Water Quality and Sediment Behaviour of the Future: Predictions for the 21st Century
(Proceedings of Symposium HS2005 at IUGG2007, Perugia, July 2007). IAHS Publ. 314, 2007.

The assessment of groundwater vulnerability in China

TANG LIHUA[1,2], ZHANG SICONG[1] & YAO WENFENG[1]

1 *Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China*
tanglh@mail.tsinghua.edu.cn

2 *State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China*

Abstract China is one of the countries suffering severely from water shortage. Its water availability per capita is only 25% of the world average. According to new statistics for 2000–2002, the fresh groundwater resource is about 883.7 billion m^3, which amounts to 33% of the total water resources in China. Moreover, groundwater plays an important role in water supply. Nearly 20% of the total water consumption is from groundwater, especially in northern China where the percentage of supply from groundwater exceeds 50%, and in some cases even up to 80%. With such a great degree of exploitation, as well as excessive development, many environmental problems have been caused, such as groundwater pollution and overexploitation, which greatly affect humans. In order to further understand the characteristics of groundwater quantity and quality, and to protect groundwater resources, a research assessment of groundwater vulnerability for the whole of China was carried out during the second Comprehensive National Water Resources Planning (CNWRP) exercise that commenced in 2002. Based on abundant data and GIS technology, an integrated assessment model was developed and applied to evaluate the groundwater vulnerability. The results show trends of increasing groundwater vulnerability from north to south, as well as from west to east. Terrain slope, shallow groundwater depth and aquifer media are the three most dominant factors influencing groundwater vulnerability in China as a whole.

Key words assessment of groundwater vulnerability; integrated assessment model; GIS

INTRODUCTION

China is one of the countries that suffer severely from a shortage of water resources, with only 25% of the world average water availability per capita. According to the results of the newest water resources survey in China, 2000–2002, the fresh groundwater reserve is about 883.7 billion m^3 (Jiang *et al.*, 2004), which accounts for 33% of the country's total water resources. Moreover, groundwater plays an important role in water supply in China; nearly 20% of the total water consumption depends on groundwater. In the north of China, including Beijing City, Hebei, Shanxi, Henan, Shandong and Liaoning provinces, the percentage of groundwater supply exceeds 50%, and sometimes up to 80%. With such high rates of exploitation and excessive development, many environmental problems, such as groundwater pollution and overexploitation, have been caused. Therefore, it is crucial to understand further the characteristics of groundwater quantity and quality, and then to adopt reasonable strategies for sustainable development of groundwater resources.

Groundwater vulnerability refers to the potential for pollution due to some unexpected factors (Fritch *et al.*, 2000; Jiang Guihua, 2002). It results from the complicated influences of geomorphology, geology, climate, etc. The assessment of groundwater vulnerability involves the delineation of areas that are more susceptible to contamination, and supports good decisions to inform sustainable groundwater development. Based on the Second Comprehensive National Water Resources Planning (CNWRP) exercise, which began in 2002, an assessment of groundwater vulnerability in China was carried out for groundwater protection.

METHODOLOGY AND DATA

Integrated assessment model

Based on the DRASTIC (Aller, 1987) model and ArcView GIS, and also taking into account data availability, an integrated assessment model was developed to evaluate the groundwater vulnerability scores (GVSs) for the whole of China.

The integrated assessment model is combined with GIS technology, because the vector or grid format provides an appropriate unit of assessment for groundwater vulnerability. At the same time, the classification and overlying analysis processes provide a suitable means of index gradation and weighting-summation (Gogu & Dassargues, 2000; Insaf *et al.*, 2005). In ArcView GIS software, the *ModelBuilder* facility was very convenient for building the integrated assessment model (Lei Jing, 2002). The assessment flow chart is shown in Fig. 1.

Index system There are many factors which affect groundwater vulnerability (Sun Caizhi & Pan Jun, 1999). Taking account of actual conditions and characteristics in China, data availability, and the need to develop a system that is representative, comparable and includes essential information, eight key variables were used in the index system. These included terrain slope, soil type, aquifer properties, groundwater enrichment, depth to shallow groundwater, infiltration recharge, a groundwater exploitation coefficient, and soil organic content.

