ON METHODS FOR REGIONAL GROUND- AND SURFACE WATER PROTECTION AND ZONING: APPLICATION TO THE ZHANGJI CASE STUDY AREA (CHINA)

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ABSTRACT

The main goal of this key-lecture is to introduce an original way of identifying effective and sustainable policies for the management of surface and groundwater, taking into account their relationships with food production and human health, based on the achievements of EU sponsored ManPoRivers project.

Concerning water resources management, two main objectives were considered: (1) a geographical zoning methodology valid for both surface and groundwater; and (2) its application a Chinese case-study area. To achieve these objectives management tools have been researched, taking into account the pollution risk, the vulnerability of the area, the modelling of groundwater flow and transport, and the definition of protection zones as mechanisms of water resources protection.

The application of the DRASTIC vulnerability assessment method to the fissured-karstic aquifer of the Zhangji area, Xuzhou city is also presented in this key-lecture. By using GIS/Arcinfo, a score was assigned to each parameter and the DRASTIC index for the region was derived. The assessment result enables a preliminary delineation of groundwater vulnerability to pollution in the study area. This tool will help the decision makers to take scientific and effective measures for safeguarding groundwater resources in the area.

1 INTRODUCTION

Several methodologies have been developed to characterise surface water risk, *e.g.* (a) Methodology of the ECOMAN Project (*cf.* Harum et al., 2004), (b) Methodology used by the Californian Department of Health Services (CDHS, 2000); (c) USGS Methodology (developed for the State of North Carolina) (Eimers et al., 2000); (d) WRASTIC index (NMED/DWB, 2000).

Regarding groundwater vulnerability to pollution Aller *et al.* (1987) developed for the U.S. Environmental Protection Agency (E.P.A.) the DRASTIC method. This method has been widely used in USA. In 1991, Lobo-Ferreira and Costa-Cabral proposed DRASTIC for the vulnerability mapping of the European Union (at that time the EEC). In 1996, in the EU-China Groundwater cooperation project, DRASTIC was applied to Dalian peninsula and Guangzhou city for the assessment of groundwater vulnerability to pollution by Yangqing (1999).

Xuzhou, located in the northwest of Jiangsu province, is one of the cities with severe water shortage problems in China. Since it lies in the downstream of the Huai River Basin, the surface water is easily polluted and cannot guarantee the quality for water supply. Under these conditions, groundwater is the dominant source for water supply in this area. However, overexploitation of groundwater in this area has resulted in serious environmental and geological consequences such as land subsidence and groundwater pollution. Zhangji, situated in the southeast of Xuzhou city, 25 km from the city center, is proposed as a place for drinking water supply to Xuzhou city due to the presence of abundant groundwater resources.

In this paper, as part of the EU-China cooperation project MANPORIVERS - *Management policies for priority water pollutants and their effects on foods and human health* (Contract ICA4-CT-2001-10039), DRASTIC was applied to Zhangji case-study area for the assessment of groundwater vulnerability to pollution (*cf.* Yuanyuan *et al*., 2005). The results identified the areas which are more or less vulnerable than others to contamination and will be helpful for the local government to make policy and take measures for protecting the groundwater resources in this area.

The quality of groundwater resources is susceptible to be affected by social-economic activities, especially in the case of using and occupying the soil, such as with urban areas, infrastructures, agriculture, etc. One preventive instrument to assure the protection of the groundwater resources used for abstraction is setting up protection zones around wells extracting groundwater for public supply. The limits of these areas are a function of the geology, hydraulic characteristics of the concerned aquifer and amount of extracted water. In these defined areas around wells, restrictions should be set up concerning public use and transformation of soil, in order to protect the quality of the groundwater resources beneath it.

