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Methodologies for pollution risk assessment of water resources systems

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Abstract Water resources systems (both surface water and groundwater resources) are subject to different anthropogenic pollution impacts. Their intrinsic characteristics to better support pollution impacts or their intrinsic vulnerability to pollution, may or may not allow them to resist pollution accidents of different types. The assessment of water resources systems vulnerability to pollution is therefore not only important *per se*, but is also relevant for drawing pollution risk maps. In this paper a brief approach for the assessment of recently developed methodologies for risk assessment of water resources systems to pollution is presented. Some of the methodologies were applied in the Jiang Su Province case-study area (PR China). That application required the GIS mapping of several parameters that were considered to influence vulnerability and risk. The expected influence of those factors is integrated using indexes. The final results enable the mapping of risk of surface and groundwater resources.

Key words groundwater; risk assessment; surface water; vulnerability; Zhangji

INTRODUCTION

Vulnerability has been used several times 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 characterized 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 characterize 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*.

To characterize groundwater risk, three methodologies are referred to: (a) DRASTIC vulnerability index, developed by Aller *et al.* (1987), coupled with pollutant hazard; (b) Groundwater Vulnerability Scoring System (GVSS), a ranking methodology presented by Hathhorn & Hubbena (1996) to assess the relative threat posed by a known contaminant inventory within a protection area; (c) USGS Methodology (developed for the State of North Carolina, USA), an overlay and index method based on the definition of an unsaturated zone rating (Eimers *et al.*, 2000).

For surface water several methodologies exist that intend to represent surface water risk. These were mainly developed to define the risk of contamination of surface water sources, i.e. if a water source is in a more threatened situation than another. The following methodologies may be referred to: (a) the methodology of the ECOMAN Project (cf. Harum *et al*., 2004), that defines vulnerability of surface water to pollution based on the following five input variables: land cover, slope, soil, river network and urban distribution. The vulnerability assessment map of surface water to pollution is combined with the hazard map and pollution sources map, resulting in a potential risk map of surface water to pollution; (b) methodology used by the Californian Department of Health Services (CDHS), that considers the location of the drinking water source, the delineation of source area and protection zones, the drinking water physical barrier effectiveness, and the inventory of possible contaminating activities and risk (vulnerability) of drinking water sources to contamination (CDHS, 2000); (c) USGS methodology (developed for the State of North Carolina), is an overlay and index method for rating the watershed characteristics (Eimers *et al*., 2000); (d) the WRASTIC index, that allows the evaluation of the watershed susceptibility to surface water contamination in any hydrogeologic setting based on major watershed characteristics and land uses (NMED/DWB, 2000).

Some of these methodologies were 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 as it represents an area of China with intense food production and human activity, whose effects on 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).

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, USA. These authors state 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.