Data sources The data on aquifer properties, and groundwater enrichment were extracted by digitizing the *HydroGeological Map of the People's Republic of China*. Recharge by infiltration, depth to shallow groundwater, and exploitation coefficient

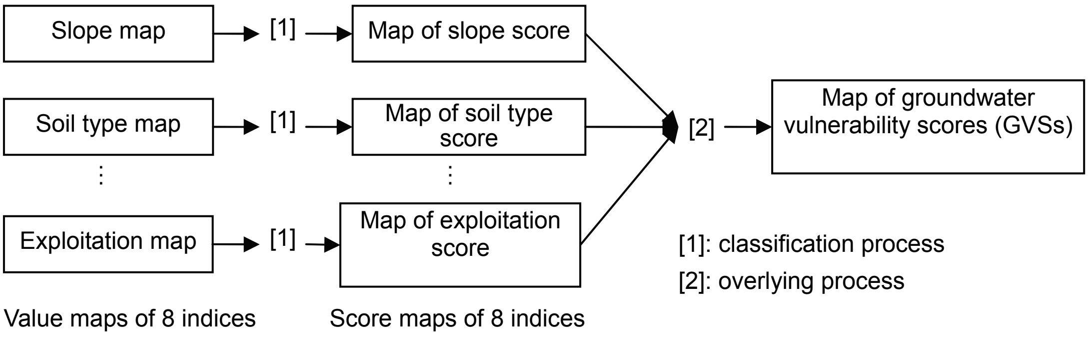

Fig. 1 Assessment flow chart in *ModelBuilder*.

were obtained from the results of CNWRP. Terrain slope, soil type and organic content data were obtained from the *Global Soil Data Products* CD-Rom (IGBP-DIS) which was provided by the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics, Tennessee, USA.

Assessment units The basic unit of assessment was a 1 km × 1 km grid the data from which were aggregated for statistics and analysis into the third-class water resources sub-areas. According to the CNWRP results, there are a total of 214 third-class sub-areas in China, and 212 sub-areas were used in the present study. Areas in the Taklamakan Desert and islands in the Southern Sea were excluded.

Assessment steps The detailed assessment steps were as follows:

1. The whole country was divided into 1 km × 1 km grid cells by ArcView GIS software. The grid cell is the basic cell for assessment.
2. The score for each individual variable was calculated for each grid cell.
3. An integrated GVS for each grid cell was obtained and mapped by overlaying the map layers for the scores of the eight indices, which were multiplied by different weights.
4. The GVSs for the grid cells were aggregated into the third-class sub-areas for statistical analysis.

The weights for each index were determined by experts and then normalized from 0 to 1. The integrated groundwater vulnerability score (*GVS*) was calculated as follows.

$$GVI = \sum_{i=1}^{n} P_i \times W_i \qquad (1)$$

where, P_i is the individual score for index i; W_i is the weight for index i; i is the order of each index; and n is the number of indices (8).

RESULTS AND ANALYSIS

The map of integrated vulnerability scores derived from the integrated assessment model is presented in Fig. 2 and illustrates the regional differences in groundwater vulnerability in China. The GVSs for individual grid cells ranged from 14.2 to 19.6. In order to distinguish the relative differences more clearly, the scores were divided into three classes as following:

1. high vulnerability (GVS > 55),
2. medium vulnerability (GVS 40–55),
3. low vulnerability (GVS < 40).

The GVSs in third-class sub-areas are shown in Fig. 3, where the high, medium and low vulnerability classes are further subdivided into three grades, with smaller scores indicating lower vulnerability.

From Figs 2 and 3, and from Table 1, some primary observations can be drawn. Firstly, regarding the characteristics of regional distribution of GVS:

1. The general trends of variation in GVS are an increase from north to south, and also from west to east.
2. Areas with low vulnerability (GVS < 40) are mainly located in the eastern plateau of inner Mongolia, as well as in the areas adjacent to the Taklamakan Desert. The

