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A GIS Based DRASTIC Model for Assessing Groundwater in Shallow Aquifer in Yuncheng Basin, Shanxi, China

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Abstract: Long-term population growth and economic development is placing ever-increasing demands on all natural resources in China. The stress on water in different regions is heavy and groundwater has become an important resource for use in water-supply and irrigation. The main objective of this study is to find out the groundwater vulnerable zones in Yuncheng basin using DRASTIC model. This model is based on seven data layers that provide the input to the modeling. It corresponds to the initials of seven layers: depth of water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic Conductivity. Geographical Information System (GIS) was used to create a groundwater vulnerability map by overlaying the available hydrogeological data. The final DRASTIC index indicated that Yuncheng basin area is divided in 3 different vulnerable zones namely high, moderate and low vulnerable zones. The sensitivity analysis showed that once depth to water, aquifer media and impact of vadose zone parameters are removed there was a decrease in vulnerability but when net recharge, soil media, topography and hydraulic conductivity parameters are removed the vulnerability increased. The study suggests that the authorities that are responsible for managing groundwater resources at this basin should frequently monitor the zone under high vulnerability in order to monitor the changing level of pollutants.

Key words: Yuncheng basin, groundwater vulnerability, DRASTIC model, shallow aquifer, GIS

INTRODUCTION

Groundwater continues to play an important role in the development of the word's water-resource potential and then it has to be protected from the increasing threat of subsurface contamination. The growth of population, industrial and agricultural production since the Second World War, coupled with the resulting increased requirements for energy development, has for the first time in man's history begun to produce quantities of waste greater than that which the environment can easily absorb. Large amounts of domestic and industrial effluents poorly discharged lead to the pollution of groundwater in shallow aquifers (Atiqur, 2008).

Ground water supplies may be withdrawn from unconfined, confined or semi-confined aquifer zones. For purposes of this study, an "aquifer" is defined as a saturated water-bearing geologic unit capable of transmitting significant quantities of water under ordinary hydraulic gradients (Freeze and Cherry, 1979). A "confined aquifer" is defined as an aquifer bounded by less-permeable stratigraphic units, wherein hydraulic head pressure is elevated above atmospheric pressure.

Most parts of northern China do not have sufficient surface water; the dependable water resource is largely groundwater. This water resource has high nitrate levels exceeding 50 mg L^{-1} the nitrate concentration allowable limit for nitrate in drinking water. The source of this contamination is the rapid increase of N-Fertilizer application in recent years in Northern China (Zhang *et al.*, 1996). Precipitation in the most of northwest arid region of China is less than 500 mm a^{-1}.

Pollution impairs the use of water and can create a hazard to public health through toxicity or the spread of disease. Most pollution originates from the poor disposal of wastewater following the use of water for any of wide variety of purposes. Thus, a large number of sources and causes can modify groundwater quality, ranging from septic tanks to irrigated agriculture. In contrast with surface water pollution, subsurface pollution is difficult to detect and is even more difficult to control and may persist for decades. With the growing recognition of the importance of underground water resources, efforts are increasing to prevent, reduce and eliminate groundwater pollution (Todd and Mays, 2005).

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To ensure that Yuncheng basin aquifer remains as a source of water for the area, it is necessary to estimate whether certain locations in this groundwater basin are susceptible to receive and transmit pollution. Therefore, the first objective of this study was to evaluate the Yuncheng basin aquifer vulnerability using Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic Conductivity (DRASTIC), the empirical model of the U.S. Environmental Protection Agency (USEPA, 1985). The second objective is to evaluate the relative importance of the DRASTIC model parameters for assessing aquifer vulnerability in Yuncheng basin heights through sensitivity analysis. The third objective was to demonstrate the combined use of DRASTIC and Geographical Information System (GIS) as an effective method for groundwater pollution risk assessment and water resource management.

Vulnerability as used in this paper refers to the sensitivity of groundwater to contamination and is determined by intrinsic characteristics of the aquifer. It is distinct from pollution risk, which depends not only on vulnerability but also on the existence of significant pollutant loading. The seriousness of the impact on water use will depend on the magnitude of the pollution episode and the value of the groundwater resource.

Groundwater vulnerability is a function of the geological setting of an area, as this largely controls the amount of time, i.e., the residence time of the groundwater that has passed since the water fell as rain, infiltrated through the soil, reached the water table and began flowing to its present location (Prior *et al.*, 2003).

The concept of groundwater vulnerability was first introduced in France by the end of 1960s to create awareness of groundwater contamination (Vrba and Zoporozec,1994). It can be defined as the possibility of percolation and diffusion of contaminants from the ground surface into groundwater system. Vulnerability is usually considered as an “intrinsic” property of a groundwater system that depends on its sensitivity to human and/or natural impacts.” specific” or “integrated” vulnerability, on the other hand, combines intrinsic vulnerability with the risk of the groundwater being exposed to the loading of pollutants from certain sources (Vrba and Zoporozec, 1994). Groundwater vulnerability deals only with the hydrogeological setting and does not include pollutant attenuation. The natural hydrogeologic factors affect the different pollutants in different ways depending on their interactions and chemical properties.

