 - a_1)/2 \\ 2(a_2 - X)/(a_2 - a_1) & a_1 + (a_2 - a_1)/2 < X < a_2 \\ 0 & X > a_2 \ or \ X \le a_1 \end{cases} \tag{17}$$

In Equations (15)–(17), a_1 and a_2 are upper and lower bounds, whose values will affect the final results. However, in practical application, the indicator values are not absolutely accurate; some are approximate estimates and have fuzziness, so the upper and lower bounds of each index value can be selected in an appropriate range.

Step 3: Calculate the catastrophic membership value of the index. According to the initial value of the fuzzy membership function, the normalization formula of the catastrophe model and evaluation criteria of the catastrophe model are used to perform comprehensive quantitative recursive operations. Finally, they are normalized into one parameter, and the total catastrophe membership value is obtained.

When using the catastrophe model for comprehensive analysis, three different evaluation criteria can be adopted depending on the properties of the actual problem:

1) Non-complementary criterion. When the control variables of the system cannot replace each other, the minimum value from the corresponding mutation values of the control variables (a, b, c, d) is chosen as x; that is, $x = \min\{x_a, x_b, x_c, x_d\}$.
2) Complementary criterion. If the control variables of the system can compensate for other's shortcomings, the average values of x_a, x_b, x_c, x_d corresponding to the control variables a, b, c and d are selected.
3) Over-threshold complementary criterion. The control variables of the system must reach a certain threshold before they can complement each other.

Step 4: Comprehensive evaluation and comparative analysis. Comparing the evaluation result with the risk grade, the problems reflected by the evaluation value of each index are comprehensively analysed, which provides a mechanism for performing the comprehensive evaluation and decision-making.

2.2.3. Improving the Catastrophe Risk Assessment Model

As the index system becomes more complex and the number of catastrophe types increase, the calculation results will increase and ability to discriminate a comprehensive catastrophe membership value will decrease. This problem has become a major drawback of the catastrophe assessment model.

In this study, the hierarchical transformation method is adopted, and the values of the underlying indices are taken as $x_i(i = 1, 2, \cdots, n)$. Using the catastrophe theory evaluation method, the catastrophe membership values $y_i(i = 1, 2, \cdots, n)$ of each index in the index layer are obtained. When n is large enough, the corresponding relationship table between the catastrophe membership value y_i and the index x_i of the index layer can be established. In this way, y_i can be converted to the corresponding risk value.

Then, the risk value of each single index in the index layer is taken as x_i, and according to the Catastrophe Theory Evaluation Method, the corresponding relationship between the catastrophe membership value y_i and index x_i of the criterion layer is established until the target layer is calculated. Thus, each index in each layer, index, criteria and target, can be converted into a unified risk value, which can be used to evaluate the risk of each index (Figure 1).

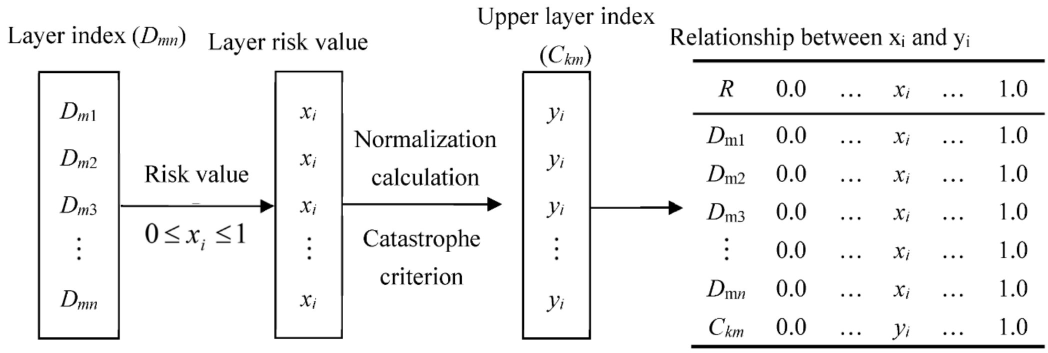

Figure 1. Conversion method for index risk value x_i and catastrophe subordinate function y_i at each level.

3. Study Area and Data

3.1. Study Area

Shanghai City is located between 120°51′–122°12′ E and 30°40′–31°53′ N, covering 6340 km^2 (Figure 2).

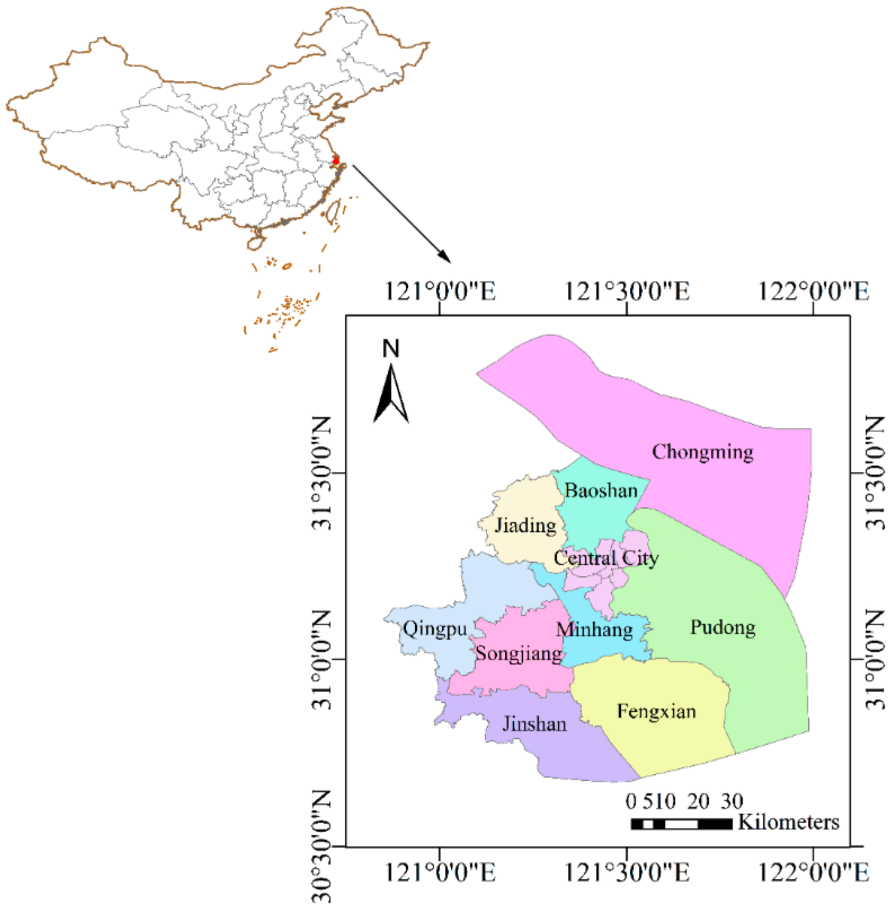

Figure 2. Geographical location and zoning map of Shanghai, China.