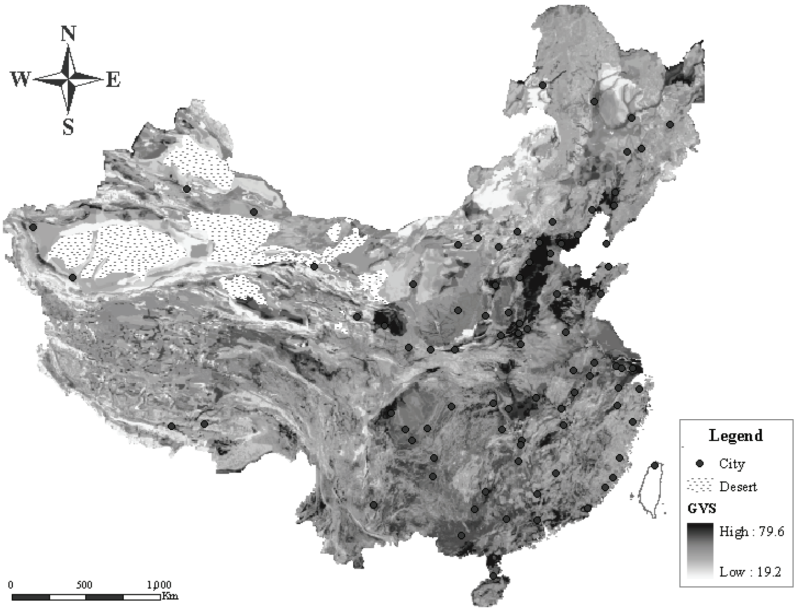

Fig. 2 Groundwater vulnerability scores in China.

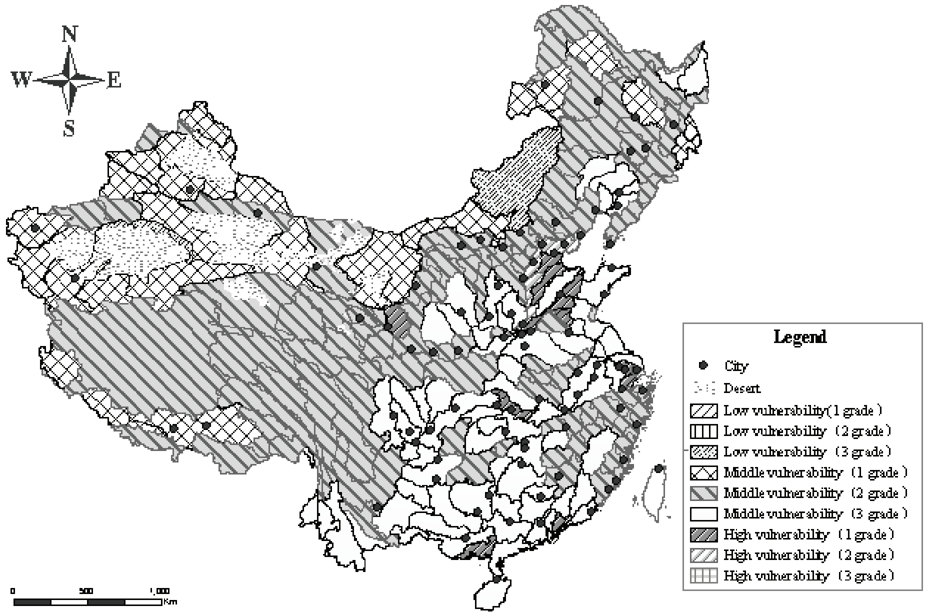

Fig. 3 The classification of GVSs in third-class sub-areas.

hydrogeological and climate conditions are probably the main reasons for low vulnerability. In general, the groundwater table is deeper in these areas, and infiltration recharge is smaller and has weaker effects on groundwater quality.

3. Sub-areas with high vulnerability are scattered mainly along the southeastern seaboard, in the north of China and in southwestern regions, with different factors contributing to higher vulnerability in different areas.

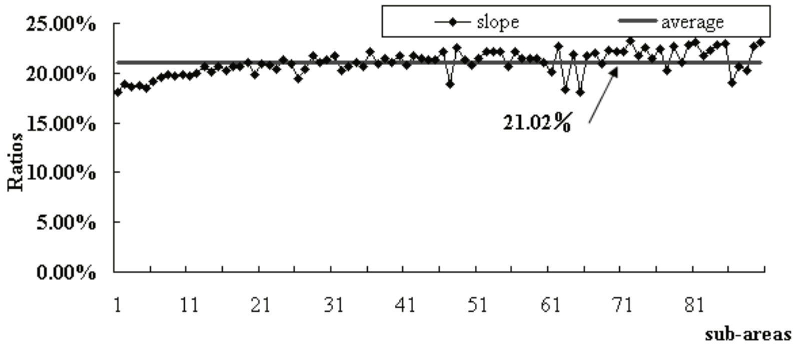

Fig. 4 The ratios of the terrain slope index in higher vulnerability sub-areas.