Many approaches have been developed to evaluate aquifer vulnerability. These include process-based methods, statistics methods and overlay and index methods. The process-based methods use simulation models to estimate the contaminant migration but they are constrained by data shortage and computation difficulties. Statistical methods use statistics to determine associations between spatial variables and actual occurrence of pollutants in the groundwater. The limitations include insufficient water quality observation, data accuracy and careful selection of spatial variables. Overlay and index methods combine factors controlling the movement of pollutants from the ground surfaces into the saturated zone resulting in vulnerability indices at different locations. The main advantage of this method is that some of the factos such as rainfall and depth to groundwater can be available over large areas, which makes them suitable for regional scale assessment. However, their major drawback is the subjectivity in assigning numerical values to the descriptive entities and relative weights for different attributes.

DRASTIC is a method developed in the United State of America by the National Ground Water Association in 1987 to evaluate the potential for ground water contamination in any hydrogeologic setting. DRASTIC is an acronym for depth to water (D); net recharge (R); aquifer media (A); soil media (S); topography (T); impact of vadose zone media (I); and aquifer hydraulic conductivity (C). The method assigns a relative weight to each of these factors to determine the relative sensitivity of a given supply well to surface-derived contamination. The higher the DRASTIC Index, the more sensitive the well is to contamination.

DRASTIC has been the most commonly used aquifer sensitivity assessment method. However it is not intended to predict the occurrence of groundwater contamination (US EPA, 1985). It was originally developed for manual overlay of semiquantitave data layers but the simple definition of its vulnerability index as linear combination of factors shows the feasibility of the computation using GIS (Napolitano and Fabbri, 1996). GIS is designed to collect diverse spatial data to represent spatially variable phenomena by applying a series of overlay analysis of data layers that are in spatial register.

DRASTIC model has been used for vulnerability assessment in Portugal using hydrogeological parameters, aquifer recharge. The final map of DRASTIC aquifer vulnerability for Portugal at 1:500,000 scale was developed in ARC/INFO GIS software.

MATERIALS AND METHODS

Study area: Yuncheng basin is located in the North-Western part of China between 35°00′54.48"N and 110°59′24.29"E. It is bounded by Zhongtiao Shan Mountain in the South, Jiwangshan Mountain in the

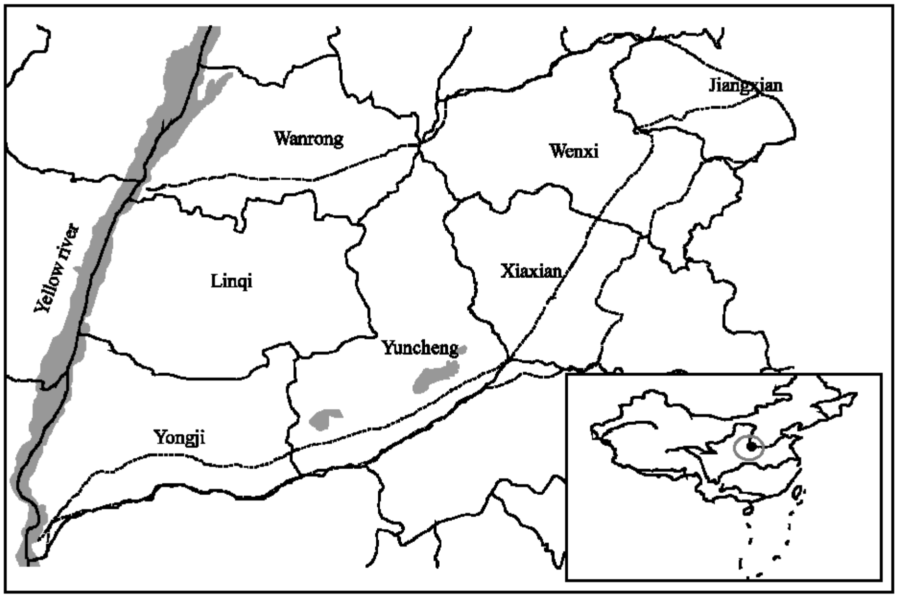

Fig. 1: Locattion of yuncheng basin

Table 1: Data used for creation of hydro-geological parameters for DRASTIC mode

S.no	Data type	Sources	Format	Scale of map	Date	Output layer
1	Borehole data(water table level)	1st hydrogeological team of Shanxi province	Table		1960s-2006	D
2	Average annual rainfall	Meteorological Bureau of Shanxi province	Table		1956-2006	R
3	Geological map	Digital data from geological Survey Bureau of Shanxi province	Map	1:250,000		A
4	Soil map	Digital data from geological Survey Bureau of Shanxi province	Map	1:250,000		S
5	Topographical map	Digital data from geological Survey Bureau of Shanxi province		1:250,000		T
6	Geological map	Digital data from geological Survey Bureau of Shanxi province	Map			I
7	Hydraulic conductivity	1st hydrogeological team of Shanxi province	Table		1960s-2006	C

North, Zijishan Mountain in the North-East and Yellow river in the West. Along the Zhongtiaoshan Mountain, Zijinshan Mountain, Jiwangshan Mountain; there is a narrow path where main sediments are alluvial and fluvial phase with gravels. The center of the basin (The plain of Sushui River) is mostly alluvial phase and Lake Phase sediments with fine sand to middle sand. To the West of Kaolaoyuan Platform, there is an alluvial plain of the yellow river. The west part of the plain is mainly river face with fine sand and silt sand while the aquifer of uplift plate is mainly fine sand.