The area lies in the subtropical humid monsoon climate with a strong contrast between the four seasons. The annual average temperature is 17.6 °C and the annual average precipitation is about 1173.4 mm, which falls mainly during flood reason from May to September. As part of the Yangtze River Delta Plain, the city is bounded by the Yangtze River to the north, the East China Sea to the east, Hangzhou Bay to the south and Jiangsu and Zhejiang provinces to the west. It extends 120 km from south to north and 100 km from east to west and includes Central District, Pudong New Area, Minhang District, Baoshan District, Jiading District, Jinshan District, Songjiang District, Qingpu District, Fengxian District and Chongming County. In 2016, Shanghai had a total population of 14.395 million.

Shanghai has a long history of exploiting deep groundwater and quaternary porous aquifers in Shanghai can be sub-divided into a phreatic aquifer and five confined aquifers (layers I, II, III, IV and V). Figure 3a shows hydrogeologic map and two hydrogeological sections (I-I′, II-II′) in the study area, which describes the geological structures and lithostratifraphic units in Shanghai. Figure 3b describe the hydrogeological profile of confined aquifers. Along the northwest-southeast direction, six hydrogeological profiles (A-A′, B-B′, C-C′, D-D′, E-E′ and F-F′) of confined aquifers in Shanghai are obtained and the specific locations of each profile and borehole are shown in Figure 3b. The hydrogeologic map clearly shows the soil texture, water quality and aquifer water-rich degree of each hydrogeological profile. Considering that the phreatic aquifer and layer I of the confined aquifer remain largely unexploited, layers II, III, IV and V of the confined aquifer are the research objects in this study. The depth of the bottom of the phreatic aquifer is 3–25 m and the thickness is 2.5–24 m. The first confined aquifer has a depth of 20–40 m and thickness of 3–18 m. Because the phreatic and first confined aquifers are shallowly buried, groundwater is easily polluted and water-quality is poor; therefore, it has not yet been exploited and utilized. The roof depth of the second and third confined aquifer are approximately 60–70 m and 110–120 m, respectively; the aquifer is thick and abundant in water, so has been the primary exploitation target and recharge aquifer in Shanghai. The fourth confined aquifer is generally divided into upper and lower aquifers, which have good water abundance, especially in areas with thicker aquifers. The fifth confined aquifer is controlled by a fluctuating bedrock depth and inclines from southwest to northeast; it is the deepest buried aquifer in the area. The fourth and fifth confined aquifers are currently the largest and second largest aquifers in Shanghai. The mean values of hydrogeological/seepage parameters (e.g., hydraulic conductivity, groundwater quantity exploitable, aquifer thickness, groundwater depth and aquitard thickness) of each aquifer are shown in Table 4.