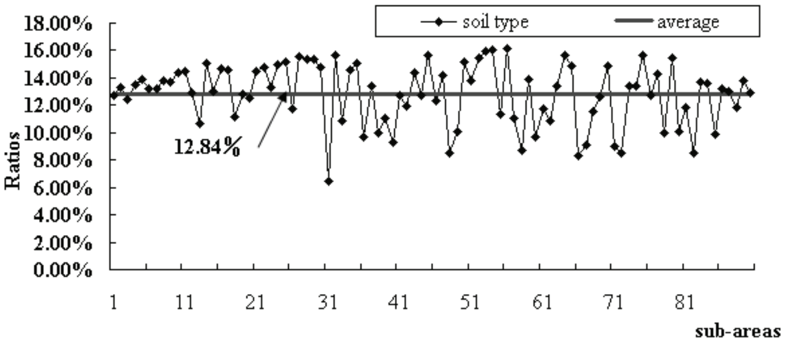

Fig. 5 The relative scores of the soil type index in higher vulnerability sub-areas.

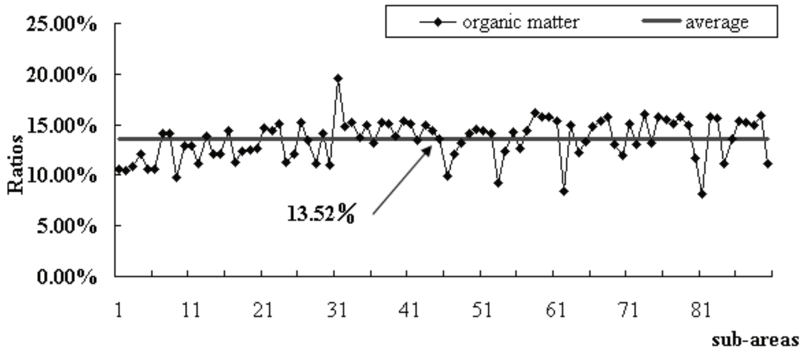

Fig. 6 The relative scores of the soil organic content index in higher vulnerability sub-areas.

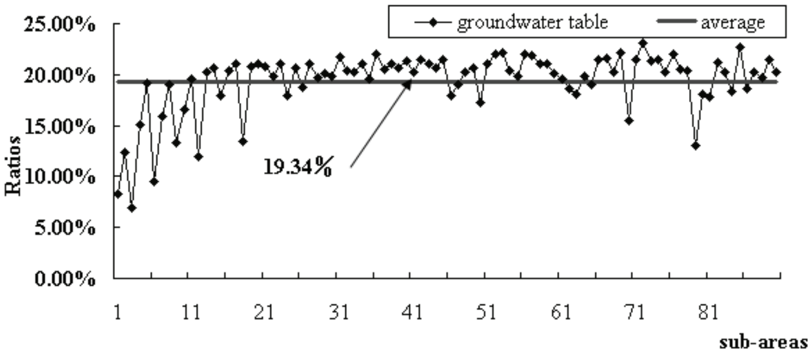

Fig. 7 The relative scores of the groundwater depth index in higher vulnerability sub-areas

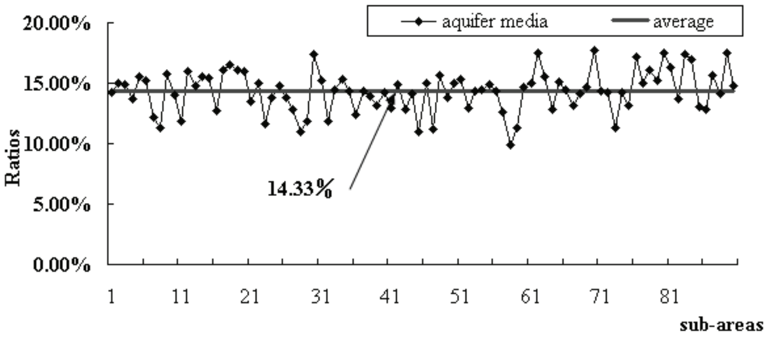

Fig. 8 The relative scores of the aquifer media index in higher vulnerability sub-areas.

