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Study on the antipollution of phreatic system in Northern Shaanxi, China

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ABSTRACT

The concept and evaluation method of the anti-polluting capacity of groundwater was assessed in this study to describe the vulnerability of groundwater system in northern Shaanxi Province of China. With a total area of 22,604 km^2, the study area was divided into nodes of 80,719 and triangular elements of 125,377. The values of the seven evaluation parameters at each site were identified based on data from the overburden depth, boreholes, local precipitation, groundwater quality, and hydrogeological information. An antipollution map for the area of study was prepared, which suggested that the phreatic system in Northern Shaanxi can be classified into 3 grades of antipollution zones by a comprehensive index of vulnerability. Based on such index, the loess hilly region has the highest capacity of antipollution with an area of 11,300 km^2, while the valley area and the area of wind- blown sand with a buried depth of less than 1.5 m have the lowest antipollution with an area of 3,391 km^2.

Keywords: Antipollution capacity; Groundwater; Index of vulnerability; Phreatic; Shaanxi

1. Introduction

1.1. Antipollution capacity and vulnerability of groundwater

Groundwater vulnerability is an index designed to show areas of greatest susceptibility for groundwater contamination based on hydrogeologic and anthropogenic factors, which was first proposed by J. Margat in 1968. Since then, this index was widely used in groundwater assessments and many methods have been developed to improve its applications. [1,2]. Studies involving groundwater vulnerability index in China began in the middle of 1990s, and it turned out that further modifications on the groundwater vulnerability in terms of definition and evaluation method are needed due to the specific groundwater situations in China.

Both qualitative and quatitative characterizations of the groundwater should be addressed in the evaluation of groundwater antipollution capacity. The vulnerability of groundwater quantity refers to the capacity of large consumptions of groundwater,such as overdraft, which could lead to the continual descent of regional groundwater level and the exhaustion of groundwater sources. The vulnerability of the groundwater quality is defined as the capacity of pollution resistance and/or self restoration in the groundwater when exposed to environmental contaminants.

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1.2. Definition of groundwater system and antipollution

1.2.1. Definition of groundwater system

(1) An independent groundwater system consists of the water bodies that have close hydraulic links and the uniform flow field between each other. It includes the following situations:

1) The groundwater systems belong to the same aquifer, such as groundwater on the same side of the river with a terrace of the same level, the groundwater of the basin or plain in the same confined aquifer;
2) The mixed aquifer without a separation of aquitard or with the two superimposed aquifers, such as the mixed aquifer consisting of the loose aquifer and the underlying basement crust of weathering, the mixed aquifer consisting of fracture aquifer and the karst aquifer and so on;
3) The runoff groundwater from one aquifer transited to another one.

(2) An independent groundwater system could be shown by more than two grades of antipollution depending on the locations of the water body. The capacity of antipollution may affect by the thickness of the aeration zone, lithology, soil properties, terrain slope, infiltration capacity of the precipitation and the self-permeability variations of groundwater system.

1.2.2. Definition of the antipollution

The antipollution capacity of groundwater is defined as the performance of pollution resistance and prevention from external environments of the groundwater system. It is the intrinsic property of groundwater system under specific environmental conditions.

2. Research methods

2.1. Antipollution evaluation of the groundwater system

2.1.1. The zoning method based on the antipollution grade

The sections with the similar antipollution grade are zoned in one. The antipollution zoning is carried out by the antipollution grade of different places in a certain area. The higher the grade indicates the stronger of the antipollution capacity. For example, the antipollution capacity in the area of Grade 2 is stronger than that of Grade 1.

2.1.2. The zoning method based on the comprehensive index of vulnerability

The antipollution grade of groundwater system is determined in accordance with the comprehensive index of vulnerability. The smaller the index of vulnerability indicates the groundwater system is more difficult to be contaminated, which also shows the higher capacity of antipollution in this area. For example, an area with an index of vulnerability of 1 will have a stronger capacity of antipollution than that with an index of vulnerability of 100.