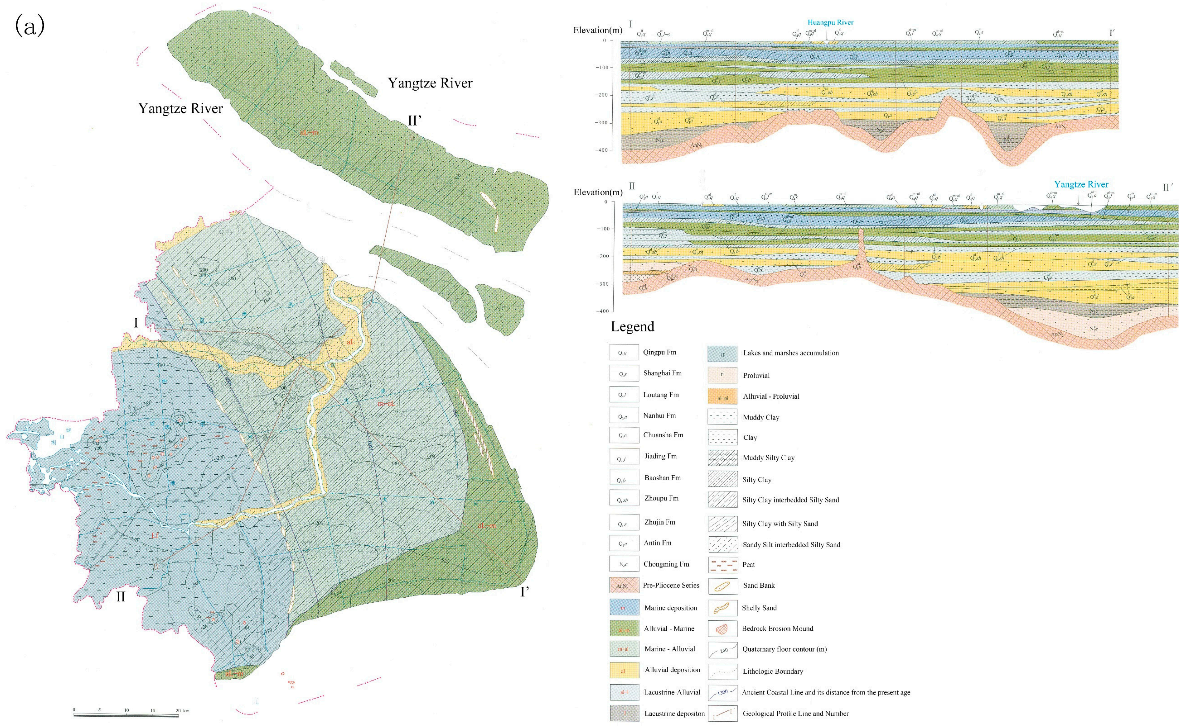

Figure 3. *Cont.*

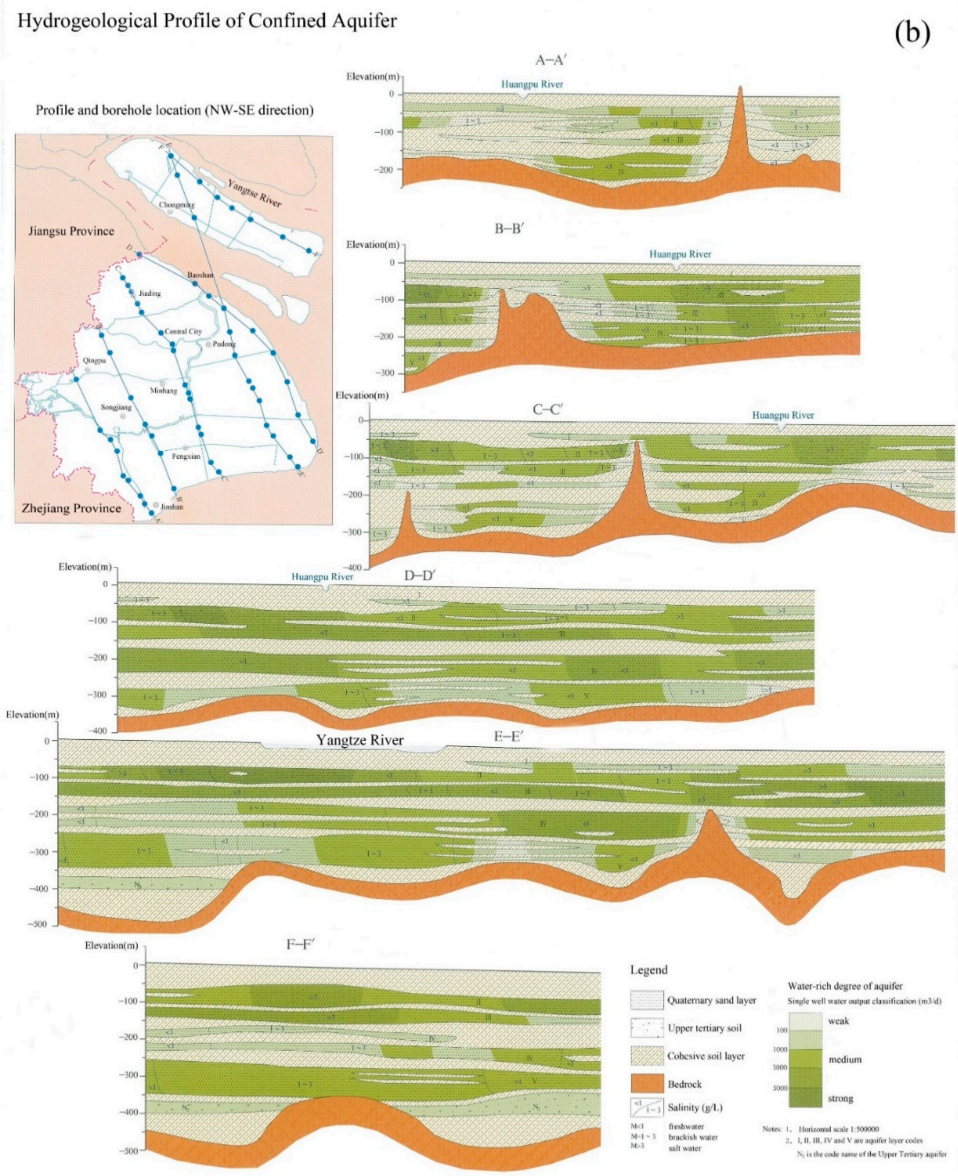

Figure 3. Hydrogeologic map and hydrogeological sections in Shanghai, China from Shanghai Geological Environment Atlas [39], (**a**) hydrogeologic map and two hydrogeological sections, (**b**) hydrogeological profile of confined aquifers.

3.2. Data

The data sources for this study are as follows: (1) the data of groundwater overexploitation area were obtained from the report on the division of deep confined water overexploitation areas and groundwater protection planning in Shanghai, 2008 [40]. (2) accumulative land subsidence data were obtained from the evaluation report of groundwater overexploitation areas in Shanghai, 2004 [41]. (3) the data of hydraulic conductivity, aquifer thickness, aquitard thickness, groundwater exploitation, artificial recharge, groundwater level change rate, TDS in Shanghai were obtained from the Shanghai Geological Environment Atlas, 2002 [39]. (4) data of groundwater depth were provided by Shanghai Geological Environment Bulletin (2001–2003, 2005–2009) [42–49]. (5) the data of groundwater quantity exploitable and degree of groundwater exploitation are based on the results of groundwater resources evaluation in Shanghai during the Eleventh Five-Year Plan and (6) Report on Groundwater Dynamic in Shanghai (1982–2010) [50].

Table 4. The hydrogeological/seepage parameter values of each aquifer in Shanghai.

Index	Aquifer	Central City	Pudong	Minhang	Baoshan	Jiading	Jinshan	Songjiang	Qingpu	Fengxian	Chongming
hydraulic conductivity (m/day)	II	23.65	24.18	33.69	35.46	39.46	14.98	13.02	21.72	37.99	44.27
	III	18.31	28.72	14.06	27.91	12.76	11.05	9.28	12.36	18.09	26.29
	IV	16.88	19.6	14.94	26.82	15.63	11.8	11.67	12.65	14.09	7.21
	V	4.5	6.82	1.04	7.52	11.11	0.89	0.19	3.28	-	10.72
groundwater quantity exploitable (10^4 m^3/a)	II	186.87	472.64	225.68	327.38	369.5	168.93	128.96	197.44	199.14	1129.16
	III	57.75	457.91	57.55	299.12	111.88	134.98	40.57	119.09	200.21	1287.23
	IV	316.17	2698.61	194.38	755.88	149.24	268.54	233.23	141.65	504.06	199.18
	V	23.71	109.38	3.84	101.41	46.1	0	0	36.48	0.73	424.11
aquifer thickness (m)	II	39.39	41.47	64.17	31.42	40.71	28.72	36.45	28.57	65.2	34.29
	III	25.66	31.98	24.56	26.95	19.99	20.75	9.51	10	17.81	28.89
	IV	38.59	51.11	37.39	54.53	21.71	27.3	34.09	16.94	23.93	25.36
	V	11.98	20.45	6.73	19.05	29.91	3.97	1.04	9.58	1.75	55.89
groundwater depth (m)	II	−3.52	−4.13	−3.67	−2.72	−3.45	−12.04	−5.73	−4.96	−2.92	0.41
	III	−4.12	−4.7	−3.96	−3.85	−4.83	−14.91	−8	−8.24	−3.69	−0.49
	IV	−17.85	−15.95	−14.43	−21.16	−16.55	−22.93	−20.88	−24.61	−14.32	−6.96
	V	−24.97	−16.04	−33.07	−27.33	−31.88	-	-	−33.8	−12.71	−24.71
aquitard thickness (m)	II	20.63	9.52	4.91	34.03	24.89	18.59	15.63	28.22	0.29	35
	III	7.38	6.23	6.78	8.98	10.86	10.04	11.18	10.91	8.39	5.22
	IV	24.08	23.88	19.18	28.13	18.7	15.53	21.21	26.36	19.45	27.71
	V	16.64	12.4	13.04	33.15	26.36	8.3	2.36	5.09	4.38	21.81

3.3. Data Analysis

3.3.1. Analysis of Groundwater System Conditions

The groundwater system status mainly reflects the constitutive characteristics of the groundwater system, including hydraulic conductivity, exploitable groundwater quantity, aquifer thickness, groundwater depth, and aquitard thickness. Hydraulic conductivity primarily reflects the hydraulic characteristics of the groundwater aquifer in terms of water abundance; the hydraulic conductivity in Shanghai decreases with increasing depth of the confined aquifer. The hydraulic conductivity of the second confined aquifer ranges from 13 to 45 m/day and the permeability coefficient of the fifth confined aquifer ranges from 0 to 12 m/day. Aquifer thickness and aquitard thickness are the two main internal causes of land subsidence, thus there are large variations between the districts in Shanghai. Exploitable groundwater quantity is the allowable exploitation quantity based on water level and land subsidence; therefore, it is a very important index because it characterizes both exploitation and utilization ability and tolerance for environmental problems (land subsidence). The Pudong New Area and Chongming County have relatively large exploitable groundwater quantities. In the Pudong New Area, it is mainly located in the fourth confined aquifer, exceeding 2500×10^4 m^3/a; whereas in Chongming County, it is mainly located in the second and third confined aquifers, more than 1000×10^4 m^3/a.