Due to the fact that the Yuncheng basin is a faulted basin; face of water bearing media changes sharply due to the effect of tectonic movement and the morphology (Fig. 1). Due to the fact that the water barrier media is different in the plain, the uplift plate and in mountain, the aquifer parameters are different but for the plain and uplift plate the aquifer parameters are similar.

A commonly used model in assessing groundwater vulnerability is the DRASTIC model (Aller *et al*., 1985, 1987).

The above model applied in GIS environment was used in this research to evaluate the vulnerability of the Yuncheng basin aquifer. The procedure was designed to provide for systematic evaluation of groundwater-pollution potential in any hydrogeologic setting.

Seven variables were used namely Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity.

The numerical ranking system, another DRASTIC component, was used to assess the groundwater-pollution potential for each hydrogeologic variable. The system contained three parts: weights; ranges and ratings (Aller *et al*., 1987). Each DRASTIC parameter was assigned a relative weight between 1 and 5, with 5 being considered most significant in regard to contamination potential and 1 being considered least significant (Table 1). In turn, each of the variables was "sub-divided" into either numerical ranges (e.g., depth to water in meter) or media types (e.g., materials making up a soil) which impact pollution potential. Finally, the ratings are used to quantify the ranges/media with regard to likelihood of groundwater pollution. The final vulnerability map was based on the DRASTIC index (Di) which is computed as the weighted sum overlay of the 7 layers using the following equation:

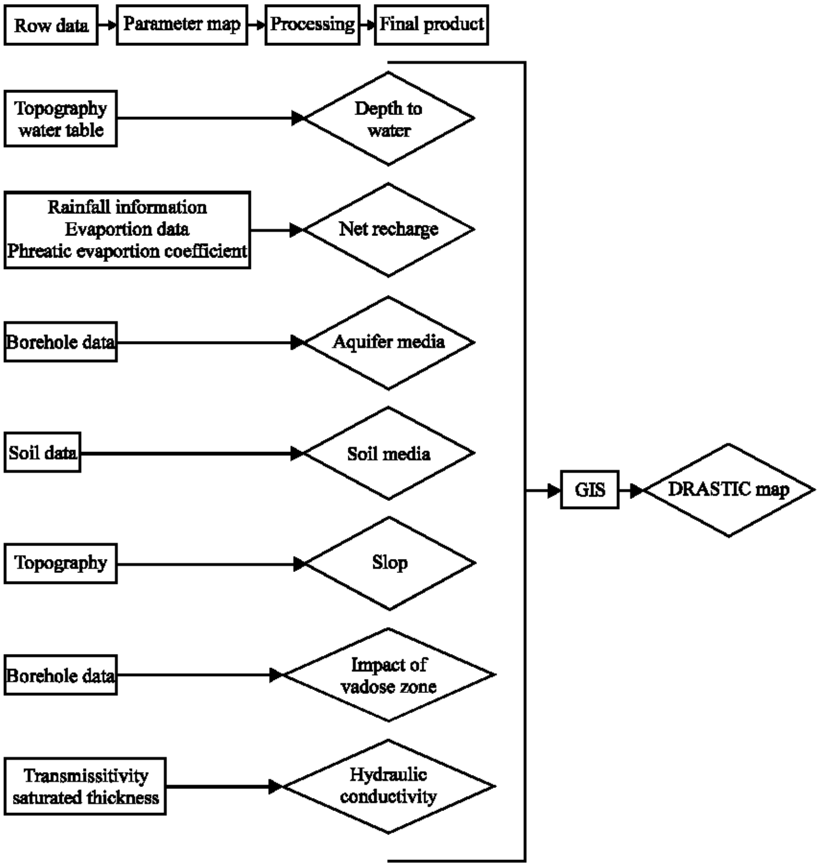

Fig. 2: Methodology Flow chart for ground water vulnerability analysis using DRASTIC model in GIS

Table 2: The DRASTIC model parameters

Factor	Description	Relative weight
Depth to water	Represents the depth from the ground surface to the water table, deeper water table levels imply lesser chance for contamination to occur.	5
Net recharge	Represents the amount of water which penetrates the ground surface and reaches the water table. Recharge water represents the vehicle for transporting pollutants.	4
Aquifer media	Refers to the saturated zone material properties, which controls the pollutant attenuation processes.	3
Soil media	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward.	2
Topography	Refers to the slope of the land surface, it dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone.	1
Impact of vadose zone	Is defined as the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone.	5
Hydraulic conductivity	Indicates the ability of the aquifer to transmit water, hence determines the rate of flow of contaminant material within the groundwater system.	3

$$\text{DRASTIC Index (Di)} = \text{DrDw+RrRw+ArAw+SrSw+TrTw+IrIw+CrCw} \quad (1)$$

Where, D, R, A, S, T, I and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively.