2.2. Calculation method of antipollution zoning of groundwater system

2.2.1. The antipollution zoning principle of groundwater system

The antipollution zoning of groundwater system should follow the principles as below:

(1) The antipollution of groundwater system is zoned by grade, and the grades are determined according to the comprehensive index of vulnerability;
(2) The comprehensive index of vulnerability (W) is calculated by the following equation:

$$W = 5D + 4R + 3A + 2S + T + 5I + 3C \quad (1)$$

where D is the overburden depth above the groundwater level; R is the net recharge of groundwater; A is the aquifer medium; S is the soil medium; T is the topography, I is the unsaturated zone medium; C is the aquifer permeability coefficient. The coefficients of grade component of evaluation parameters represent the significance of each evaluation factor, ranging between 1 and 5. The larger the coefficient is, the more significant the factor will be.

The division criteria of grade component of seven evaluation parameters are shown in Table 1.

2.2.2. Classification of the antipollution

The antipollution of groundwater system can be classified into five grades by the comprehensive index of vulnerability (W) from large to small as follows:

Grade 1 ($80 \le W \le 100$): groundwater with the poor antipollution capacity (the largest comprehensive index of vulnerability);

Grade 2 ($60 \le W < 80$): groundwater with a relatively poor antipollution capacity;

Grade 3 ($40 \le W < 60$): groundwater with medium capacity of antipollution;

Grade 4 ($20 \le W < 40$): groundwater with relatively good capacity of antipollution;

Grade 5 ($W < 20$): groundwater with good capacity of antipollution (the smallest comprehensive index of vulnerability).

The region with relatively large comprehensive index of vulnerability shows poor antipollution, where the groundwater is easy to be polluted with a lower antipollution grade; and vice versa.

2.2.3. Calculation method of the comprehensive index of vulnerability

According to Eq. (1), the calculated original value (W_y)

Table 1
The division grade criteria of seven evaluation parameters

Parameter	D		R		A			S	
Value	Buried depths of groundwater(m)	D value	Net recharge (mm/a)	R value	Aquifer medium	Values range	Typical A value	Soil medium	S value
	≤1.5	10	≤8	1	Masssive shale	1–3	2	Thin or lost	10
	1.5–3	9	8–16	3	Metamorphic rock, igneous rock	2–5	3	Gravel layer	10
	3–4.5	8	16–28	6	Weathering metamorphic rock, igneous rock	3–5	4	Sand	9
	4.5–9	7	28–40	8	Thin-bedded sandstone, limestone	5–9	6	Shrinked or aggregated clay	7
	9–15	5	$r > 40$	9	Shale	5–9	6	Sandy loam	6
	15–22.5	3			Massive sandstone	4–9	6	Loam	5
	22.5–30	2			Massive limestone	4–9	6	Silty loam	4
	>30	1			Sand and sandy conglomerate	6–9	8	Clay loam	3
					Basalt	2–10	9	Non-shrunk or non-aggregated clay	1
					Karst-developed limestone	9–10	10		

Table 1 (continued)
The division grade criteria of seven evaluation parameters

Parameter	T		I			C	
Value	Topography slope (%)	T value	Unsaturated zone medium	Values range	Typical I value	Permeability coefficient (m/d)	C value
	≤2	10	Sandy soil, clay	1–2	1	0–4.1	1
	2–6	9	Shale	2–5	3	4.1–12.2	2
	6–12	5	Limestone	2–7	6	12.2–28.5	4
	12–18	3	Sandstone	4–8	6	28.5–40.7	6
	>18	1	Stratified limestone, sandstone, shale	4–8	6	40.7–81.5	8
			Metamorphic rock, igneous rock	2–8	4	>81.5	10
			Sand and sandy gravel layer	6–9	8		
			Basalt	2–10	9		
			Karst-developed limestone	9–10	10		

of the comprehensive index of vulnerability can range from 23 to 226. In order to facilitate the evaluation and zoning, the original value (W_y) will be converted with a coefficient of 1/(2.26–0.23), which will make the W_y in a range between 0 and 100. The conversion calculation equation is shown as follows:

$$W = \left(W_v - 23\right) / 2.03 \quad (2)$$

The comprehensive index of vulnerability of 5 grades mentioned in Section 2.2.2 is the comprehensive index of vulnerability W converted with Eq. (2).

3. Preparation of antipollution zoning map of the groundwater system

3.1. The content and method of antipollution zoning map of the groundwater system

This map indicates the 5 grade antipollution zoning, the distribution range of each zone, and the grade code of zones, according to the comprehensive index of vulnerability (*W*).