Groundwater vulnerability has several times been used with the meaning of risk, but the authors prefer to use the term vulnerability for the situation in which it only represents the intrinsic characteristics of the natural medium, determining the likelihood of this medium to be adversely affected by an imposed contaminant load. As a general definition risk could be defined as the superimposition of two factors that can be characterised separately: the vulnerability of the physical medium and the pollutant load or hazard applied on the subsurface environment as a result of human activity. However most methods developed to characterise risk already combine these two aspects in their formulation. Assuming this interaction, it is possible to have high vulnerability but no pollution risk if a significant contaminant load is absent, and vice versa.

Besides the above mentioned DRASTIC method, to characterise groundwater vulnerability and risk, two other methodologies are addressed in this paper: (a) Groundwater Vulnerability Scoring System (GVSS), a ranking methodology presented by Hathhorn and Hubbena (1996) to assess the relative threat posed by a known contaminant inventory within a protection area; (b) USGS Methodology (developed for the State of North Carolina), an overlay and index method based on the definition of an unsaturated zone rating (Eimers et al., 2000). These methodologies have been applied to the Zhangji case-study area, in PR China, located in the northwest part of Jiang su Province, in Xuzhou, Tongshan County. This region was selected once it represents an area of China with intense food production and human activity, whose effects in surface water and groundwater water quality are well known. The Hydrology and Water Resources Survey Bureau of Jiangsu Province provided the base information required to apply these methodologies. Applications and results have been published in Lobo Ferreira *et al.* (2005).

2 MAPPING SURFACE WATER RISK TO POLLUTION OF ZHANGJI CASE-STUDY AREA

The WRASTIC index and the USGS method were applied to Zhangji case-study area, in PR China, located in the northwest part of Jiang su Province, in Xuzhou, Tongshan County. This region was selected once it represents an area of China with intense food production and human activity, whose effects in surface water and groundwater water quality are well known. The Hydrology and Water Resources Survey Bureau of Jiangsu Province provided the base information required to apply these methodologies. As the required information is not available for the entire Huai River basin, the case-study area of Zhangji (that includes the Old Yellow River) serves as an example for application. Applications and results have been published in Lobo Ferreira *et al.* (2005).

2.1 WRASTIC index

WRASTIC is a method developed to evaluate watershed susceptibility to surface water contamination in any hydrogeologic setting based on major watershed characteristics and land uses. It was developed for US-EPA, in 1991, by the American Water Works Association and afterward adapted by NMED/DWB (New Mexico Environment Department Drinking Water Bureau) (NMED/DWB, 2000). WRASTIC is an acronym for the following parameters: Wastewater discharges (W); Recreational land use impacts (R); Agricultural land use impacts (A); Size of watershed (S); Transportations avenues (T); Industrial land use impacts (I); and Amount of vegetative ground Cover (C). The classes considered on each parameter are given in Table 1. Each parameter is assigned a rating from 1 to 5, except the I parameter where the rating varies between 1 and 8. These parameters are weighted and combined to indicate the overall vulnerability of the watershed to contamination; the higher the WRASTIC Index, the more sensitive the water supply is to contamination. The sensitivity rank to pollution considers three categories, i.e., high, moderate and low sensitivity of the water supply (NMED/DWB, 2000). As it considers the land use impacts, the watershed susceptibility given by WRASTIC may be regarded as a first approach for risk assessment.

The first issue to be referred concerning the application of this methodology to the case-study area of Zhangji is that it represents just a small part of the entire Huai River watershed. The second issue is the lack of information concerning the parameters that were presented before. Most of the information used to determine vulnerability of surface water was empirically inferred by the knowledge of the case-study area problem and represents a possible scenario for this area. The land use map divides the area into five categories: lakes, villages, barren land, agricultural land and paddy land. This distribution allows us to infer about the WRASTIC factors in the study area and assign an expected value regarding each feature. Table 1 presents the results of this application scenario. Considering the scenario presented before, the WRASTIC index value for Zhangji area is 58, which classifies the area as high sensitivity to pollution water supply.

