Development of groundwater sustainability indicators

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Abstract Sustainable management and assessment is currently becoming more and more important all over the world in order to prevent the deterioration and scarcity of groundwater resources. In this paper, two systems of groundwater sustainability indicators are proposed for sustainable assessment and management of groundwater. These relate to safety status warnings regarding groundwater exploitation and to the bearing capacity of the groundwater environment. Each system establishes two assessment models based on four and eight indicators. These two indicator systems are demonstrated to be practical through discussion of two case studies.

Key words bearing capacity of the groundwater environment; environmentally negative effects; safety status warning for groundwater exploitation; sustainability indicators

INTRODUCTION

Groundwater sustainability is a concept that most stakeholders, who use and manage groundwater resources, regard as being inherently important and achievable in the long-term for most groundwater systems. To meaningfully address the theme of groundwater sustainability, it is necessary to select indicators that can help simplify information and establish effective communication between various stakeholders. It is noted that the sustainable development, management, protection and use of groundwater resources act as guiding principles for indicator development and assessments.

Recent work by WWDR, UNESCO, IAEA, IAH and others has stated that indicators are instruments that are used for communicating key information about key systems in a simplified form to policy makers and the general public. The main function of indicators is simplification, quantification, communication, ordering and allowing for comparison of different regions and different aspects. Indicators provide information on the system or process under consideration in an understandable way to make complex phenomena quantifiable so that information can be communicated. Therefore, they act as an important communication tool for policy-makers and the public. In particular, indicators can be used to reduce the confusion potentially caused by large amounts of groundwater data. To this end, indicators should also enable the identification of trends over time and provide a basis for comparisons.

Groundwater indicators, based on monitoring and assessment, support the policy and sustainable management of groundwater resources, provide simplified information about the current status and future trends in the groundwater system, help to analyse the extent of natural processes and human impacts on the groundwater system in space and time and can be a suitable instrument to facilitate communication with the public.

In this paper, two groundwater sustainability indicator systems are discussed for sustainable assessment and management of groundwater, which relate to safety status warning regarding groundwater exploitation, and the bearing capacity of the groundwater environment. Each system establishes two assessment models based on four and eight indicators. Two case examples are also analysed on the basis of the two indicator systems.

PROPOSED GROUNDWATER INDICATORS

Groundwater exploitation: safety status warning

Groundwater is the main water resource for use in industry, irrigation and drinking water in many countries, so groundwater over exploitation is a worldwide problem. In many regions of China, the demand for water has risen rapidly with the development of population, agriculture and industry. Groundwater resources have often been over-exploited without any control and plans in these regions, leading to disturbance of the water balance in the groundwater system and causing many negative environmental effects, such as groundwater depletion, salt water intrusion, land subsidence, decline in aquifer storage, and deterioration of wetland ecosystems.

The safe (sustainable) exploitation of groundwater causes no negative effects on the natural and ecological environment in the short or longer term. The safety status warning refers to providing information on the maximum exploitation that can take place without causing any non-recoverable negative impacts (Zou Hai-Lin, 1999).

In the past, the amount of groundwater exploitation was determined by the maximum groundwater recharge in north China. However, this method often ignored the negative effects caused by groundwater over-exploitation. In this paper, the negative effects on the ecological environment arising from groundwater exploration are studied using principles of sustainable development, and a system of assessing when this exploitation exceeds safe limits is proposed. Detailed principles are developed in relation to analytical hierachical, performance and integration criteria, and the Harbin region of northeast China is used as a case study to illustrate this approach.

Regional groundwater level decline

In the Harbin region, groundwater exploitation has risen gradually from the 1980s, causing a regional decline in groundwater level and a change from confined to unconfined conditions in the aquifer. The hydraulic characteristics of aquifer have also changed and overflow per well has declined gradually from 4000–5000 m^3 day^{-1} in 1984 to 2000–3000 m^3 day^{-1} in 1986. A large cone of depression was formed in the groundwater around the Harbin Mechanic Factory with a maximum depth of 30.5 m in 1986. The area of the cone increased from 280 km^2 in 1986, to 320 km^2 in 1988 and to 390 km^2 in 1992. However, subsequently with a decline in groundwater exploitation through local government control, the area of the cone reduced to 290 km^2 in 2000.

Land subsidence

During the period of 1984 to 1986, groundwater exploitation and the development of the cone of depression led to the development of cracks in buildings and the disruption of road surfaces. The largest cracks were 6 m long and 5 m wide, and the area subject to land subsidence was 55 km^2. In a second investigation during 1998, the area of land subsidence centred on the Harbin Mechanic Factory had increased to 100 km^2, and the amount of subsidence at the centre of the cone of depression was 35 mm.