Once the DRASTIC Index was computed, it was possible to identify the area which was more likely to be susceptible to GW contamination relative to others (Table 2). The higher the DRASTIC Index, the greater the Ground Water (GW) pollution potential. The methodology flow chart is shown in Fig. 2.

Sensitivity analysis: Aquifer vulnerability methods require validation to reduce subjectivity in the selection of rating ranges and to increase reliability (Ramos-Leal and Rodríguez-Castillo, 2003). Sensitivity analysis provides valuable information about the influence of rating values and weights assigned to each parameter and helps hydrogeologists to judge the significance of subjective elements (Gogu and Dassargues, 2000).

Some scientists argue that GW contamination vulnerability may be worked out without using all the parameters of DRASTIC model (Barber *et al.*, 1993; Merchant, 1994). Some others (Napolitano and Fabbri, 1996) have argued that weights and ratings used in the model are subjective and there is no reason not to doubt the accuracy of the vulnerability index thus worked out. Still some may doubt the results of this model in the absence of supporting experimental evidence. In order to remove all these doubts, sensitivity analysis of the model and GW contamination analysis are carried out. In the first instance the rated parameters of the model have been examined for interdependence and variability as a high degree of interdependence of the parameters may lead to the risk of misadjustment (Babiker *et al.*, 2005; Rosen, 1994). They carried out two sensitivity tests: the map removal sensitivity analysis and the single parameter sensitivity analysis. The first test was for the first time carried out by Lodwick *et al.* (1990) and the second test was introduced by Napolitano and Fabbri (1996). These two tests were also used by the Babiker *et al.* (2005). The first test identifies the sensitivity of vulnerability map by removing one or more layer maps and is worked out using the following equation:

$$S = (|V/N - V'/n|)*100 \qquad (2)$$

Where, S is the sensitivity measure, V and V'are the unperturbed and the perturbed vulnerability indices respectively and N and n are the number of data layers used to compute V and V'. The unperturbed vulnerability index is the actual index obtained by using all seven parameters and the perturbed vulnerability index was computed using a lower number of parameters.

The single parameter sensitivity test was carried out to assess the influence of each of the seven parameters of the model on the vulnerability measure. In this analysis, the real or ''effective'' weight of each parameter was compared with its assigned or ''theoretical'' weight. The effective weight of a parameter in a sub-area was calculated by using Eq. (3):

$$W = (PrPw/V)*100 \qquad (3)$$

where, W refers to the ''effective'' weight of a parameter in a polygon, Pr and Pw are the respective rating and weight of that parameter respectively and V is the overall vulnerability index of that polygon. The GW contamination analysis was carried out by taking samples of water from 264 wells (July 2006). The samples were tested for TDS and NO^{-3}. The analysis was carried out to compare the experimental results with the contamination vulnerability levels as shown by overall vulnerability map prepared by using the DRASTIC model.

RESULTS AND DISCUSSION

Preparation of the parameter maps: The white part on the all maps shows the Salt River; this river was not considered during map preparation.

Depth: The depth to the water table was obtained by subtracting the groundwater level from the elevation map, the elevation of the well and the mean water level table was provided for the last 14 years (1980-2004).

The depth to water table map was then classified into ranges defined by the DRASTIC model and assigned rates ranging from 1 (minimum impact on vulnerability) to 10 (maximum impact on vulnerability). The deeper the groundwater, the smaller the rating value. The Depth to Water Table (DTWT) provides us with a measurement of how deep the unsaturated material is through which the contaminant must travel through before reaching the water table (or the saturated zone). This is important because the depth of the water table increases with greater depth of the unsaturated zone, therefore it will take longer for the contaminants to reach the water table.

Depth to water was computed using two datasets: land-surface topography available at 1:250,000 and water-table-surface topography, available at 1:250,000.

The point data were contoured by interpolating and divided into three categories i.e., <5 m, 5-10 m and >10 m. Thereafter, it was converted into grid to make it raster data for GIS operation. The depth-to-water table interval range, DRASTIC rating, weight and resulting index are shown in Table 3. Areas with high water tables are vulnerable because pollutants have short distances to travel before contacting the GW. So, the deeper the GW the smaller the rating value. The depth was determined by considering 2 major areas namely the plain area and the remaining area.

Net recharge: The primary source of ground water is precipitation, canal seepage and irrigation seepage that infiltrate through the unsaturated zone to the water table. Net recharge indicates the amount of water per unit area of land which penetrates the ground surface and reaches the water table (Table 4).