Table 1. Application of the WRASTIC index to the case-study area of Zhangji considering a possible scenario

Feature	Range (NMED/DWB, 2000)	Rating	Assigned ratings to Zhangji case-study area	Weights
Wastewater Presence (W)	Public WWTP effluent introduced into watershed area and private septic systems present	5	**5**	**3**
	Public WWTP effluent introduced into watershed area	4		
	> 50 Private Septic systems present	3		
	< 50 Private Septic systems present	2		
	No Wastewater discharges present	1		
Recreational Activity (R)	Motorized activity allowed on water	5	**3**	**2**
	Non-motorized activity allowed on water	4		
	Vehicle Access	3		
	No Vehicle Access	2		
	No Recreational Access	1		
Agricultural Impact (*) (A)	5 or more activities present	5	**5**	**2**
	4 activities present	4		
	3 activities present	3		
	2 activities present	2		
	1 activity present	1		
Size of Watershed (S)	> 1942.35 km^2	5	**3**	**1**
	388.47 - 1942.35 km^2	4		
	155.39 – 388.47 km^2	3		
	38.85 – 155.39 km^2	2		
	< 38.85 km^2	1		
Transporta-tion Avenues (T)	Railway or Interstate avenue through watershed area	5	**3**	**1**
	Highway avenues through watershed area	4		
	State highway or other paved avenues through watershed area	3		
	Unimproved avenues (dirt roads) through watershed area	2		
	No transportation avenues through watershed area	1		
Industrial Impact (I)	Industry has a very large discharge or very heavy impact on surroundings	8	**4**	**4**
	Industry has a large discharge or heavy impact on surroundings	6		
	Industry has a moderate discharge or moderate impact on surroundings	4		
	Industry has minimal discharge and minimal impact on surroundings	2		
	No Industry in watershed	1		
Vegetative Cover (C)	0 - 5 % Ground Cover	5	**5**	**1**
	6 - 19 % Ground Cover	4		
	20 - 34 % Ground Cover	3		
	35 - 50 % Ground Cover	2		
	> 50 % Ground Cover	1		
	WRASTIC index for Zhangji case-study area			**58**

(*) Pesticide Application; Presence of Feedlots / Barnyards / Cattle lots; Presence of Heavy Grazing Activities; Presence of Minimal Grazing Activities; Presence of Farming; Presence of Wildlife

2.2 USGS Method

The USGS method is described in Eimers *et al.* (2000). The rating of the watershed characteristics represents a practical and effective mean of assessing part of the risk of water supplies to potential contamination. The watershed characteristics rating is based on a combination of factors that contribute to the likelihood that water, with or without contaminants, will reach a public surface-water supply intake by following the path of overland flow or the path of shallow subsurface flow. The selected factors include: (a) average annual precipitation, (b) land-surface slope, (c) land cover, (d) land use and (e) groundwater contribution (Eimers et al., 2000). The groundwater contribution uses the same procedure of the unsaturated zone rating presented in the "Groundwater risk to pollution" section; however it is only defined for a 300 m strip around surface water bodies. Ratings are computed for delineated source water assessment areas upstream of each intake. The range of possible ratings is 10 to 100.

Fig.1 presents the final map of the watershed characteristics rating and shows the rating classes and percentage of the study area in each class; it shows also a classification of possible ranges of values for this method.

Watershed characteristics rating classes	% of the study area	Range	Watershed characteristics vulnerability
11 - 19	23		
20 - 28	18	10 - 40	Low
29 - 37	35		
38 - 46	23		
47 - 55	< 1	40 - 70	Intermediate
56 - 64	0		
65 - 73	0		
74 - 82	0	70 - 90	High
83 - 91	0		
91 - 100	0	90 - 100	Very high