Groundwater quality deterioration

The hardness of groundwater in the Harbin region has shown a rising trend with increasing groundwater exploitation. The area experiencing extra hard groundwater increased from 30 km^2 in 1984 to 90 km^2 in 1986, and the annual average hardness of groundwater also increased from 350 mg L^{-1} to 600 mg L^{-1}. The investigation showed that the saltiness and the concentration of Cl^-, NO_2^- and NO_3^- ions also rose with increasing groundwater exploration, reflecting saline intrusion of the Songhuajiang River.

Reduction of surface water area

During the period of 1984 to 1986, over-exploitation of groundwater and the decline of groundwater level led to increasing infiltration of water from inland rivers, wetlands and lakes in the groundwater system of the Harbin region. In consequence, the area of surface water has decreased from 30 025 km^2 to 26 000 km^2, which represents a decline of 200 km^2 $year^{-1}$.

Development of a Safety Status Warning Index

Indicators should be aggregated into an index that provides concise and targeted information for groundwater policy making and management. Therefore four indicators were combined into an index, which was classified into four grades representing the worst to best conditions. Therefore, the four criteria used for the classification were (Zhan Xie-Qin & Wei Li-Jie, 2003): (1) the decline in groundwater level; (2) the maximum vertical land balance; (3) the increase in groundwater contamination measured via a water quality index; and (4) the decline in area of surface water. The latter is considered to be in the worst state when the decline exceeds 0.08 km^2 $year^{-1}$.

The different indicators were combined for the study area using a GIS and a data grid structure. The index for estimating safe groundwater exploitation was calculated by summation of the individual indicators according to equation (1) for each grid cell:

$$EP = \sum_{i=1}^{n} EP_i \cdot W_i \tag{1}$$

where EP denotes the index for estimating the safety status of groundwater exploitation; EP_i denotes the state of the ith environment indicator and W_i denotes the

Table 1 Classification of indicators.

Safety status (*EP*)	Worst	Bad	Neutral	Best	Weight
Water level decline depth (m)	> 2/3 *H*	1/2H–2/3*H*	1/3H–1/2*H*	<1/3*H*	0.3
Sum of decline depth (m)	>30	20–30	10–20	<10	0.3
Comprehensive contamination index	>20	10–20	1–10	<1	0.2
Surface water area decrease (km^2 $year^{-1}$)	>0.08	0.08–0.04	0.0–0.01	<0.01	0.2

H refers to the depth of the aquifer.

weight of the *i*th environment indicator, which varies according to the degree impact on groundwater exploitation (Table 1).

Application of this approach to the Harbin region revealed that groundwater exploitation exceeded 2000 m^3 km^{-2} day^{-1} in the area near the Harbin Mechanic Factory and that this was in the worst category regarding the safety status in the region. Exploitation of groundwater in the range between 1000 and 2000 m^3 km^{-2} day^{-1} indicated a bad safety status and applied to the area to the south and west of Harbin City. Exploitation of groundwater in the range between 500 and 1000 m^3 km^{-2} day^{-1} was characteristic of a neutral safety status and was found in the area to the east of Harbin City. The best safety status equates with groundwater exploitation less than 500 m^3 km^{-2} day^{-1}, but no part of the study area fell into this category.

BEARING CAPACITY OF THE GROUNDWATER ENVIRONMENT

Groundwater provides water resources for human activity and has a certain capacity for containing contaminants, but not beyond a threshold value. The bearing capacity of the groundwater environment is defined by that threshold value. The principle of selecting indicators of the bearing capacity is based on the quantity and usability of groundwater. The selection of indicators should be different in different groundwater systems, but it should, as far as possible, be consistent for the same groundwater system. Indicators of the bearing capacity of the groundwater environment can be classified in two types(Tang Jia, Wu & Guo Huaicheng, 1997): firstly those relevant to the state of the groundwater system, which reflects its quality and quantity, and secondly those relevant to society, population and economic activity, which reflect the impacts of social economic activity on the groundwater environment.

Indications for assessing the bearing capacity of the groundwater environment

The following eight indicators were selected:

A supply water quantity / total groundwater resource;

B comprehensive contamination index of the groundwater system;

C extent of groundwater contamination (area of groundwater contamination / total groundwater area, %);

D excess rate of contaminant (%);
E population (10^4);
F gross product per person (10^4 Yuan);
G water consumption per 10^3 m^3;
H rate of urban wastewater treatment (%).