Recharge map was constructed from the rainfall data according to the following formula:

$$N\,R = (R-(E^* E_p)) \qquad (4)$$

where, N R refers to Net Recharge, R to Rainfall, E to Evaporation and E_p refers to Phreatic Evaporation Coefficient.

According to phreatic evaporation coefficient (Table 5), a map of true evaporation considering the type of rock and the depth to the water table was provided; finally it was subtracted from the precipitation map.

Table 3: Depth to Water

Ranges (m)	Rating	Index
<5	10	50
5-10	9	45
>15	7	35

Weight = 5

Table 4: Net Recharge

Ranges(mm/year)	Rating	Index
<0	0	0
0-51	1	4
51-76	2	8
76-102	4	16
102-123	6	24

Weight = 4

Table 5: Phreatic evaporation coefficient values

	Depth(m)								
Rock	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
Silt	0.887	0.522	0.331	0.198	0.143	0.068	0.050	0.039	0.016
Silt, clayey soil	0.471	0.330	0.228	0.154	0.091	0.044	0.030	0.020	0.010

Table 6: Aquifer media

Aquifer	Rating	Index
Fine sand	4	12
Medium sand	6	18
Coarse sand	8	24
Gravel	9	27

Weight = 3

Table 7: Soil media

Soil Media	Rating	Index
Clay	1	2
Clayey silt	3	6
Silt	4	8
Fine sand	6	12
Medium sand	8	16
Coarse sand	9	18
Gravel	10	20

Weight = 2

Aquifer media: Aquifer media refers to the consolidated or unconsolidated rock that serves as an aquifer (Table 6). The larger the grain size and the more fractures or openings within the aquifer, the higher the permeability and thus vulnerability of the aquifer.An aquifer is defined as a subsurface rock unit which will yield sufficient quantities of water for use. Aquifer media describes consolidated and unconsolidated rock where water is contained. This will include the pore spaces and fractures of the media where water is held. The aquifer media therefore affects the flow within the aquifer. This flow path controls the rate of contaminant contact within the aquifer (Aller *et al.*, 1987).

Soil media: In general, the soil's pollution potential is affected largely by the type and amount of clay present, shrink/swell potential (controlling the development of macropores and other secondary permeability features) and the soil's grain size. The DRASTIC index includes soils ratings appropriate for the pollution potential associated with development of secondary permeability (Table 7).

Soil media represents a significant factor for influencing groundwater pollution potential, particularly from agrochemical applications. Commonly taken to mean the upper weathered zone of the earth's surface, the six feet (on average) of the uppermost portion of the vadose zone is where the most significant biological activities occur. The makeup of soil media on groundwater vulnerability directly impacts the amount of recharge and the ability of contaminants to infiltrate the vadose zone. Therefore, soil permeabilities and contaminant migration are directly linked to soil type, shrink and swell potential and grain size of the soil (Aller *et al.*, 1987).

Topography: In terms of slope and slope variability, topography is a controlling factor for pollutant runoff or infiltration. Inherent to this component is soil development as an input to contaminant attenuation. At 0-2% slope, the greatest potential exists for pollutant infiltration whereas with 18+% slope, little potential exists for infiltration. However, contamination to surface water increases along with a greater probability of erosion (Aller *et al.*, 1987).

Topography is considered as the slope and slope variability of the land surface. When the slope is steep, there tends to be more potential for pollutant runoff and therefore little pollutant retention and in turn little infiltration of contaminants. On the other hand, gentle slopes have more potential for pollutant retention and in turn infiltration of contaminants. Areas with low slope tend to retain water for a longer period of time. This allows greater infiltration or recharge of water and a greater potential for contaminant migration. Areas with steep slopes, having large amounts of runoff and smaller amounts of infiltration are less vulnerable to GW contamination. Regions of consistently low topography are vulnerable as water can pool and infiltrate into the sub-surface in these areas. Topography will give an indication on whether a pollutant will run off or remain on the surface long enough to infiltrate into the GW (Lynch *et al.*, 1994).

In this research, percent slope of the land surface was calculated using the ArcGIS 9.1 and the topography variable was the easiest and most straightforward to calculate out of the seven DRASTIC variables. The slope variation in the study area is very small, i.e., <5 %, 5-10% and >10% (Table 8). Flat areas were assigned high rates because in flat areas the runoff rate is less, so more percolation of contaminants to the GW.

Table 8: Topography

Slope ranges (%)	Rating	Index
<5	10	10
5-10	5	5
>10	1	1

Weight = 1

Table 9: Impact of vadose zone

Ranges	Rating	Index
Gravel	9	45
Coarse sand	8	40
Medium sand	7	35
Fine sand	6	30

Weight = 5

Table 10: Hydraulic conductivity

Ranges(GPD/FT^2)	Rating	Index
<100	1	3
100-300	2	6
300-700	4	12
1000-2000	8	24
>2000	10	30

Weight = 3

Table 11:Classification of groundwater sensitivity

Index	Sensitivity classification
93-116	Low
117-126	Moderate
127-256	High

Table 12: Area under different groundwater pollution vulnerability degrees in Yuncheng basin

S.N.	Drastic index value	Area (in Km Sq)	Vulnerability zones
1	93-116	1158.375	Low
2	117-126	2584.313	Moderate
3	127-156	956.1875	High
Total		4698.875	

Impact of vadose zone: The vadose zone is defined as that zone above the water table which is unsaturated or discontinuously saturated. Lying between the soil horizon and water table, the type of media in this zone determines attenuation characteristics.

Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion are all processes which may occur within the vadose zone (Aller *et al.*, 1987).

The vadose zone comprises of the zone below the soil layer but above the saturated zone of the aquifer. This zone is important to consider because the material comprising this zone can adsorb or attenuate contaminants as they pass through (Table 9).

Hydraulic conductivity: Hydraulic conductivity, or the coefficient of permeability, refers to the ability of an aquifer to transmit water, which in turn largely controls the rate at which ground water and any contaminant contained within the aquifer will flow under a given hydraulic gradient. Hydraulic conductivity is dependent upon the sedimentary characteristics of the aquifer media. Therefore, it is a function of the grain size, shape, sorting and packing of the aquifer materials and properties of the fluid passing through the aquifer.

There are a number of methods available to determine the hydraulic conductivity of an aquifer. Values can be obtained by conducting aquifer pumping tests, consulting published hydrogeologic reports, or estimating based on the properties of the sedimentary characteristics of an aquifer (Freeze and Cherry, 1979).

Hydraulic conductivity is generally a function of the aquifer media. It is tested wherever test wells are drilled (Table 10). The materials used in this research were assigned hydraulic conductivity according to standard values found in Groundwater by Freeze and Cherry (1992).

According to the same authors the rock is classified as silty sand, clean sand and gravel aquifers: 10^{-2}-10^{3}.

This final component of the DRASTIC model can be described in terms of aquifer material and its ability to transmit water for a given hydraulic gradient. Contamination is controlled by the rate at which groundwater flows. Hydraulic conductivity is a measure by which voids, fracturing and bedding planes are the controlling elements. With a higher hydraulic conductivity, there exists a greater potential for pollution (Aller *et al.*, 1987).

Rates of hydraulic conductivity used in this research were taken from a number of different sources. Data were not available for all aquifers; and where gaps existed, values were assumed based on aquifer media and typical hydraulic conductivity data reported in the literature. This approach allowed the aquifer data layer to be converted to the appropriate DRASTIC rating for each aquifer based on its hydraulic conductivity.

According to the results in Table 11 and 12, this study shows that of the total 4698.875 ha an area of about 2584.313 ha is in Moderate vulnerable zone with DRASTIC index range between 117 and 126. About 1158.375 ha are low vulnerable zone with a DRASTIC index ranging between 93 and 116 and about 956.1875 ha are in high vulnerability zone with a DRASTIC index between 127 and 156. This means about the half of the total area (55%) is under moderate vulnerability due to the higher depth (deep) and Moderate net recharge. 20.35% of the total area is at a high risk in terms of pollution potential. The Southwest part (Yongji County) receives a considerable amount of water from the centre plate and is characterized by gentle slope and gravel aquifer media. It is also characterized by high pollution rating due to gentle slope hence the wastewater from households remains stagnant in this area and hence leading to the high vulnerability.

Table 13: Statistical summary of the DRASTIC parameter map

	D	R	A	S	T	I	C
Min	7	1	4	1	1	6	1
Max	10	5	9	10	10	9	10
Mean	7.65	2.97	5.97	3.89	6.73	7.17	1.40
SD	1.134	0.941	1.964	1.806	3.85	1.259	1.057
CV (%)	14.82	32.45	32.89	46.42	57.2	17.56	75.5

SD: Standard Deviation, CV: Coefficient of Variation

Table 14: Summary of rank-order correlation analysis result between seven DRASTIC parameters

Correlated parameters	Correlation coefficient r	p-value
Depth to water and net recharge	-0.282	0.01
Depth to water and aquifer media	-0.347	0.01
Depth to water and topography	0.231	0.01
Depth to water and impact of vadose zone	0.05	0.01
Net recharge and aquifer media	0.051	0.05
Net recharge and soil media	0.24	0.01
Net recharge and topography	0.099	0.01
Net recharge and impact of vadose zone	-0.137	0.01
Net recharge and hydraulic conductivity	0.122	0.01
Aquifer media and soil media	0.085	0.01
Aquifer media and topography	-0.187	0.01
Aquifer media and impact of vadose zone	-0.082	0.01
Soil media and impact of vadose zone	0.099	0.01
Topography and hydraulic conductivity	0.10	0.01
Conductivity and the impact of vadose zone	-0.103	0.01
Topography and impact of vadose zone	-0.112	0.01
Soil media and topography	-0.132	0.01