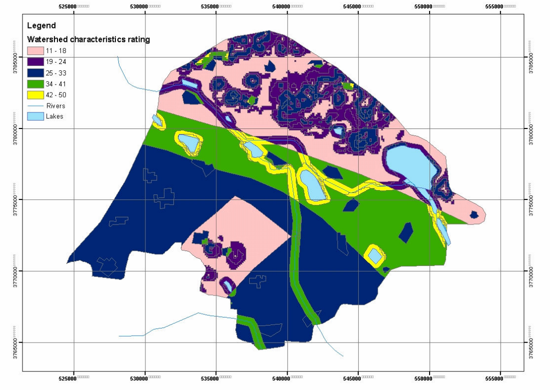

Fig. 1. Watershed characteristics mapping and rating classes and percentage of the study area in each class

Zhangji area is essentially divided in three zones concerning watershed characteristics ratings. This division is related to the land use map that has the higher weight. Most vulnerable areas concerning surface water are located in the paddy fields with ratings ranging from 38 to 46. The lower vulnerability areas are located in the flat areas of the barren land, with ratings extending from 10 to 19. Around rivers and lakes an higher vulnerability was calculated, with one rating class difference regarding the surrounding area, due to the buffer distance of groundwater contributing factor (an exception occurs in the river and lakes in the paddy land). The watershed characteristic rating values for a water supply intake would be obtained by averaging the ratings of the Huai River basin located upstream the water-supply intake. For the all Zhangji area, that represents a small part of the Huai River watershed, the weighted average rating is 28. For this case-study and considering the specific assigned conditions, a low vulnerability is determined for this watershed section.

3 THE DRASTIC VULNERABILITY INDEX

DRASTIC vulnerability index focuses on the intrinsic features of the aquifer including hydrogeological, morphological and other aquifer characteristics.. The index of vulnerability DRASTIC corresponds to the weighted average of 7 values of 7 hydrogeological parameters: Depth to the water (D), Net Recharge (R), Aquifer material (A), Soil type (S), Topography (T), Impact of the unsaturated zone (I) and Hydraulic Conductivity (C).

A value between 1 and 10 to each parameter, except R for which the value ranges between 1 and 9, is attributed, depending on local conditions. High values correspond to high vulnerability. The attributed values are generally obtained from tables, which give the correspondence between local hydrogeological characteristics and the feature value. The local index of vulnerability is computed through multiplication of the value attributed to each parameter by its relative weight, and adding up all seven products. The factors are presented together with the weights respectively for standard DRASTIC applications and for DRASTIC pesticide applications (Table 2). For standard DRASTIC, DRASTIC INDEX was computed by: $DRASTIC=5*D+4*R+3*A+2*S+T+5*I+3*C$

The minimum value of the standard DRASTIC index is therefore 23 and the maximum value is 226. Such extreme values are very rare, the most common values being within the range 50 to 200. Whereas the corresponding minimum and maximum values for pesticide DRASTIC index are 26 and 256 respectively.

Table 2 - Assigned weights for DRASTIC features used in Standard and Pesticide DRASTIC

Feature	Standard Weight	Pesticide Weight
Depth to Water (D)	5	5
Net Recharge (R)	4	4
Aquifer Media (A)	3	3
Soil Media (S)	2	5
Topography (T)	1	3
Impact of the Vadose Zone Media (I)	5	4
Hydraulic Conductivity of the Aquifer (C)	3	2

(Aller *et al.*, 1987)

3.1 Geological and hydrogeological conditions in case study area

Zhangji covers an area of 360 km^2 and the population is around 160 000. The Old Yellow River, the largest river in this area, runs through the area from the northwest to the southeast. Several lakes and reservoirs distribute along the river. The runoff from the precipitation and the water from the upstream are the main surface water resources. Due to the geological conditions, most of the lakes and reservoirs are connected to the underlying fissured rocks and the water may infiltrate into the aquifer or ex-filtrate from the aquifer very easily, depending on water levels. There exist two main groundwater aquifer systems in the area: the porous aquifer and the fissured-karstic aquifer. The river alluvial Quaternary deposits consisting of sands, fine sands, clay and calcareous clay covers the whole plain area with the thickness of less than 40m, where the porous groundwater exists. Groundwater in the fissured-karstic aquifer flows in fissures, fractures and caves of limestone and dolomite. In the hilly area, the rocks outcrop and cover an area of some 170 km^2, where the karstic aquifer has the characteristic of phreatic. In the plain area, the karstic aquifer is overlaid by the porous aquifer and so it is a confined aquifer with an area of 190 km^2. A big fault occurs along the old yellow river extending from the northwest to southeast, with abundant groundwater storage, where a large amount of groundwater is abstracted. The magnetic rock also takes place in some part of the area, which can be considered as impermeable.