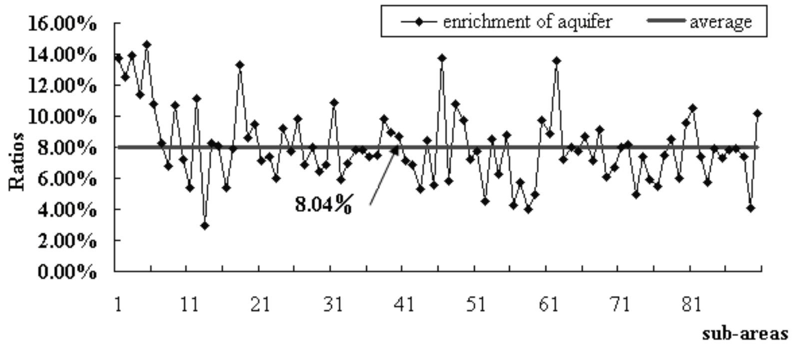

Fig. 9 The relative score of the groundwater enrichment of aquifer index in higher vulnerability sub-areas.

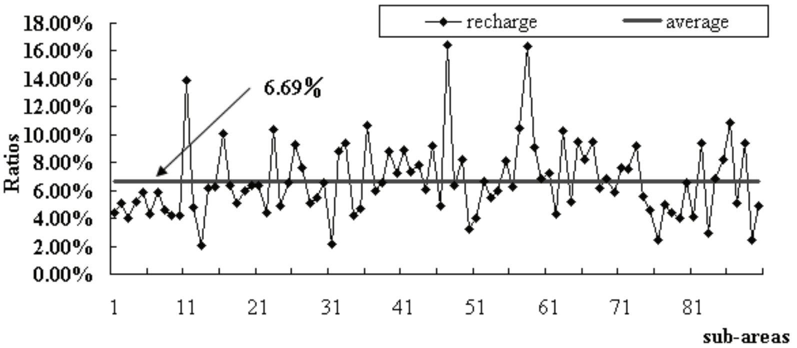

Fig. 10 The relative scores of the infiltration recharge index in higher vulnerability sub-areas.

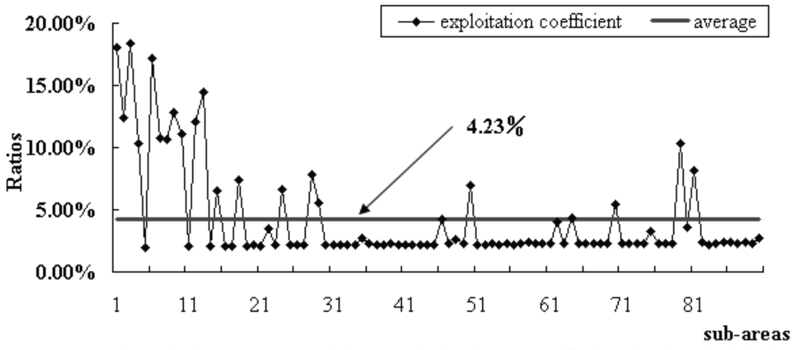

Fig. 11 The relative scores of the exploitation coefficient index in higher vulnerability sub-areas.

Table 1 The distribution of GVSs based on sub-area.

Vulnerability grade		Numbers	Area (km^2)	Proportion of number (%)	Area and proportion	Proportion of area (%)	Accumulation (%)
Low GVSs	1sub-grade	0	0	0.00	242 796	0.00	0.00
	2sub-grade	0	0	0.00	2.74%	0.00	0.00
	3sub-grade	2	242 796	100.00		2.74	2.74
Medium GVSs	1sub-grade	29	1 737 736	20.76	8 370 263	19.61	22.35
	2sub-grade	91	4 480 318	53.53	94.47%	50.57	72.92
	3sub-grade	71	2 152 209	25.71		24.29	97.21
High GVSs	1sub-grade	13	179 000	72.44	247 104	2.02	99.23
	2sub-grade	6	68 104	27.56	2.79%	0.77	100.00
	3sub-grade	0	0	0.00		0.00	100.00
Total		212	8 860 163				

Groundwater vulnerability of medium status is typical of most of China; 90% of the sub-areas (191 out of 212) have medium groundwater vulnerability and occupy 94.47% of the total area of China. In contrast, the two sub-areas with low vulnerability occupy 2.74%, and the 19 sub-areas with high vulnerability occupy 2.79%, of the total area. Among those areas with medium GVSs, there are 71 sub-areas with higher vulnerability (belonging to the third sub-grade); 91 sub-areas belonging to the second sub-grade, and 29 sub-areas belonging to the first sub-grade.