The groundwater depth in each aquifer in Shanghai varies with changes in exploitation. The early 1960s and 1990s were two peak periods of exploitation, which corresponded with two valleys in groundwater level. The groundwater levels in aquifers II, III, IV and V across the whole city has declined with increasing exploitation. Moreover, as the amount of exploitation has changed in each aquifer throughout the development and utilization process, groundwater levels have changed correspondingly, with rising and falling rates of the water table differing with time. As shown in Table 5, the groundwater table has gradually risen over the past 10 years, and the rate of rise in the past five years has been greater than that for the previous 10 years. Particularly in the last three years, the groundwater table has been rising at a relatively large rate.

Table 5. Changes in groundwater level from typical observation wells in different Shanghai aquifers.

Aquifer	Number	Water Level (m)					Groundwater Level Change Rate (m/a)		
		1980	2001	2005	2007	2010	1980–2010	2001–2010	2005–2010
II	Chang012-02F	−0.49	-	-	−4.82	−3.15	−0.13	-	-
	Bao040-03S	-	−0.82	−0.65	−0.61	−0.33	-	0.05	0.06
	Chong039-04S	-	2.56	1.52	1.33	1.38	-	−0.12	−0.03
	Feng049-03S	-	−1.76	−2.06	−2.72	−2.52	-	−0.08	−0.09
	Hai051-01G	−1.41	-	−4.2	−4.32	−3.03	−0.08	-	0.23
	Pu218-01C	−1.41	−5.76	−4.67	−4.34	−2.57	−0.06	0.32	0.42
III	Bao040-02S	-	−1.28	−1.2	−1.09	−0.74	-	0.05	0.09
	Chong039-03S	-	2.25	1.27	1.13	1.26	-	−0.1	0
	Feng049-02S	-	−1.98	−2.26	−2.77	−2.51	-	−0.05	−0.05
	Pu009-02	−2.18	−9.88	−7.51	−6.25	−5.75	−0.18	0.41	0.35
	Yang029−01	−1.46	−5.5	−3.91	−3.41	−3.07	−0.08	0.24	0.17
IV	Bao040-01S	-	−20.5	−20.83	−19.59	−16.3	-	0.42	0.91
	Chong039-02S	-	−20.05	−15.6	−15.64	−15.8	-	0.43	−0.04
	Feng049-01S	−8.53	−24.38	−21.22	−19.7	−18.17	−0.48	0.62	0.61
	Pu017-13	-	−36.14	−36.13	−25.77	−17.72	-	1.84	3.68
	Yang034-01G	−13.18	−33.16	−29.76	−23.99	−17.72	−0.23	1.54	2.41
V	Bao122-01	-	−21.87	−23.23	-	−22.53	-	−0.07	0.14
	Chong039-01S	-	−30.24	−33.18	−33.6	−34.16	-	−0.39	−0.2
	Hui035-01S	−2.55	-	-	-	−9.5	−0.35	-	-
	Jia026-01W	-	-	−35.01	−31.83	−27.4	-	-	1.52

Note: '-' stands for data missing of observation wells at this time.

3.3.2. Analysis of Groundwater Exploitation and Utilization

(1) Groundwater exploitation and recharge

Since the first deep well was drilled in Shanghai Bund in 1860, the number of deep wells and their exploitation have increased. According to historical data, groundwater exploitation and recharge in Shanghai (Figure 4) can be divided into four stages: development (1860–1948), peak (1949–1970), sub-peak (1971–2000) and trace change (2001–present). From 1922 to 1936, the number of deep wells increased sharply, and groundwater exploitation increased to an average of 1450×10^4 m^3/a–2000×10^4 m^3/a. After the founding of New China, the national economy has developed rapidly, and the demand for groundwater continues to grow. By the end of 1949, there were 708 deep wells in urban areas and 95 deep wells in suburban areas, with an exploitation volume of 8750×10^4 m^3/a. In 1963, groundwater exploitation reached a historical peak, mainly concentrated in urban areas. Annual groundwater exploitation reached 2.03×10^8 m^3 and land subsidence in Shanghai entered the most serious period. Groundwater recharge increased from 0 to 0.13×10^8 m^3, groundwater level began to rise, and urban surface rebounded accordingly.

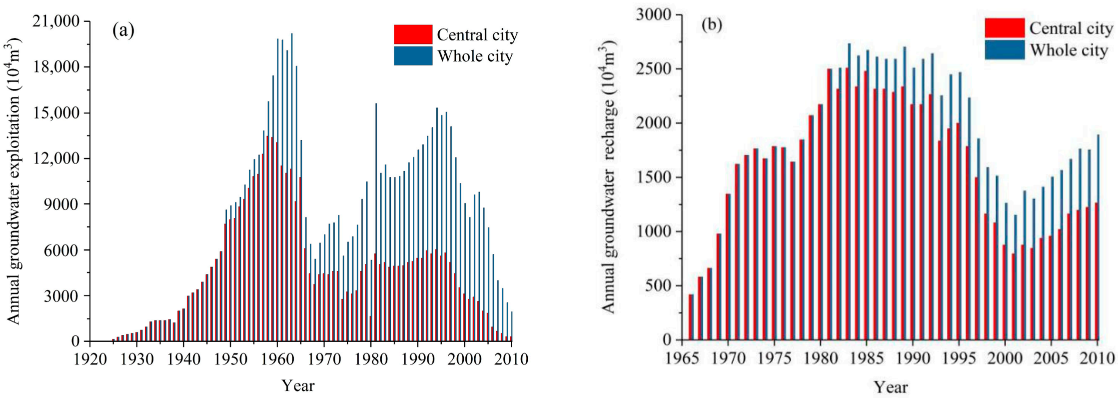

Figure 4. Changes in annual groundwater exploitation (**a**) and recharge (**b**) in Shanghai

In the 1970s, groundwater exploitation across the city was maintained between 5500 × 104–10,500 × 104 m^3/a and recharge was between 1500 × 104–2200 × 104 m^3/a. In the 1980s and 1990s, due to the development of market economy brought about by reform and opening, groundwater exploitation experienced another peak, exceeding 1.5×10^8 m^3/a in 1981. Concurrently, groundwater recharge also increased to 2750×10^4 m^3/a. Since 1995, management departments have actively implemented measures to replace groundwater with tap water, so that the groundwater exploitation has decreased annually; groundwater exploitation was less than 1.0×10^8 m^3/a by 2000. In the middle and late 1990s, due to changes in industrial structure, recharge changed from approximately 2500×10^4 m^3 in 1995 to 1513.2×10^4 m^3 in 2000.