Table 15: Statistics on Sensitivity removal of one parameter

Parameter of sensitivity	Minimum	Maximum	Mean	S.D.
D	0	4	1.16	1.042
R	2	7	4.01	0.932
A	0	6	2.83	1.066
S	2	7	4.81	0.779
T	3	7	5.01	0.875
I	0	3	.88	0.819
C	1	7	5.51	0.819

Table 16: Variation index of the excluded parameter in the DRASTIC

	Mean	SD
D	0.199297	0.052779
R	-0.05301	0.036147
A	0.003103	0.050816
S	-0.09352	0.031019
T	-0.10312	0.03617
I	0.174094	0.046773
C	-0.12685	0.02735

Table 17: Statistics of single parameter sensitivity analysis

			Effective weight (%)	
Parameters	Theoretical weight	Theoretical weight (%)	Mean	SD
D	5	21.7	31.3	18.76
R	4	17.4	12.8	12.87
A	3	13	12.6	18.09
S	2	8.7	7.2	11.03
T	1	4.3	5.4	12.87
I	5	21.7	27.3	16.64
C	3	13	3.4	9.74

Sensitivity analysis of the DRASTIC model: The Table 13 presents a statistical summary of the seven rated parameters of the DRASTIC model to workout the vulnerability of groundwater in Yuncheng basin. An examination of the means of the parameters reveals that the highest contribution to the vulnerability index is made by the Depth to water (mean = 7.65) followed by impact of vadoze zone (mean = 7.17). The third place is occupied by the topography (mean = 6.73) followed by the aquifer media which contributes moderately to the vulnerability index (mean = 5.97). The soil media (mean = 3.89), net recharge (mean = 2.97) and hydraulic conductivity (mean = 1.40) contribute least to the contamination of groundwater. The coefficient of variation indicates that a high contribution to the variation of vulnerability index is made by the hydraulic conductivity (75.5%). Moderate contribution is made by the topography (57.2%) and soil media (46.42%), while the least contribution is made by aquifer media (32.89%), net recharge (32.45%), Impact of vadose zone (17.56%) and the depth to water (14.82%).

In order to examine interdependence of rated seven parameters of the DRASTIC model, Spearman's rank order correlations were computed as n (n-1)/2 (where n is the number of parameters = 7), i.e. 7(7-1)/2 =21.

In statistics, when r is close to 0, the dispersion is large and the variables are uncorrelated. As the correlation is a measure of the relationship between two or more variables, the research showed that the relationship between the parameters was very poor and in some cases is almost uncorrelated. Out of the 21 correlations, only 17 (Table 14) are significant at or more than 95% confidence level.

That means the parameters were largely independent and there was very little risk of misadjustment in the final index.

Sensitivity analysis: Table 8 shows the statistics on sensitivity to removal of one parameter on the vulnerability values. The most sensitive parameters to contamination were the hydraulic conductivity, topography, soil media and net recharge followed by the aquifer media and the depth to water. The impact of vadose zone shows the lowest sensitivity value.

In this research the variation index (Vxi) measures the effect of the removal of each parameter. For each DRASTIC parameter, Vxi was computed and the results were presented as shown in Table 16. The (D, A, I) parameters showed a positive variation index indicating that the removal of the parameter decreases the vulnerability index, thereby increasing the calculated vulnerability. Other remaining parameters(R, S, T and C) had negative variation indices indicating that the removal of the parameter increases the vulnerability index, thereby reducing the calculated vulnerability (Ela-Naqa *et al*., 2006).