The annual average rainfall in the area is 830 mm and the infiltration coefficient ranges from 0.24 to 0.38. The dominant recharge for the porous aquifer comes from the precipitation, the irrigation and the surface water. For the fissured-karstic aquifer, the recharge is mainly from three sources: (1) the precipitation where the fissured-karstic formations outcrop; (2) The surface water where the lakes exist and connect to the fissured-karstic aquifer; (3) The overlaid porous aquifer. The major discharge of the groundwater is artificial abstraction. In 2002, the total abstraction rate is 6193 m^3/d from the porous aquifer and 110 456 m^3/d from the karstic aquifer.

3.2 Assessment of DRASTIC vulnerability

According to DRASTIC method, the values for the 7 parameters of DRASTIC are computed based on the collected data in the area. By using GIS-ARC/INFO, the ratings and maps of the 7 parameters are generated. The final DRASTIC index for the selected fissured-karstic aquifer is derived by joining the 7 parameters.

Rating of DRASTIC parameters

Depth to the water table (D): based on the collected data of the groundwater level for the fissured-karstic aquifer, together with the derived digital elevation map, the mapping of the depth to the water table is generated and the rating is assigned accordingly by using ARC/INFO. The results indicate that in the west part, a small part of the east boundary and also some part of the northern hilly area, the depth to water is >30.5m, D=1; the depth to water in most of the plain area ranges from 15.2~30.5m, D=2 or D=3. Small value of the depth of 0~4.6m happens in south boundary area and a small section of the north area, R=9 or R=10; 5 and 7 are given to the other areas with a depth of 4.6~15.2m. The depth to water is generally a reflection of topographic variation.
Net recharge (R): the recharge is computed by the calibrated model based on the collected data of precipitation, the infiltration coefficient and other parameters. For the area with magmatic formations, which can be taken as impermeable and with a recharge of nearly 0, R=1; for the north hilly area, the recharge is >254mm, R=9; 8 is assigned to the other areas with recharge of 200~254mm.
Aquifer media (A): according to the lithology and the hydraulic conductivity of the karstic aquifer, the rating of parameter A is assigned and the map is derived. For limestone formations with developed fissures and karst corresponding to areas represented by C larger than 1: A = 9; other limestone formations: A = 6; for magmatic formations: A = 2.
Soil type (S): in Zhangji, in the area where the fissure-karstic formations outcrop, the soil may be considered as very thin or inexistent, S=10; the other area overlaid by alluvial Quaternary deposits of sand and Clay, S=6.
Topography (T): the T parameter in the area was computed using the information of the digital elevation model (fig 2). The results show that in most of the area, the slope is less than 2, T=10; in some part of the hilly area, the slope ranges from 2 to 6, T=9; the other areas have a large fluctuation, where T is assigned a value of 1 to 5.
Impact of the unsaturated zone (I): the I parameter was characterized in the following way: where the aquifer is confined: a value of I = 1 is assigned. Where the aquifer is unconfined, a similar approach was carried out as for the A parameter: limestone formations with developed fissures and karst, I = 8; other limestone formations, I = 6; magmatic formations: I = 2.
Hydraulic Conductivity (C): the hydraulic conductivity k is derived by using numerical model. The largest k value between Kx, Ky and Kz is taken for C parameter rating. K is less than 4.1 in the south of the old yellow river and some area in northeast, C=1; for most of the area in north part of the river, K is from 4.1to 12.2, C=2； around the area of the old yellow river, k ranges from 28.5 to 81.5, C=6 or C=8; the area with k more than 81.5, C=10.