The antipollution areas will be marked with different symbols and the numbers based on their antipollution grades.

3.2. Quantitative calculation of antipollution zoning

The specific calculation method of antipollution zoning can be carried out according to the following six steps:

(1) The zoning of landform: according to the hydrogeological conditions of the study area, the landform zones are initially classified.
(2) Parameter subregion partition: based on the landform zone, the subregions are further zoned by each parameter value.
(3) Calculation element meshing: based on steps 1 and 2, the entire study area is meshed into a number of calculation elements.
(4) The grade values of seven single parameters are assigned to each calculation element, and then a grade array of single parameter is formed;
(5) The calculation program is designed, and the grade array files of single factor are used in Eq. (2) for calculating the comprehensive index *W* of each element;
(6) The calculated comprehensive index of vulnerability (*W*) of each element is attributed into a zone of a grade among the five grades according to 2.2.2.

3.3. Element meshing method

As in the aforementioned, the antipollution of ground water system can be studied by each block. The calculation of comprehensive index of vulnerability and the zoning of antipollution grades of groundwater system are carried out according to each block, so that the element meshing is required; that is, each block is meshed into one or more elements, and the shape and size of the block will be described by elements. For the zoning map of groundwater vulnerability commonly seen in this study, their element meshing methods are to mesh by rectangular grid with equal intervals even by the square grid. This meshing method has obvious limitations, that is, any geometry of a block and its size naturally and objectively exists but it is irregular. In order to use the element for describing its shape and size, necessary generalizations must be made. Rectangular grids (in particular as the square grid with equal intervals) are meshed by fixed element shape and size, which is difficult to adapt for the irregular shape and size of one block. Therefore, the shape of antipollution zoning map would be distorted. Accordingly, the triangular elements are used to mesh in this study, which is useful and more flexible in the description of the shape and size of individual blocks than that of the rectangular and square grids.

4. Application case — a study on antipollution of phreatic system in northern Shaanxi

4.1. Overview of the study area

The study area is located in the region north of Shaanxi Province by N 38°, including the entire area of three counties (districts) such as Fugu County, Shenmu County and Yuyang County of Yulin City and part area of Jiaxian County and Hengshan County, covering an area of 22,604 km^2. Geological terrain zoning includes three major regions of an area of sand blown by wind (with the range roughly equivalent to Zone 2 in Fig. 1), the valley area (roughly equivalent to Zone 1 in Fig. 1) and the loess hilly region (roughly equivalent to Zone 4 in Fig. 1). Among them, the area of sand blown by wind is covered by modern aeolian sand with a thickness of dozen meters and its underlying is the alluvial-lacustrine sedimentary sand layer in the Upper Pleistocene of Quaternary with a thickness of dozen meters; the Quaternary river sedimentary layers are distributed in the valley area; and the loess hilly region is accumulated by loess with a thickness of tens and hundreds of meters [3,4].

In this study, the groundwater refers to the phreatic, mainly including the pore — fissure phreatic in the aeolian loess layer of the loess hilly region, the pore phreatic in the alluvial sand and gravel layers of the valley region, the pore phreatic in the aeolian layers of the area of sand blown by wind and the alluvial-lacustrine sedimentary layers; of which, the buried depth of the phreatic level in the loess hilly region is tens of meters, while that is several meters in the valley area and the area of sand blown by wind.

This study is based on overburden data of the phreatic level at 1,078 points (for the determination of the buried depth of phreatic level and the thickness of aeration zone), borehole data of 134 holes (for the determination of geologic and hydrogeological zoning under different conditions and parameters of aquifer and aeration zone in different blocks), the precipitation data of five counties, the water quality analysis data of 1,251 points, and other relevant hydrogeological materials.

4.2. Zone determination and zoning map preparation

4.2.1. Zoning and element meshing

The entire study area is divided into 3 major zones in this study, including the area of blown sand, the valley, and the loess hilly region.