Since 2001, groundwater exploitation in Shanghai has entered a stage of micro-exploitation. Every year, Shanghai formulates designs for groundwater exploitation and recharge to utilize groundwater resources in a planned way. As shown in Figure 5 and Table 6, groundwater exploitation in Shanghai decreased significantly from $10{,}163.4 \times 10^4$ m^3 in 2001 to 2021.9×10^4 m^3 in 2010, while the groundwater recharge increased steadily from 1216.7×10^4 m^3 in 2001 to 1934.1×10^4 m^3 in 2010. Generally, exploitation from each aquifer declined; exploitation in 2010 was about 1/5 of that in 2001. Because aquifers IV and V have been exploited the most, their decreases are the most obvious. Recharge has been primarily distributed in the second aquifer, although it has increased in aquifers III, IV and V. The recharge quantity in 2010 was about 2.5 times that in 2000. The groundwater exploitation in 2011 was 1351×10^4 m^3, and the recharge exceeded 2×10^8 m^3; this was the first year that recharge exceeded exploitation. Shanghai is striving to control groundwater exploitation at about 1000×10^4 m^3 and recharge at over 2000×10^4 m^3, a proportion of exploitation to recharge of 1:2, by the end of the Twelfth Five-Year Plan period.

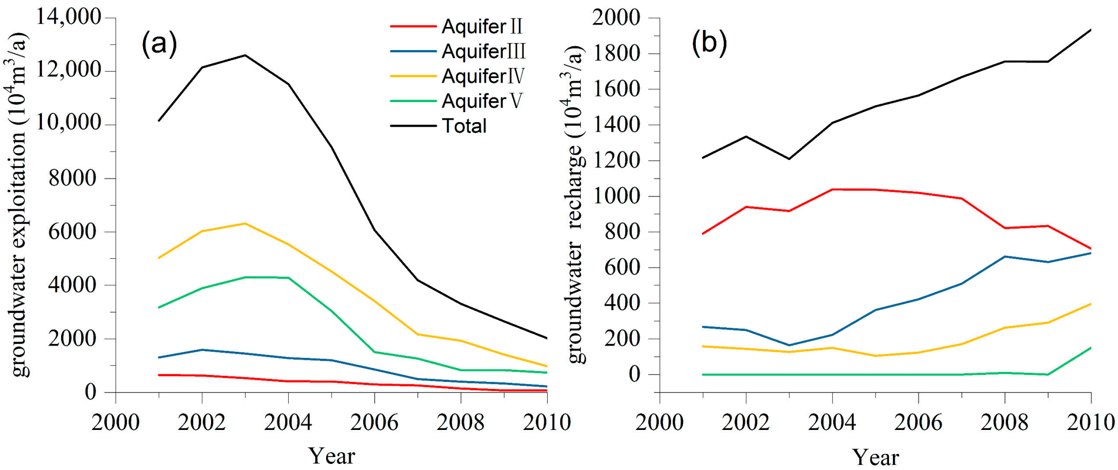

Figure 5. Groundwater exploitation (**a**) and recharge (**b**) in different aquifers in Shanghai 2001–2010.

Table 6. Groundwater exploitation and recharge in different Shanghai districts and aquifers in 2010.

District	Aquifer II			Aquifer III			Aquifer IV			Aquifer V			Total		
	E	R	D	E	R	D	E	R	D	E	R	D	E	R	D
Central city	0	295.8	0	13.5	380	23.4	14	131.7	4.4	24.1	0	101.8	51.6	807.5	8.8
Pudong New Area	0.9	37.8	0.2	108.6	33.9	23.7	694	12	25.7	0	0	0	803.5	83.7	21.5
Minhang District	0	27	0	0	0	0	33	3.7	17.0	16.6	0	432.9	49.6	30.8	10.3
Baoshan District	0	195.7	0	15	165.4	5.0	14.4	45.8	1.9	2.7	0	2.7	32.1	406.9	2.2
Jiading District	9.5	32.7	2.6	17.2	0	15.3	0.3	0	0.2	97.6	0	211.8	124.6	32.7	18.4
Jinshan District	4.2	5.1	2.5	1.7	101.4	1.2	11.6	140.7	4.3	0	0	-	17.5	247.2	3.1
Songjiang District	0	0	0	0	0	0	1	0	0.4	0	0	-	1	0	0.3
Qingpu District	0	0	0	71.6	0	60.2	9.6	0	6.8	0	0	0	81.2	0	16.4
Fengxian District	2.2	4.1	1.1	0	0	0	199.8	30.6	39.6	0	0	0	202	34.8	22.3
Chongming County	56.9	108	5.0	0	0	0	0	32	0	601.8	150.5	141.9	658.8	290.5	21.7
Total	73.8	706.3	2.2	227.6	680.6	8.2	977.6	396.6	17.9	742.9	150.5	99.6	2021.9	1934.1	16.3

Note: E represents groundwater exploitation (10^4 m^3/a), R represents groundwater reinjection (10^4 m^3/a), and D represents the degree of groundwater exploitation (%).

According to the statistical analysis of groundwater exploitation and utilization in Shanghai (Table 6), total groundwater exploitation was 2021.9 × 10^4 m^3 in 2010, which was mainly concentrated in Pudong New Area and Chongming County, 39.7% and 32.6%, respectively. Groundwater exploitation in the city centre accounts for only 2.6% of total exploitation. In terms of aquifer level, groundwater exploitation was mainly drawn from confined aquifers IV and V, 48.4% and 36.7%, respectively; the second confined aquifer accounted for only 3.6%. In 2010, the total amount of recharge in Shanghai was 1934.1 × 10^4 m^3. Regionally, recharge was mainly concentrated in the city centre, 41.8% of the total, followed by Baoshan District, Chongming County and Jinshan District, accounting for 21.0%, 15.0% and 12.8%, respectively. Recharge was mainly concentrated in confined aquifers II and III, 36.5% and 35.2% of the total recharge, respectively. The ratio of groundwater exploitation to recharge was 1.05:1 in Shanghai.

(2) Degree of groundwater exploitation

The degree of groundwater exploitation in Shanghai was calculated for 2010 based on the exploitation of confined aquifers and exploitable storage of groundwater during the Eleventh Five-Year Plan period (16% for the whole city; Table 6). Compared with 1999, the degree of groundwater exploitation in all districts declined significantly; the degree of exploitation exceeded 20% only in Pudong New Area, Fengxian District and Chongming County. However, the exploitation degree of confined aquifers was highly variable: confined aquifer II had the smallest (2.17%), while confined aquifer V had a value of nearly 100%.