DRASTIC index in the area

By integrating the evaluated results of the above 7 parameters, the DRASTIC index of vulnerability is computed by using ARC/INFO concerning normal condition and the mapping is created (Fig. 2). The map indicates that, except some part of the hilly area which has a high value of DRASTIC index, the index ranges from 45 to 159 for most of the area. In general, the groundwater vulnerability to pollution for fissured-karstic aquifer is relatively small.

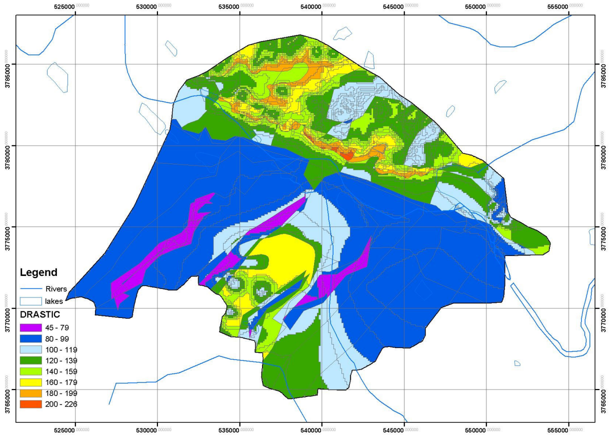

Fig. 2 DRASTIC index of the fissured-karstic aquifer

4 WELLHEAD PROTECTION ZONES

In order to protect Portuguese groundwater resources, Portuguese law (Decreto-Lei n.º 382/99 of 22 September 1999) states guidelines for the perimeters of protection zones. Since these perimeters are a function of the geology and hydraulic parameters of the aquifer, as well as the extraction rate of the concerned well, the fact is that every well has to be looked individually. Towards an easier fulfilment of those aims, a more general approach has been proposed by Krijgsman and Lobo-Ferreira (2001).

The protection zone is the area around the well in which installations or activities susceptible to polluting groundwater resources are prohibited or restricted. As an example, the Portuguese law, as other national laws from other countries, define three protection zones: zone of immediate protection (all activities are prohibited, except those for conservation, maintenance or better exploration of the aquifer), zone of intermediate protection (the objective is to reduce or eliminate pollution of the groundwater resources and installations or activities susceptible of favouring infiltration in the zone close to the well are restricted or prohibited), extended zone of protection (activities or installations capable of polluting the groundwater resources with persistent pollutants, like organic compounds, radioactive substances, heavy metals, hydrocarbons and nitrates area prohibited or restricted).

4.1 Krijgsman and Lobo-Ferreira methodology and application to Zhangji porous aquifer

Krijgsman and Lobo-Ferreira (2001) developed a new methodology that consists on solving the following equations for the evaluation of the upgradient and downgradient distances and also the distance perpendicular to the direction of flow:

For the upgradient protection distance: $r_{max} = (0.00002x^5 - 0.0009x^4 + 0.015x^3 + 0.37x^2 + x)/F$

with $x = \sqrt{\dfrac{2Ft}{A}}$, $F = 2\pi Kbi / Q$ and $A = n / Ki$

and where K = hydraulic conductivity (m/day), b = aquifer thickness (m), i = hydraulic gradient, n = effective porosity, Q = extraction rate (m^3/day) and t = travel time (days).

For the downgradient protection distance equation: $r_{min} = (- 0.042x^3 + 0.37x^2 - 1.04x)/F$

For the protection distance perpendicular to the direction of flow equation: $r_p = 4\sqrt{\dfrac{Q}{n\,b}}$

The area under analysis must be that of an unconfined aquifer. For confined aquifers the confining strata significantly increase the time required for the pollutant to penetrate the aquifer. The travel time through the confining strata probably would exceed 50 days.