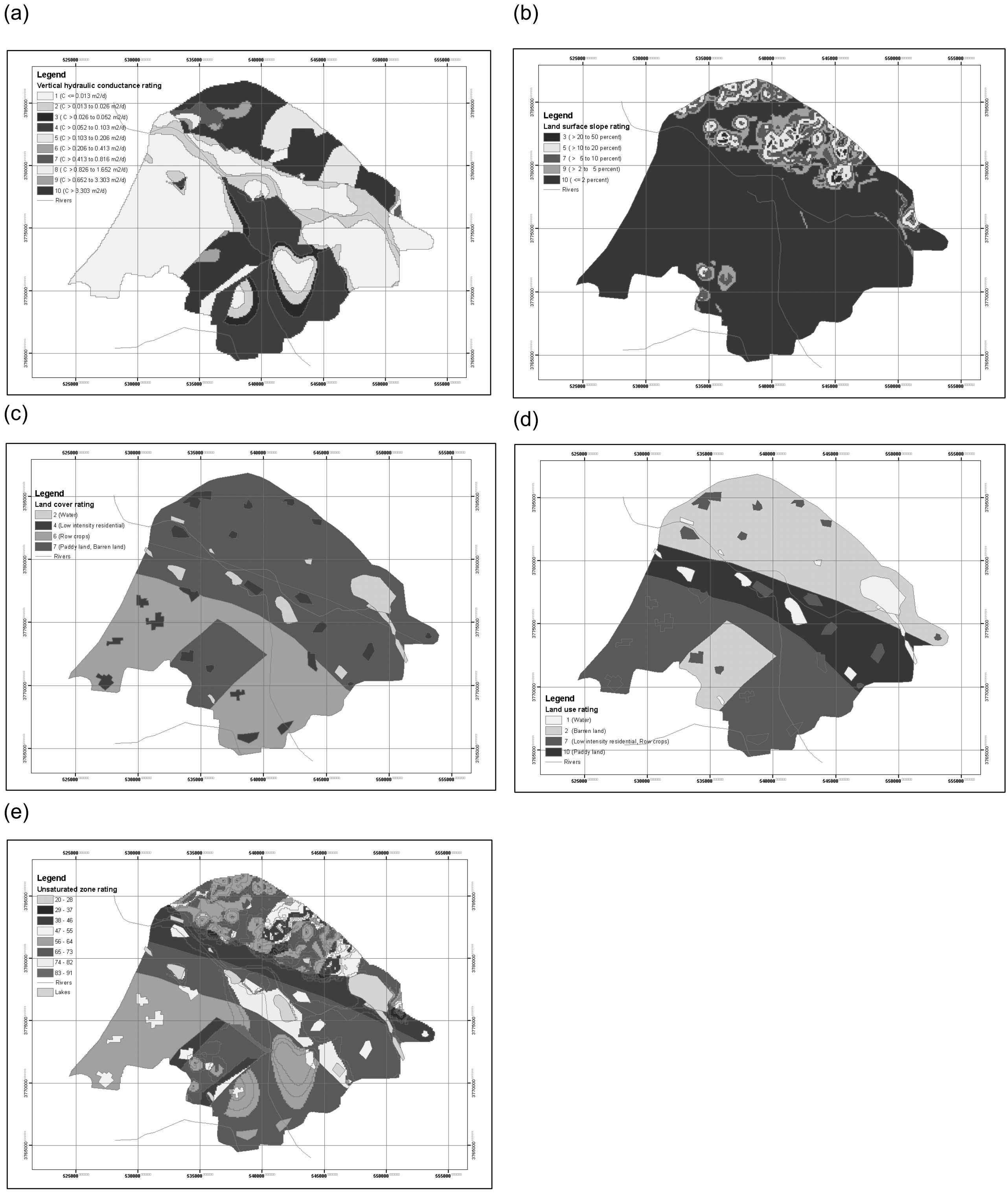

Fig. 1 (a) Vertical hydraulic conductance rating for unsaturated zone. (b) Land surface slope rating for unsaturated zone. (c) Land cover rating for unsaturated zone. (d) Land use rating for unsaturated zone. (e) Unsaturated zone rating distribution in the case-study area.

Figure 1 shows the application of this method to the Zhangji case-study area regarding: (a) vertical hydraulic conductance rating; (b) land surface slope rating; (c) land

Table 1 Unsaturated zone rating classes and percentage of the study area in each class. Possible unsaturated zone vulnerability classification.

Unsaturated zone rating classes	% of the study area	Range	Unsaturated zone vulnerability
10–19	0		
20–28	<1	10–40	Low
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		
92–100	0	90–100	Very high

cover rating; and (d) land use rating. Figure 1(e) represents the unsaturated zone rating distribution. Table 1 shows the distribution of the unsaturated zone rating 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 mostly corresponds to an intermediate risk to pollution of the 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.

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

The WRASTIC index and the USGS method were applied to the Zhangji case-study area. Both methods may be considered as a risk assessment evaluation because they consider the presence of sources of pollution in their analysed factors. 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.

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 2. 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

Table 2 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		
Transportation 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.

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 from 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 2 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 highly sensitive to pollution of the water supply. It should be noted that the study area used for this application is just a small part of the Huai River basin and also that to achieve a correct value for the Huai River the entire watershed should be considered, as well as more detailed information concerning some WRASTIC features.

USGS Method

The USGS method is described in Eimers *et al.* (2000). The rating of the watershed characteristics represents a practical and effective means 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 as 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 also 10 to 100.

The results of the application of this method to Zhangji case-study area are presented in Fig. 2 for: (a) average annual precipitation rating, (b) land surface slope rating, (c) land cover rating, (d) land use rating and (e) groundwater contribution rating. Figure 2(f) presents the final map of the watershed characteristics rating and Table 3 shows the 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 (besides the average annual precipitation that is rated with just one value for the all area). Most vulnerable areas concerning surface water are located in the paddy fields with ratings rangeing 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 a higher vulnerability was calculated, with one rating class difference regarding the surrounding