3.3.3. Analysis of Land Subsidence

Land subsidence in Shanghai occurs in Quaternary unconsolidated sedimentary strata and began in 1921, mainly due to the development and utilization of groundwater resources. As groundwater exploitation and exploitation layers have changed, land subsidence in Shanghai has undergone different development stages. Using the control measures implemented in the mid-1960s as a dividing line, the period of serious subsidence is defined as prior to 1965, and the period of basic control is defined as 1966 to present. Changes in land subsidence in Shanghai for >80 years are illustrated in Figure 6: 1921–1965 was a period of serious land subsidence in Shanghai, with an average land subsidence in urban area of 1760 mm, average annual subsidence of 39 mm, and maximum cumulative subsidence of 2630 mm.

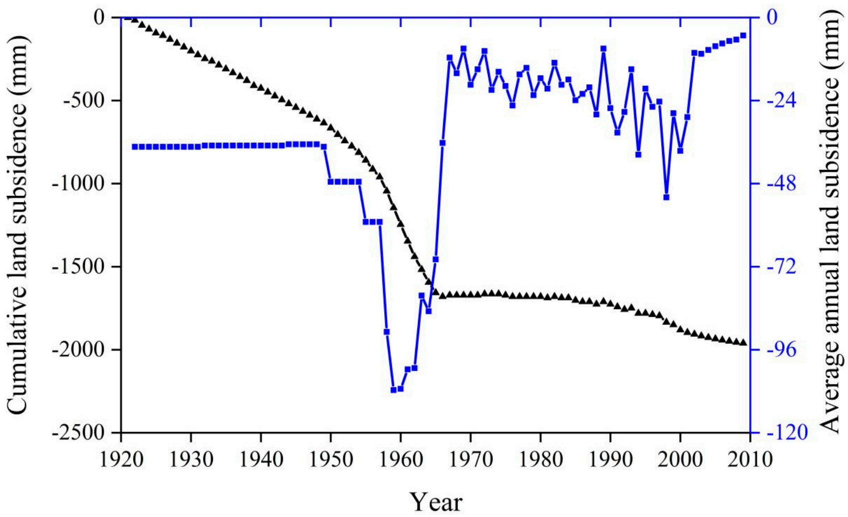

Figure 6. Changes in land subsidence in Shanghai 1920–2010.

To control serious land subsidence, groundwater exploitation has decreased since 1966, and artificial recharge of the main aquifers has been performed to adjust the exploitation pattern. Between 1966 and 1971, the groundwater level began to rebound, with corresponding rebounds in urban land, 18.1 mm. Groundwater exploitation continued to rise during between 1972 and 1989, while the land subsidence decreased slightly, with a cumulative settlement of 62.1 mm and annual average settlement of 3.5 mm. Shanghai entered the period of reform and opening up in the late 1980s, which corresponded to an increased rate of land subsidence; in the next 11 years from 1990 to 2000, the cumulative land subsidence was 171.62 mm and average annual subsidence was 15.6 mm. In the 21st century, the municipal government strengthened the management of groundwater resources, which reduced groundwater exploitation while increasing artificial recharge. By 2010, the groundwater exploitation was less than 2000×10^4 m^3 and recharge increased to 1934.1×10^4 m^3, almost balancing exploitation, which increased groundwater levels in each aquifer to varying degrees and alleviated the slightly accelerated land subsidence.

Surveying and mapping data obtained from the Shanghai Geological Survey Research Institute, the distribution of land subsidence in Shanghai from 1980 to 1995 and 1996 to 2001 is shown in Table 7. From 1980 to 1995, land subsidence in Shanghai remained a problem: average cumulative land subsidence was 81.4 mm and average annual subsidence was 5.4 mm. The main subsidence funnels were in central urban areas, Yangpu, Hongkou and Huangpu, with an average cumulative subsidence of 118.6 mm and average annual subsidence of 7.9 mm. From 1996 to 2001, land subsidence in Shanghai accelerated for a short period, with an average cumulative land subsidence of 75.3 mm and average annual subsidence of 12.6 mm. The main settlement funnel remained in the central city, with an average cumulative subsidence of 129.1 mm and average annual land subsidence of 21.5 mm. However, the average cumulative subsidence of Qingpu District, Songjiang District and Chongming

County was less than 50 mm. The maximum subsidence area changed: Jinshan District, Fengxian District and the southern part of Pudong New Area linked together to form a larger subsidence funnel, which has become a concentrated developed area of land subsidence.

Table 7. Statistical analysis of land subsidence regions in Shanghai.

Year	1980–1995		1996–2001		1980–2001	
Region	**ALS (mm)**	**AALS (mm/a)**	**ALS (mm)**	**AALS (mm/a)**	**ALS (mm)**	**AALS (mm/a)**
Central city	118.6	7.9	129.1	21.5	247.7	11.8
Pudong New Area	77.6	5.2	85.5	14.2	163.1	7.8
Minhang District	111.8	7.5	92	15.3	203.8	9.7
Baoshan District	90	6	71.7	12	161.7	7.7
Jiading District	76.9	5.1	89.8	15	166.7	7.9
Jinshan District	55.2	3.7	41.2	6.9	96.4	4.6
Songjiang District	62.2	4.1	54.5	9.1	116.7	5.6
Qingpu District	57.7	3.8	65.8	11	123.5	5.9
Fengxian District	52.7	3.5	30.1	5	82.8	3.9
Chongming County	59.6	4	45.2	7.5	104.8	5
Total	81.4	5.4	75.3	12.6	156.7	7.5

Note: ALS is cumulative land subsidence, AALS is average annual land subsidence.

With the increasing overexploitation of groundwater, regional ground subsidence funnels will continue to expand. From 1980 to 2001, there were three clear land subsidence areas in Shanghai: the central urban area, western suburbs and southern end of Chongming. However, their causes were different. For a long time, the exploitation and recharge of groundwater in the central city has been balanced, and the recharge remains larger than the exploitation. Nonetheless, land subsidence remains a significant problem because of the large-scale urban reconstruction and engineering activities conducted in the 1980s and 1990s. Subsidence in the western suburbs developed rapidly, directly related to changes in the industrial structure and transfer of groundwater exploitation concentrated areas to the west. Concurrently, subsidence has been affected by increases in groundwater exploitation in the urban and rural areas of Jiangsu Province. Southern Chongming Island is a new sedimentary area for reclamation, and its groundwater exploitation has been increasing. In summary, these three development trends are responsible for the land subsidence in Shanghai in recent years.

4. Results and Discussion

4.1. Construction of the Evaluation Index System of Shanghai Region

Based on the basic conditions and data for the study area, we define the groundwater system condition (B1), groundwater exploitation and utilization (B2) and groundwater environmental problems (B3) as the criterion layer and perform a multi-level comprehensive evaluation of groundwater exploitation and utilization risks in various districts (counties) and confined aquifers in Shanghai.