Data of extraction rates of wells (Q) are not necessarily required from all wells, since an output map can be made assuming average extraction rates. Extraction rates are never constant per well throughout a year and can vary considerably between wells even close to each other. Depending on the area, the methodology is applied depending on the density of data.

Krijgsman and Lobo Ferreira method was applied to calculate the intermediate protection zone (t = 50 days) for the porous and unconfined aquifer of Zhangji study area.

For extraction rate (Q), the only available information is the total abstraction in the porous aquifer: 6193 m^3/day. Knowing the number of wells located in this aquifer (62), an average value of 100 m^3/day was considered for the extraction rate of each well. Knowing that the extraction rates are in a range between 50 and 500 m^3/day, the calculations were made for the following four values of extraction rate: 50, 100, 300 and 500 m^3/day.

Examples of the results achieved with the application of Krijgsman and Lobo-Ferreira method are presented in Fig. 3 and Fig. 4.

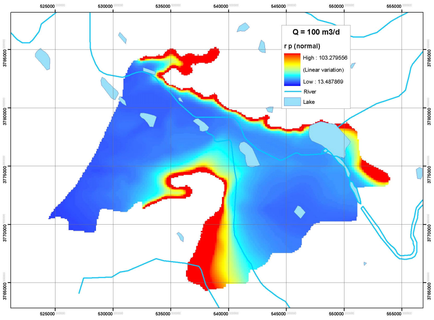

Fig. 3 - Protection distance (meters) perpendicular to flow direction of the porous aquifer, obtained with Krijgsman and Lobo Ferreira method, for an extraction rate of 100 m^3/day

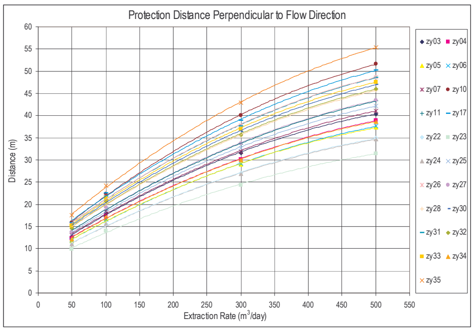

Fig. 4 - Mathematical relation of discharge *versus* perpendicular protection distances of the porous aquifer, obtained with Krijgsman and Lobo-Ferreira method

5 MAPPING GROUNDWATER RISK TO POLLUTION IN ZHANGJI CASE-STUDY AREA

The methodology used relies on an unsaturated zone rating and was developed by the USGS to assess public water supply wells risk of pollution. The method was applied by Eimers *et al*. (2000) in the State of North Carolina. These authors refer that the specific ratings are not necessarily transferable to other regions; however the methods used to develop the ratings are transferable. This method considers the presence of sources of pollution indirectly in one of its variables. It is based on a combination of factors that contribute to the likelihood that water, with or without contaminants, will reach the water table by following the path of aquifer recharge. The selected factors, which are represented by Geographic Information Systems (GIS) spatial-data layers, include: (a) vertical conductance of the unsaturated zone; (b) land surface slope; (c) land cover, and (d) land use. The values of each of these four factors have been categorized, and the categories were assigned a rating on a scale of 1 to 10; a rating of 1 reflects a low contribution to inherent vulnerability and 10 reflects a high contribution. Each of these four factors is weighted on the basis of the importance of the factor in determining vulnerability. The factor weights were multiplied by factor ratings and summed, resulting in an unsaturated zone rating that ranges from 10 to 100. Fig. 5 represents the unsaturated zone rating distribution in Zhangji and classifies the possible ranges of values for this method: 70% of the area is rated between the values of 56 and 73, which corresponds mostly to an intermediate risk to pollution unsaturated area. The groundwater risk assessment value of a specific pumping well is given by the weighted average index in the area of influence of the well under research.