DISCUSSION

In order to find out the major causes of high vulnerability, an analysis of key indices in the 90 sub-areas with higher GVSs was carried out. Relative scores (the ratio between the unweighted individual index score and the total score for all unweighted indices in each sub-area) were used to reflect the effects on groundwater vulnerability. Figures 4 to 11 illustrate the relative score of the eight indices in the 90 sub-areas with higher GVSs.

The results (Table 2) indicate that terrain slope (relative score of 0.21), groundwater depth (relative score of 0.193) and aquifer properties (relative score of 0.144) have the three most significant effects on groundwater vulnerability.

If the weight for each index is considered, different results are obtained (Table 3) and the depth to shallow groundwater and aquifer properties become the most and second-most important variables, respectively. Soil organic content is the third most significant variable while terrain slope becomes only the seventh most important.

CONCLUSION

An integrated assessment model for groundwater vulnerability in China has been developed using eight key indices; the results demonstrate vulnerability is at medium or higher levels for most of the country. In general, vulnerability increases from north

Table 2 The average ratio for each index using equal weighting.

Index	Terrain slope	Soil type	Soil organic content	Shallow groundwater depth	Aquifer media	Enrichment of aquifer	Infiltration recharge	Exploitation coefficient
Relative score	0.210	0.128	0.135	0.193	0.144	0.080	0.067	0.042
Order	1	5	4	2	3	6	7	8

[1] Relative score is the average value for the 90 sub-areas.

Table 3 The averaged relative score for each index using different weights.

Index	Terrain slope	Soil type	Soil organic content	Shallow groundwater depth	Aquifer media	Enrichment of aquifer	Infiltration recharge	Exploitation coefficient
Relative score	0.075	0.091	0.096	0.344	0.153	0.086	0.095	0.060
Order	7	5	3	1	2	6	4	8

to south and from west to east across China, and sub-areas with high GVSs are scattered along the southeastern seaboard, in the north of China and in southwest regions; while those with low GVSs are mainly located in inner Mongolia and some areas adjacent to the Taklamakan Desert. With equal weighting of indices, the dominant factors affecting groundwater vulnerability are terrain slope, groundwater depth and aquifer properties, while these change to groundwater depth, aquifer properties and soil organic content, if unequal weighting is employed. The results of this research will provide useful information for groundwater protection and sustainable groundwater development in China.

REFERENCES

Aller, L., Bennet, T. & Lehr, J. H. (1987) *DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings.* EPA6002-87-036, US Environmental Protection Agency, Ada, Oklahoma, USA.

Gogu, R. C. & Dassargues, A. (2000) Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environ. Geol.* **39**(6), 549–559.

Insaf, S., Babiker, Mohamed, A. A. M., Hiyama, T. & Kato, K. (2005) A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. *Sci. Total Environ.* **345**, 127–140.

Jiang Guihua (2002) The development of study on groundwater vulnerability. *World Geology* **21**(1), 33–38.

Jiang Wenlai, Tang Qu & Lei Bo (2004) *Water Resources Management Study Theory*. Chemical Industry Press, Beijing, China.

Lei Jing (2002) Study on groundwater vulnerability. MSc Thesis, Tsinghua University, Beijing, China.

Sun Caizhi & Pan Jun (1999) Concept and assessment of groundwater vulnerability and its future prospect. *Adv. Water Sci.* **10**(4), 444–449.

Fritch, T. G., Mcknight, C. L., Yelderman, J. C. Jr & Arnold, J. G. (2000) An aquifer vulnerability assessment of the Paluxy aquifer, central Texas, USA, using GIS and modified DRASTIC approach. *Environ. Manage.* **25**(3), 337–345.