The groundwater system condition (B1) includes five indicators, which mainly reflect the constitutive characteristics of groundwater system. The hydraulic conductivity (C1) and the groundwater depth (C4) mainly reflect the characteristics of groundwater aquifer from water-bearing capacity and flow field; and the groundwater quantity exploitable (C2) is the allowable exploitation quantity obtained by water level and land subsidence as constraints; aquifer thickness (C3) and aquitard thickness (C5) are the main internal causes of land subsidence. Water storage coefficient, water-abundance, soil layer characteristics are not selected, mainly because the data are difficult to obtain.

Groundwater exploitation and utilization (B2) mainly reflects the current situation and characteristics of development and utilization. Groundwater exploitation (C6) and artificial recharge (C7) are the two main forms of groundwater exploitation and utilization in Shanghai, which belong to the indispensable indicators. In addition, if the area is rich in water, large-scale exploitation of groundwater will not necessarily lead to adverse consequences, on the contrary, in areas with poor water-rich, even a small amount of exploitation may lead to adverse consequences, and the degree of groundwater exploitation (C8) indicators can well characterize this situation.

Groundwater environmental problems (B3) include four indicators. The main problem in Shanghai is land subsidence caused by overexploitation of groundwater. Therefore, the accumulative land subsidence (C9), groundwater level change rate (C10) and area of groundwater overexploitation (C11) are selected to reflect the groundwater environmental problems. Because there is no groundwater overexploitation caused by groundwater pollution in Shanghai, TDS (C12) index is selected as the representative of groundwater quality index.

We note that socio-economic level indicators are not included in the evaluation system, because the influence of Shanghai's social economy on groundwater development and utilization is mainly reflected in the amount of groundwater exploitation and recharge. We lack the relevant information on additional groundwater in Shanghai used for special purposes so are unable to conduct analyses on these. Choosing 2010 as the base year, the specific index system is shown in Table 8.

Table 8. Risk evaluation index system for groundwater exploitation and utilization in Shanghai.

Target Layer	Criterion Layer	Index Layer	Unit
Comprehensive Risk Situation of Groundwater Exploitation and Utilization	groundwater system condition (B1)	hydraulic conductivity (C1)	m/day
		groundwater quantity exploitable (C2)	10^4 m^3/a
		aquifer thickness (C3)	m
		groundwater depth (C4)	m
		aquitard thickness (C5)	m
	groundwater exploitation and utilization (B2)	groundwater exploitation (C6)	10^4 m^3/a
		artificial recharge (C7)	10^4 m^3/a
		degree of groundwater exploitation (C8)	%
	groundwater environmental problems (B3)	accumulative land subsidence (C9)	mm
		groundwater level change rate (C10)	m/a
		area of groundwater overexploitation (C11)	km^2
		TDS (C12)	g/L

4.2. Comprehensive Analysis of Groundwater Risk Assessment Results

First, according to the number of indices for each item, the basic catastrophic type is determined. Then, the normalized formula and evaluation criteria of the catastrophe type are selected to calculate the catastrophe membership value of each index in the evaluation system. Finally, the conversion relationship between the catastrophic membership value and standard risk value is established, and the membership value for each evaluation index in Shanghai is transformed into a unified risk value. The final comprehensive evaluation index values for groundwater exploitation and utilization risk in Shanghai are shown in Table 9.

Table 9. Evaluation index values for groundwater exploitation and utilization risk in Shanghai.

Index	Central City	Pudong	Minhang	Baoshan	Jiading	Jinshan	Songjiang	Qingpu	Fengxian	Chongming
C1	0.662	0.648	0.519	0.493	0.436	0.786	0.814	0.690	0.457	0.368
C2	0.951	0.501	0.952	0.800	0.880	0.953	0.988	0.943	0.914	0.189
C3	0.562	0.507	0.287	0.597	0.548	0.681	0.595	0.683	0.276	0.563
C4	0.236	0.262	0.243	0.203	0.233	0.588	0.328	0.296	0.212	0.074
C5	0.516	0.238	0.123	0.710	0.622	0.465	0.322	0.438	0.007	0.495
C6	0.028	0.116	0.015	0.019	0.064	0.014	0.003	0.019	0.015	0.093
C7	0.186	0.918	0.963	0.595	0.960	0.629	1.000	1.000	0.954	0.588
C8	0.105	0.068	0.069	0.019	0.195	0.039	0.005	0.048	0.032	0.065
C9	0.875	0.447	0.466	0.653	0.440	0.213	0.111	0.042	0.247	0.153
C10	0.586	0.718	0.580	0.522	0.310	0.329	0.194	0.096	0.872	0.864
C11	0.761	0.129	0.201	0.170	0.556	0.469	0.000	0.451	0.000	0.000
C12	0.063	0.111	0.157	0.014	0.032	0.019	0.026	0.015	0.195	0.149

To evaluate the risk of groundwater exploitation and utilization, it is necessary to divide the risk value for each index into different grades using the risk evaluation criteria; this provides a mechanism for clearly evaluating the risk degree for each index. Considering the few prior studies evaluating risks from groundwater exploitation and utilization, we draw from the classifications for flood risk degree. Thus, five risk classes for groundwater exploitation and utilization are defined based on their comprehensive evaluation values (Table 10). Ten districts in Shanghai are classified for risks from groundwater exploitation and utilization, the specific results are shown in Figures 7 and 8.

Table 10. Classification criteria for groundwater exploitation and utilization risk.

Risk Rank	Risk Level	Comprehensive Evaluation	Coping Strategy
1	Extreme risk	$R \geq 0.95$	Prohibit exploitation
2	High risk	$0.85 \leq R < 0.95$	Prohibit exploitation
3	Moderate risk	$0.5 \leq R < 0.85$	Pressure exploitation
4	Mild risk	$0.30 \leq R < 0.50$	Planned exploitation
5	Low risk	$R < 0.30$	Planned exploitation

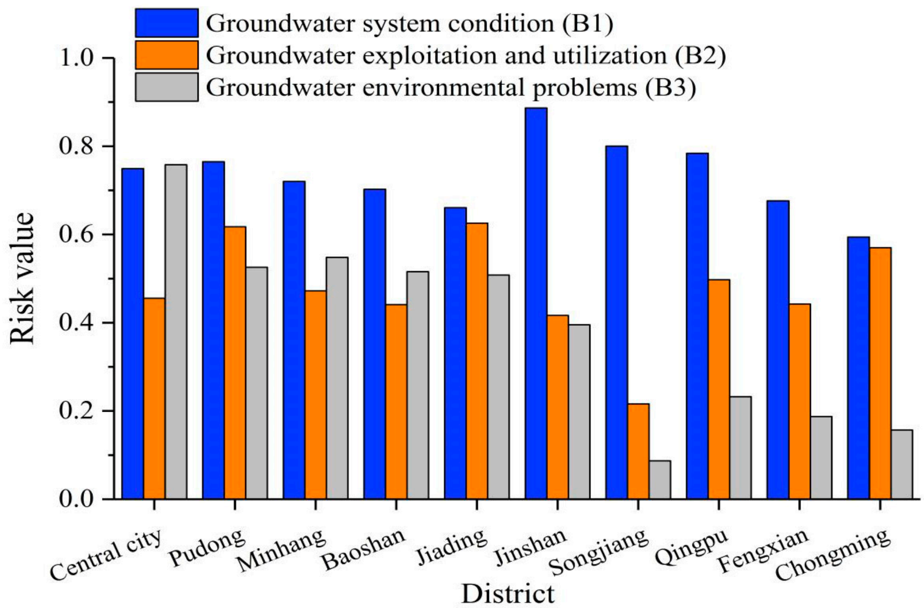

Figure 7. Criteria layer risk values for groundwater exploitation and utilization risk in Shanghai.