Unsaturated zone rating classes	% of the study area	Range	Unsaturated zone vulnerability
10 - 19	0	10 - 40	Low
20 - 28	< 1		
29 - 37	3		
38 - 46	16	40 - 70	Intermediate
47 - 55	7		
56 - 64	31		
65 - 73	39	70 - 90	High
74 - 82	4		
83 - 91	< 1	90 - 100	Very high
92 - 100	0		

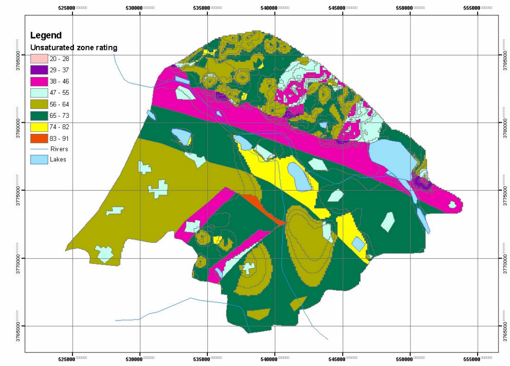

Fig. 5 Unsaturated zone mapping, rating classes and percentage of the study area in each class.

6 CONCLUSIONS

Two aspects should be highlighted about the risk assessment of the case-study area of Zhangji; the first one concerns the data availability and the second one concerns the methodology limitations with regard to the study area. For a suitable risk evaluation one should have a more detailed and updated information concerning land cover and land use of the Zhangji area. For surface water risk assessment the results obtained using the two methods are completely different (low vulnerability using USGS method and high sensitivity using WRASTIC index). Possible explanations are the different type of information used and the scale of application of each one. The first method gives just one weighted value for the entire study area and the second one gives the distribution of values in a map. WRASTIC index uses very simple features that are weighted considering their influence in surface water pollution and calculates a single value for the entire area. The sensitivity rank to pollution considers only three categories, *i.e.*, high, moderate and low sensitivity of the water supply. The final result of this method is an indicative value that represents the sensitivity of the water supply. This method could be improved concerning the adopted features using sub-ranges and ratings more suitable.

By using GIS-ARC/INFO, the evaluation and the rating are made for each parameter according to the DRASTIC method and the DRASTIC index for fissured-karstic aquifer in Zhangji is derived. Although the assessment result is only a relative indication for the aquifer susceptivity to contamination, in reality, it will provide the guideline for the local government to take scientific and effective measures such as changing the land use by modifying the agriculture thus to safeguard the groundwater resources in the area towards the goal of sustainable development. Furthermore, based on the aquifer vulnerability concept and the corresponding data acquisition process, DRASTIC contains an excellent conceptual basis for the application of mathematical groundwater flow and mass transport models.

Some conclusions concerning the application of Krijgsman and Lobo-Ferreira method can be stated as follows:

- There were some computation instabilities in the assessment of the upgradient and downgradient distances due to the case study area very flat water table. The distance selected for protection, in these cases, should be the larger one.
- There are significant changes in the three protection zones regarding the computations with the four selected discharge rates (50, 100, 300 and 500 m^3/day). The variation of protection distances with the variation of discharge rate (Q) is positive, *i.e.* the larger the discharge rate, the larger the protection distances. The mathematical relation of the protection distances *versus* discharge rates showed that the variation of protection distances is bigger for smaller values of Q than for bigger values (Fig. 2).
- The variation of protection distances with the variation of saturated thickness (b) is negative, *i.e.* the larger the saturated thickness, the smaller the protection distances. Based in the formulas of the curves it was concluded that the variation of protection distances is bigger for smaller values of b than for bigger values.

About the risk assessment of the case-study area of Zhangji two aspects should be highlighted; the first one concerns the data availability and the second one concerns the methodology limitations with regard to the study area. For a suitable risk evaluation one should have a more detailed and updated information concerning land cover and land use of the Zhangji area.

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