According to differences in hydrogeological condi-

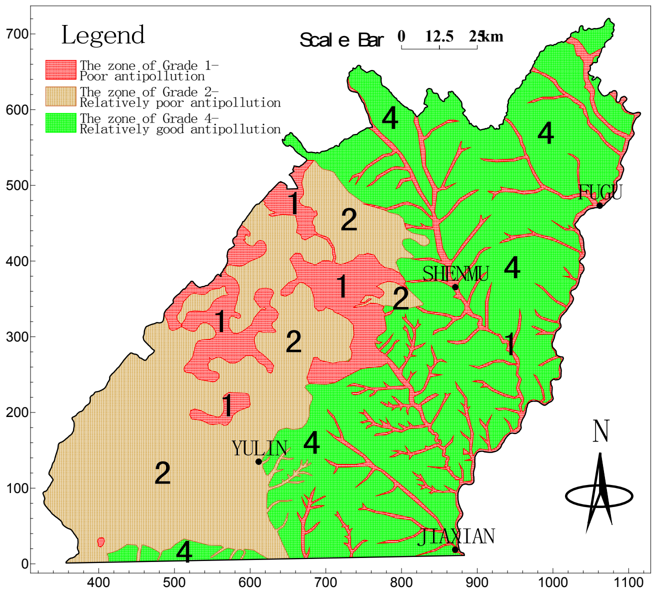

Fig.1. The antipollution zoning map of phreatic system in northern Shaanxi. ■ – zone of Grade 1 — poor antipollution, ■ – zone of Grade 2 — relatively poor antipollution, ■ – zone of Grade 4 — relatively good antipollution.

tions, the three major zones of the study area are divided into 104 secondary segments, comprising 17 blocks of the loess hilly region, 76 blocks of the area of sand blown by wind and 11 blocks of the valley area. On this basis, they are meshed further into 80,719 nodes and 125,377 triangular elements. For these 125,377 triangular elements, each element is determined and assigned with the index (or parameters) of seven evaluation parameters in the list. There are 877,639 parameters in total.

4.2.2. The value setting of the index of each evaluation parameter

Combined with the actual conditions of the study area, the division of grade component of seven evaluation parameters is carried out with the following specific activities according to the division criteria in Table 1:

(1) *D* values are set according to the grade component of groundwater buried depth in Table 1. Value 1 is taken for the loess hilly region (here only refers to intervale land), value 10 for the valley; in the area of sand blown by wind, the contour map of phreatic buried depth is prepared according to the measured phreatic buried depth in the wet season, and the segment of the phreatic buried depth 1.5, 3, 4.5 and 9 are delineated in the map; according to the delineated segments, values 10, 9, 8, 7 and 6 are assigned to the corresponding elements respectively.
(2) *R* values are set according to grade component of net recharge in Table 1, which are determined with the multi-year average precipitation of the counties' weather stations multiplied by the infiltration coefficient of precipitation in different segments, including the multi-year average precipitations of Fugu County (from 1959 to 2005), Shenmu County and Yuyang District. The infiltration coefficient of precipitation in different segments mainly considers the lithology of the aeration zone, in particular for that of the surface covered layer. The value of 0.4 is taken for the area of blown sand, 0.05 for the loess hilly region, and 0.3 for the valley-terrace overflow area. According to the delineated segments, the values of grade component of net recharge *R* are calculated respectively and assigned to corresponding elements.
(3) A values are set according to grade component of types of aquifer medium in Table 1. The phreatic aquifer of the area of sand blown by wind and the valley-terrace overflow area are mainly sand layers, corresponding to the eighth row of Table 1 in the column of sand and gravel rocks, and Typical value 8 is taken for that; no listed for the loess in Table 1, and the value of it should be lower than that of the sand and gravel rock but higher than metamorphic rock and igneous rock, and Typical value 6 can be taken for the massive sandstone.
(4) *S* values are set according to grade component of types of soil medium in Table 1. The value of 9 is taken for the area of sand blown by wind, value 4 for the loess as the silty loam, and Grade 3 for valley terrace area as the clay loam.
(5) *T* values are set according to grade component of terrain slope in Table 1. Value 10 is taken for the area of sand blown by wind and the valley terrain, and value 1 for the loess hilly region due to the broken terrains and the large valley density.
(6) *I* values are set according to the grade component of types of the aeration zone medium in Table 1. Value 1 is taken for the loess area and valley-terrace overflow area as sand soil and clay, and Grade 8 for the area of sand blown by wind as the sand and gravel layer.
(7) *C* values are set according to grade component of permeability coefficient in Table 1. Value 1 is taken for the loess and *C* = 4 is taken for the loess valley region. In the desert valley region, *C* = 2 is taken for Wuding River and Yuxi River.