As shown in Figure 8, comprehensive risk values for groundwater exploitation and utilization in Shanghai were estimated as between 0.679 and 0.850 in 2010. These values categorize Shanghai as having moderate risk, which indicates that the exploitation of groundwater will cause environmental problems and it is necessary to formulate a groundwater exploitation plan and take appropriate measures.

The comprehensive risk value for Songjiang District is 0.679, indicating that the low degree of groundwater utilization and the rising groundwater level provides good groundwater quality. Therefore, the comprehensive index risk value of Songjiang District is relatively low. The risk values for Chongming County and Fengxian District are 0.73 and 0.74, respectively, which indicate medium risk ($0.5 \leq R < 0.85$). Table 9 shows individual indices have higher risk value, such as the groundwater table change rate (C10) and groundwater exploitation (C6). The risk values for Minhang, Baoshan, Jiading and Qingpu District are around 0.80. Among them, Minhang, Baoshan and Jiading districts were challenged by earlier exploitation of groundwater, higher degree of utilization and serious environmental geological problems. Qingpu District is in two large groundwater depression cones, which results in weak bearing capacity of the system and slow recovery of the groundwater system after exploitation and utilization. The risk values of the central city, Pudong New Area and Jinshan District are relatively high, approaching 0.85. The central city was the earliest and most exploited area in Shanghai, which caused the most serious environmental geological problems and continues to pose a great threat to the safety of society, economic stability and human life. In the Pudong New Area, the population density and the intensity of urban construction have significantly impacted the groundwater system. As for Jinshan District, the aquifer V is basically bedrock with very poor water-quality, and aquifers III and IV are seriously over-exploited areas, which results in a relatively high risk of groundwater exploitation and utilization.

As we have shown, the proposed improved catastrophe theory evaluation method can be used to assess groundwater utilization with a quantitative assessment of risk. In the catastrophe evaluation model, the evaluation method of the underlying indicators directly affects the objective accuracy of the evaluation results. Our evaluation results are consistent with the observed status of the Shanghai groundwater system, which verifies that the index system and catastrophe evaluation model established in this evaluation process are reasonable, and the results are credible.

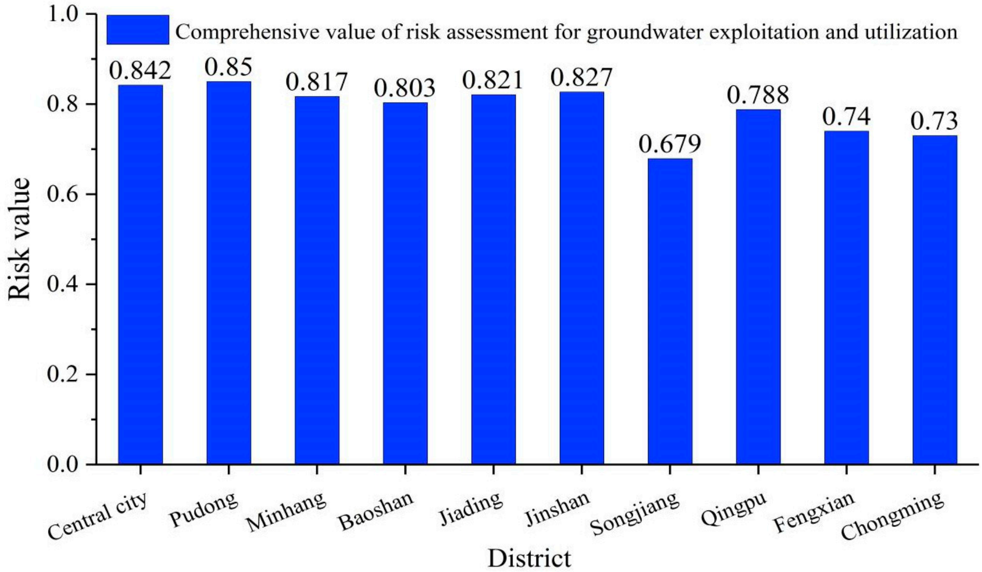

Figure 8. Target layer risk values for groundwater exploitation and utilization risk in Shanghai.

5. Conclusions

Groundwater is an important source of freshwater worldwide, especially in megacities where surface water resources are scarce. Therefore, groundwater exploitation and usage are inevitable. This study proposed a risk evaluation index system and established a catastrophe assessment model for groundwater exploitation and utilization risk in Shanghai using catastrophe theory. The main conclusions and novel aspects are as follows:

The multi-layer index system of risk evaluation of groundwater exploitation and utilization was constructed based on the features of groundwater system and its risks. Because groundwater system is an open and complex giant system, there is no clear and unified definition of groundwater exploitation and utilization risk. To comprehensively and quantitatively assess the risks of groundwater system caused by the unreasonable utilization, the multi indexes assessment is an effective method. Therefore, this paper constructed a multi-layer index system, which including three layers: target layer, criterion layer and index layer. The target layer is the risk state of groundwater exploitation and utilization, which consists of four indicators: groundwater system condition (B1), groundwater exploitation and utilization (B2), groundwater environmental problems (B3) and socio-economic level condition (B4).

The dimension of control variables of catastrophe type was extended to the unlimited. In practice, the research objects are considerably complex, and the dimension of control variables of the objects are far more than four. However, the number of the control variables of the primary catastrophe theory is less than four, which limited the application of this theory (e.g., in risk assessment). Therefore, we deduced and extended the type of cusp-like catastrophe, which breaks through the limitation of numbers of the control variables of catastrophe evaluation method. In addition, the catastrophic membership values directly obtained by the method have no risk implications and cannot be used to assess the risk. Therefore, this paper converted the catastrophic membership value of the index into the corresponding standard risk levels based on the relationship between the catastrophic membership and risk grades.

Finally, this study evaluated the exploitation and utilization risk of the groundwater system in Shanghai region. The comprehensive risk value of groundwater exploitation and utilization in all districts (counties) of Shanghai is moderate, between 0.68 and 0.85. The exploitation and utilization risk in Central City and Pudong are higher among the districts. These results can provide some information to understand and manage the groundwater risk in Shanghai region.

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