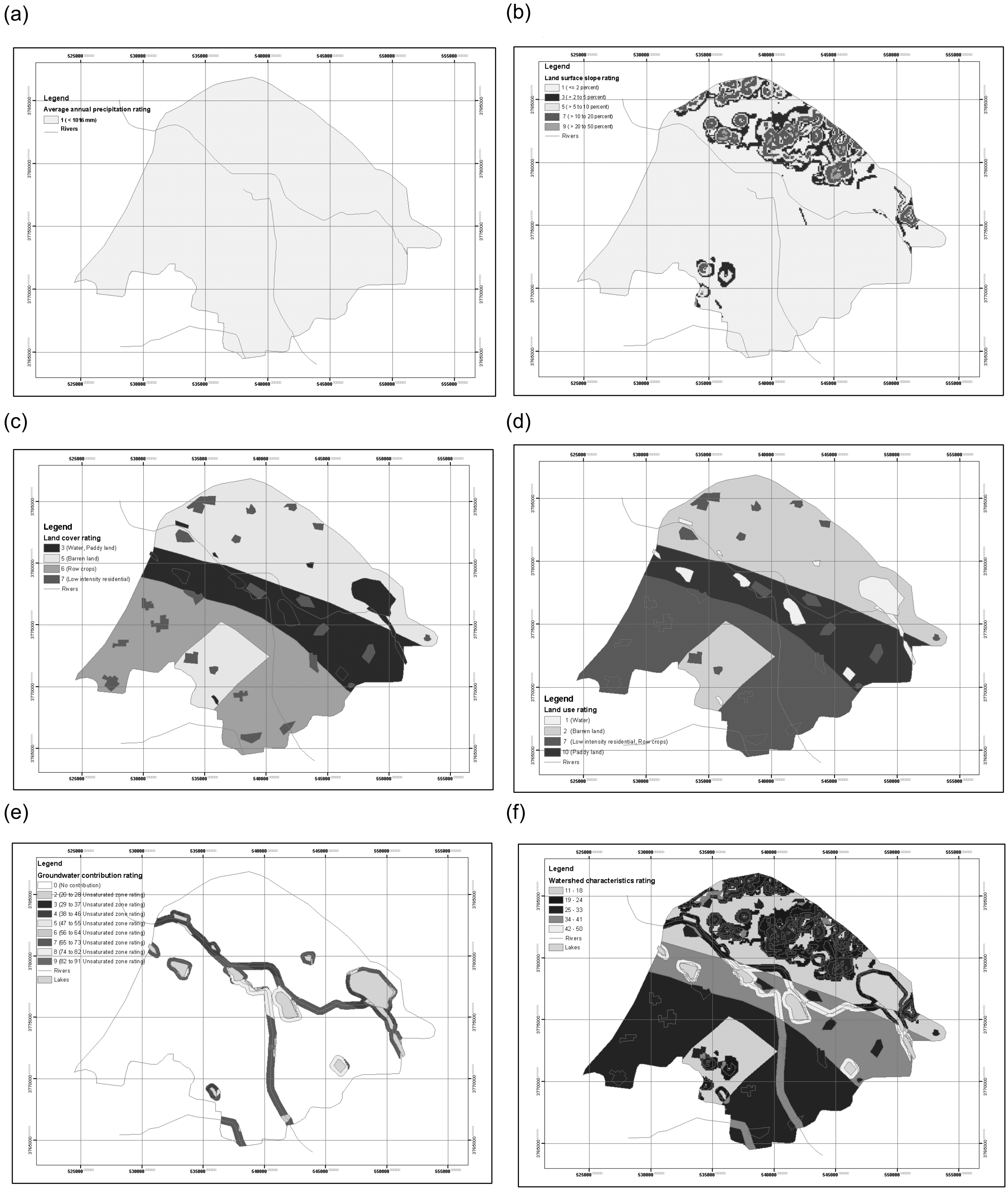

Fig. 2 (a) Average annual precipitation rating for watershed characteristics. (b) Land surface slope rating for the watershed characteristics. (c) Land cover rating for watershed characteristics. (d) Land use rating for watershed characteristics. (d) Groundwater contribution rating for surface water. (f) Watershed characteristics rating for the case-study area.

Table 3 Watershed characteristics rating classes and percentage of the study area in each class. Possible watershed characteristics vulnerability classification.

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

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 are obtained by averaging the ratings of the Huai River basin located upstream of 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. Table 3 classifies the possible ranges of values for this method. A low vulnerability was determined for this case-study of this watershed section, taking into consideration the specific assigned conditions.

CONCLUSIONS

Two aspects should be highlighted about the risk assessment of the case-study area of Zhangji; the first one concerns data availability and the second 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 the USGS method and high sensitivity using the 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.

The 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 only considers 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 more suitable sub-ranges and ratings.

The USGS method seems to give a better representation of groundwater and surface water risk, it uses more robust and detailed information, and it also allows for spatial distribution of risk to pollution. Experience of the application of this methodology has led to the following points:

- Land cover and land use classes and the respective ratings can not be extrapolated adequately to the Zhangji case-study area, because the assigned ratings do not correspond to the expected pollution scenario for this area that has specific groundwater and surface water pollution problems derived from intensive agricultural uses.
- It would be useful to have further applications of this methodology to other watersheds, particularly in China, so that the respective ratings could be adapted to these land covers.
- Average annual precipitation categories could be adapted to be used in regions with lower values of precipitation.
- Specific factors could be included that are related to the contaminant's behaviour in the unsaturated zone; those factors are the organic content of soil, soil type, land slope, erodability, buffering capacity, soil permeability, etc.
- Because each type of pollutant has a different behaviour in the soil it could be also helpful to include a map with the sources of pollution and with the main pollutants they produce.

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