Assessment model for bearing capacity of groundwater environment

In order to evaluate the bearing capacity of the groundwater environment, a systems analysis model is established. Firstly, *m* components for bearing capacity are introduced under different strategies for *n* indicators. Hypothetically, the *m* bearing capacities are as B_j (j = 1, 2, 3, …, m) and the *m* bearing capacities are constituted by *n* components decided by *n* actual indicators, that are $B_i = (B_{1j}, B_{2j}, B_{3j}, ..., B_{nj})$. After it is changed, b_j is achieved as $b_i = (b_{1j}, b_{2j}, b_{3j}, ..., b_{nj})$ and $b_{ij} = B_{ij} \Big/ \sum_{j=1}^{m} Bij$, so the *j*th bearing capacity can be expressed as follows:

$$\left|B_j\right| = \sqrt{\sum_{i=1}^{n} b_{ij}^2} \tag{2}$$

Equation (2) provides a model for evaluating the bearing capacity of the groundwater environment under the *j*th strategy among *m* strategies(Zhang Wei-guo & Yang Zhi-feng, 2002).

This approach was tested for a city in south China which has a drainage area 4 × 10^4 km^2, a mountainous area of 1.1 × 10^4 km^2, an average precipitation of 40 mm, but an evaporation of 1100 mm in many years, a total water resource of 17.2 × 10^8 m^3 and a groundwater resource of 12.1 × 10^8 m^3, with 97% of drinking water supplied from groundwater. The eight indicators of the bearing capacity of the groundwater environment for this example in different years are listed in Table 2.

The indicator values of the bearing capacity of the groundwater environment for different years in the region, as calculated by equation (2), are listed in Table 3. These

Table 2 Indicators of environmental bearing capacity of groundwater in different years.

Indicators	2000 year	2005 year	2010 year	2015 year	2020 year
A	0.95	0.90	0.92	0.93	0.88
B	0.18	0.14	0.12	0.10	0.08
C	0.43	0.36	0.27	0.21	0.14
D	0.80	0.75	0.73	0.60	0.47
E	33	43	57	84	132
F	0.40	0.80	1.43	2.92	4.32
G	356	268	185	112	97
H	0.15	0.38	0.60	0.81	0.95

A–E as defined in previous section.

indicate that the groundwater bearing capacity of the study area will rise gradually through time and may attain high values by 2020. There is some fluctuation within the projections but overall the predicted trend in bearing capacity is an optimistic one. This analysis suggests that the most important measures that should be adopted for the future to enhance the bearing capacity of the groundwater environment and in order to achieve the goal of sustainable groundwater use in this region are water pollution control and controlling the rate of population increase.

Table 3 Bearing capacity of the groundwater environment in different years.

Indicators	2000 year	2005 year	2010 year	2015 year	2020 year
A	0.207	0.197	0.201	0.203	0.192
B	0.290	0.226	0.194	0.161	0.129
C	0.305	0.255	0.191	0.149	0.099
D	0.239	0.224	0.218	0.179	0.140
E	0.095	0.123	0.163	0.241	0.378
F	0.041	0.081	0.145	0.296	0.438
G	0.350	0.263	0.182	0.110	0.095
H	0.052	0.131	0.208	0.280	0.329
I	0.642	0.559	0.534	0.597	0.731

A–E as defined in previous section.

CONCLUSIONS

An indicator system, which takes into account environmentally negative effects was established to describe and warn of the safety status of groundwater systems under exploitation. Capacity, based on a number of the groundwater bearing capacity, can be used as a criterion to assess the harmonious degree between social economic activity and the groundwater environmental system. The practical application of these approaches in groundwater assessment and management has been illustrated with reference to the Harbin region and to the city environment of south China.

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REFERENCES

Tang Jia, Wu & Guo Huaicheng, V .(1997) Environmental bearing capacity and its application on environmental planning. *Environ. Sci. J.* **17**, 6–12.

Zhan Xie-Qin & Wei Li-Jie, V (2003) Study on the safety warning volume of groundwater mining in Harbin city. *Hydrol. J.* **23**, 29–33.

Zhang Wei-guo & Yang Zhi-feng, V (2002) Assessment on bearing capacity indicator system. *Acta Sci. circumstantiae. J.* **19**, 540-544.

Zou Hai-lin, V (1999) A study on the approach of establishing indicator system for assessing sustainable development. *Environ. Sci. J.* **19**, 360–365.