The values mentioned from the above 7 items are listed Table 2.

Fig. 1 is completed as the antipollution zoning map of phreatic system in northern Shaanxi.

4.3. Rules reflected from the antipollution zoning map of groundwater system

Fig. 1 shows the following rules:

1) The vulnerability index of phreatic system *W* in the

Table 2
Value statistics of the index of all evaluation parameters

Segment		Desert pool area					Loess hilly region	Valley region
1 Grade of groundwater buried depth *D*	Groundwater depth	≤1.5 m	1.5–3 m	3-4.5 m	4.5–9 m	>9 m	>30 m	0–1.5 m
	Grade (*D*)	10	9	8	7	5	1	10
2 Grade of net recharge *R*	Annual precipitation (mm)	Multi-year average value of the counties' weather stations: In Fugu, 437.0; In Shenmu, 407.0; In Yuyang, 379.5						
	Infiltration coefficient	0.4					0.05	0.3
	Grade (*R*)	$R = 9$					$R = 6$	$R = 9$
3 Type grade of aquifer medium (*A*)		Sand, $A = 8$					$A = 6$	Sand and gravel, $A = 8$
4 Type grade of soil medium(*S*)		Sand, $S = 9$					Silty loam, S = 4	Sandy loam, $S = 6$
5 Grade of terrain slop (*T*)		2% < slope ≤ 6%, $T = 9$					Slope > 18%, $T = 1$	Slope ≤ 2%, $T = 10$
6 Type grade of aeration zone medium (*I*)		Sand, $I = 8$					Sand, clay, $I = 1$	Sand and gravel, $I = 8$
7 Grade of infiltration coefficient *C*		K = 0.5–15 m/d, $C = 2$					K = 0.0 xm/d, $C = 1$	Loess valley region, K = 10–30 m/d; Desert valley, Wuding River and Yuxi River, K = 5–15 m/d, $C = 2$

study area can be classified into three grades of antipollution zones of Grade 1, 2 and 4. No Grade 3 and 5 exist.

2) The loess hilly region has the highest capacity of antipollution to reach Grade 4, covering an area of about 11,300 km^2, which is closely related to the large phreatic buried depth, the lithology of aeration zone consisting of silty loess with a large thickness, strong protective capacity, and small permeability coefficient of phreatic aquifer.
3) The valley and the area of blown sand with the phreatic buried depth of less than 1.5 m have the worst antipollution, thus achieving the worst level of Grade 1, covering an area of about 3,391 km^2, which is closely related to the smallest phreatic buried depth, the lithology of aeration zone consisting of sands or gravels with a small thickness, poor protective capacity, and large permeability coefficient of phreatic aquifer.
4) The southern valley area with a relatively small aquifer permeability coefficient and the area of sand blown by wind with the phreatic depth of larger than 1.5 m have the relatively poor antipollution, thus achieving the relatively poor level of Grade two, covering an area of about 79,131 km^2, which is closely related to the relatively small phreatic buried depth, the lithology of aeration zone consisting of sands or gravels with a relatively small thickness, relatively poor protective capacity, and relatively large permeability coefficient of phreatic aquifer.

5. Conclusions

To distinguish from the conventional term of groundwater vulnerability to contamination, the concept of groundwater antipollution capacity was established in this study to characterize the groundwater in northern Shaanxi both qualitatively and quantitatively.

The methodology was applied to assess the antipollution capacity of the groundwater system in the northern Shaanxi, China. With a total area of 22,604 km^2, the study area was divided into nodes of 80,719 and triangular elements of 125,377. The values of the seven evaluation parameters at each site were identified based on the related buried depth data, borehole data, counties' precipitation data, quality analysis data,, and the hydrogeological information.. An antipollution map for the area of study was prepared, which showed that the phreatic system in Northern Shaanxi can be divided into 3 grades of antipollution zones by the comprehensive index of vulnerability. The loess hilly region has the highest capacity of antipollution with an area of 11,300 km^2, while the valley area and the area of wind- blown sand with a buried depth of less than 1.5 m have the lowest antipollution with an area of 3,391 km^2.

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