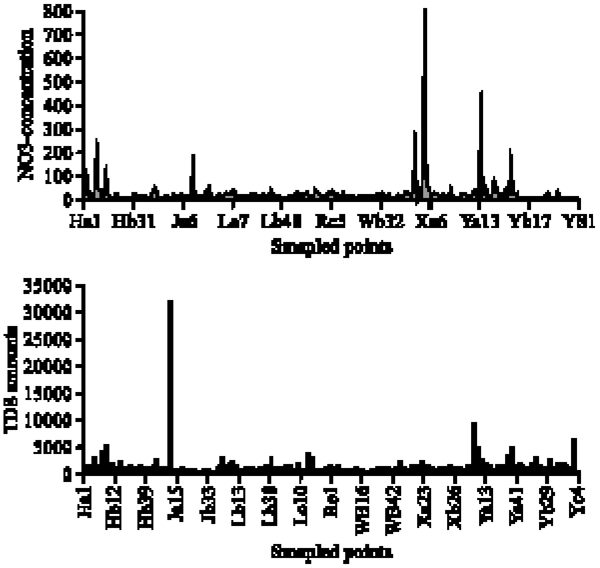

Fig. 3: NO_3^- (mg L^{-1}) and TDS (mg L^{-1}) concentration in yuncheng basin

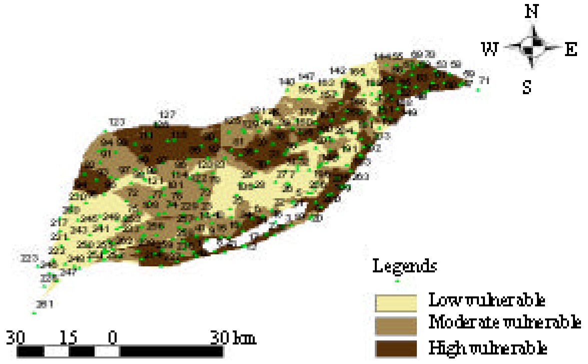

Fig. 4: Vulnerable zones and well location in yuncheng basin

Single parameter sensitivity analysis: The single parameter sensitivity analysis is normally used to compare their" theoretical" weights with that of "effective" weights. The effective weight is a function of value of the single parameter with regard to the other six parameters as well as the weight assigned to it by the DRASTIC model (Babiker *et al*., 2005; Atiqur, 2007). The effective weights of the DRASTIC parameters obtained in this research exhibited some deviation from that of the theoretical weights. Table 17 reveals that the depth and the impact of vadose zone were the most effective parameters in the vulnerability assessment because their mean effective weight, 31.3 and 27.3%, respectively, were higher than their respective theoretical weight. The aquifer media showed that its effective weight (12.6%) and its theoretical weight (13%) were almost equal. The three parameters (R, S and T) showed low effective weights when compared with their theoretical weights. The lowest effective weight was the hydraulic conductivity (3.4%) compared to its theoretical weight (13%). This explains the importance of the depth to water, Impact of vadose zone and topography layers in the DRASTIC model, however it is advised to get the accurate and detailed information on these three specific parameters.

GW contamination analysis: The purpose of this analysis was to assess the relationship between GW vulnerability map and TDS (Total Dissolved Solids) as well as NO_3^- concentration in groundwater of Yuncheng basin. The concentrations of these elements are shown in Fig. 3. It was found out that NO_3^- concentration was 65.5%, which is above the World Health Organization (WHO) maximum acceptable limit in potable waters (10 mg L^{-1}) (Arowolo, 2005), TDS (Total Dissolved Solids) concentration was 66.67% and is above 500 mg L^{-1} which is a desirable limit in drinking water.

The map showing sampled wells locations was overlaid on the vulnerability map (Fig. 4) in order to determine the wells with high concentrations in different vulnerable zones. 27.2% of NO_3^- is located in the low vulnerable zone, 32.4% is located in the moderate vulnerable zone and 40.4% is located in the high vulnerable zone. For TDS 33% is located in the low vulnerable zone, 40.9% is located in the moderate vulnerable zone and 26.1% is located in the high vulnerable zone.

CONCLUSION

In this research, an attempt has been made to assess aquifer vulnerability in Yuncheng Basin. This task was accomplished using the DRASTIC model. The results have shown that a large part of the groundwater in Yuncheng Basin is under moderate vulnerable zones. Based on the results, the vulnerable zones were classified into three zones namely Low, Moderate and high vulnerable zones. The study has showed that 55% of the total area was under the moderate vulnerable zone which is mainly the result of the higher depth (deep), moderate net recharge. About 20.35% of the area was under high vulnerable zone which could be due to the reason that the Southwest part (Yongji County) receives a considerable amount of water from the center plate. The center plate is characterized by a gentle slope and gravel aquifer media which is influenced by a high pollution rating. This is because the gentle slope allows wastewater from household to remain in the area for a long time.

Sensitivity analysis was performed in the study to validate and evaluate the consistency of the parametric methods in the vulnerability assessment. This analysis provides an efficient interpretation of the vulnerability index. Based on the sensitivity analysis, the parameters were found to follow the order Hydraulic Conductivity> Topography>Soil Media>Net Recharge>aquifer media> Depth to Water> Impact of Vadose.

The single parameter sensitivity analysis showed that the depth and the impact of vadose zone were the most effective parameters in the vulnerability assessment because their mean effective weights (31.3% and 27.3%) were higher than their respective theoretical weight. The Net Recharge, Aquifer Media, Soil Media, Topography and hydraulic Conductivity showed low effective weights when compared with their theoretical weights.

The effective-weights analysis is very useful when the user of the vulnerability-assessment method wishes to revise the weights in the chosen equation for computing the vulnerability index. In this case study, the effective weights for each parameter were sometimes different from the theoretical weights assigned by the DRASTIC method.

The DRASTIC model, which is used for preparing the pollution potential map, can be used as a screening tool to assess the degree of GW vulnerability to pollution of a particular area. This delineation allows city planners and administrators to direct their resources to those vulnerable areas, which are the most vulnerable to GW pollution, thereby allocating most of the limited resources available to them. Apart from GW vulnerability assessment, the DRASTIC model can be used for a wide range of applications. It can also be used in prioritization of areas for monitoring purposes. It can help the planners and policy makers when selecting the areas for waste disposal and industrial sites.

The study suggests that the area under high vulnerability should be given special protection measures. The authorities in charge should frequently monitor high vulnerability zone so that the changing level of pollutants can be detected. They should also assess well the water distribution lines so that they can replace the old ones.

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