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A GIS Based DRASTIC Model for Assessing Groundwater Vulnerability in Shallow Aquifer in Hangzhou-Jiaxing-Huzhou Plain, China

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Abstract: Hangzhou-Jiaxing-Huzhou plain is among the regions, which faces the shortage of water due to its increasing population, industrialization, agriculture and domestic use, hence, the high dependence on groundwater. In China, the exploitation of aquifers has been historically undertaken without proper concern for environmental impacts or even the concept of sustainable yield. In order to maintain basin aquifer as a source of water for the area, it is necessary to find out, whether certain locations in this groundwater basin are susceptible to receive and transmit pollution. That is why, the main objective of this research is to find out the groundwater vulnerable zones using DRASTIC model in Hangzhou-Jiaxing-Huzhou plain. Geographical Information System (GIS) is used to create groundwater vulnerability map by overlaying hydro-geological data. The input of the model is provided by the following seven data layers: depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. This study shows that Hangzhou-Jiaxing-Huzhou area is grouped into three categories: High vulnerable zone with 30.4% of the total area, moderate vulnerable zone, which occupy the great part of that area 62.08% and low vulnerable zone with 7.52%. This research suggests, first the prioritization of high vulnerable areas in order to prevent the further pollution to already polluted areas; next the frequent monitoring of vulnerable zones to monitor the changing level of pollutants and finally suggests that this model can be an effective tool for local authorities who are responsible for managing groundwater resources in that area.

Key words: Hangzhou-Jiaxing-Huzhou plain, groundwater vulnerability, GIS, DRASTC model, shallow aquifer

INTRODUCTION

Groundwater pollution is a growing environmental problem in the world, especially in urban areas; in developing countries, it commonly results from indiscriminate disposal of municipal wastes, industrial effluents and agriculture (Mato, 2002). Thorough the world, shallow groundwater near industrial and high intensity agriculture areas is threatened by various contaminated leachates generated by anthropogenic and other sources of pollution (Abraham, 1995). Many regions all over the globe are entirely depending on groundwater resources for the various uses (Babiker *et al.*, 2004). That high dependence on groundwater coupled with industrial and demographic expansion resulted in increasing pressures on available groundwater resources in terms of quantity and quality and contribute significantly to groundwater deterioration and pollution.

Due to high population growth, economic development and industrialization in China, greater amounts of domestic and industrial effluents are discharged and demands on all natural resources, including water is ever-increasing. Hangzhou-Jiaxing-Huzhou plain is among the regions which are more affected. Due to heavy exploitation of groundwater, Hangzhou-Jiaxing-Huzhou was and is suffering from land subsidence, which brought serious environmental problems in numerous ways. As water is pumped out from a confined aquifer, the effective pressure increases and the grains in the porous medium become more tightly packed. With continued pumping of groundwater without adequate recharge, the sediments become increasingly compressed and the land starts to settle or subside. The subsidence can cause land to become inundated and can induce ground water contamination as waters of differing quality infiltrate the aquifers (Changjiang *et al.*, 2006), hence the requirement of vulnerability studies.

Vulnerability assessment to delineate areas that are more susceptible to contamination from anthropogenic sources has become an important element for sensible

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resource management and land use planning (Babiker *et al.*, 2005). The concept of vulnerability of groundwater to contamination was introduced in the 1960s in France and is defined by Babiker *et al.* (2005) as the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system.

Groundwater vulnerability is considered as intrinsic property of groundwater that depends on its sensitivity to humans and natural impacts (El-Naqa *et al.*, 2006). Therefore, vulnerability deals with the hydro-geological settings and does not include attenuation of pollutants. The concept of groundwater vulnerability includes 2 particular notions: intrinsic vulnerability and specific vulnerability. Intrinsic vulnerability refers to the vulnerability of groundwater to contaminants generated by human activities taking into account the inherent geological, hydrological and hydro-geological characteristics of an area but being independent of the nature of the contaminants. Specific vulnerability is used to define the vulnerability of groundwater to particular contaminants or a group of contaminants taking into account the contaminant properties and their relationship with the various components of intrinsic vulnerability (Babiker *et al.*, 2005).

Vulnerability is distinct from pollution risk; pollution risk depends not only on vulnerability but also on the existence of significant pollutant loading entering the sub-surface environment. Secunda *et al.* (1998), defined pollution as addition to water of any substance, which can potentially alter the water's quality so as to decrease its usage value. Groundwater vulnerability studies are useful to evaluate land-use activity with respect to the development of pollution liability insurance and the assessment of economic impacts of disposal costs in highly vulnerable areas. Moreover, it is providing preliminary information and criteria for decision-making in such areas as: designation of land use controls, delineation of monitoring networks and management of water resources in the context of regional planning as related to protection of groundwater quality.

As said (Enrique and Dickerson, 2007), prior to the creation of DRASTIC, few diverse methodologies for evaluating groundwater pollution potential existed and can be grouped into 3 categories:

- Overlay and index methods
- Methods employing process-based simulation models
- Statistical methods

Overlay and index methods and statistical methods have been used for assessments at map scales smaller than 1:50,000 (i.e., a large study area), while methods based on simulation models are at larger map scales (i.e., a small study area). Overlay and index methods and statistical methods are used to assess intrinsic vulnerability, while methods employing process-based simulation models are used to assess specific vulnerability. Schlosser *et al.* (2002) grouped the methods of groundwater vulnerability assessments in statistical/ empirical methods and methods based on solute-transport theory.

In nowadays, vulnerability maps have proved popular tools and are a common feature of groundwater environmental management throughout the world (Connell and Daele, 2003), also groundwater vulnerability maps are effective for identifying locations warranting more detailed groundwater pollution and vulnerability investigations (Thapinta and Hudak, 2003). In recent years, DRASTIC model is highly used to create those maps. It uses 4 major assumptions: the contaminant is introduced at the ground surface, the contaminant is flushed into the groundwater by precipitation, the contaminant has the mobility of water and the area evaluated is 0.4 km^2 or larger (Rundquist *et al.*, 1991).

MATERIALS AND METHODS

Study area: Hangzhou-Jiaxing-Huzhou plain is located between the Yangtze and Qiantang rivers in northern Zhejiang province, south of Shanghai city and Jiangshu province. The total area of the Plain is about 6.490 km^2 (Fig. 1). It is among the regions where economic development and population growth are most rapid in China. Geological and hydrogeological surveys reveal a multi-layered aquifer system beneath the plain, which

Fig. 1: Location of the Hang-Jia-Hu plain in eastern China

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

Data type	Sources	Format	Scale of map	Date	Output layer
Borehole data (water table level)	Zhejiang Information center of land and resources	Table		1970-2007	Depth to water (D)
Average annual rainfall	Meteorological Bureau of Zhejiang Province	Table		1980–2007	Net recharge (N)
Geology map	Department of geology and mineral Resources in Zhejiang Province	Map	1:250000	1970-2007	Aquifer media A)
Soil map	Department of geology and mineral Resources in Zhejiang Province	Map	1:250000	1970-2007	Soil (S)
Topographical map	Zhejiang Information center of land and resources	Map	1:250000		Topography (T)
Geological map	Department of geology and mineral Resources in Zhejiang Province	Map	1:250000	1970-2007	Vadose zone (I)
Hydraulic conductivity	Department of geology and mineral Resources in Zhejiang Province	Table		1970-2007	Hydraulic conductivity

Table 2: Assigned weights for DRASTIC parameters

Factors/hydro-logical settings	Description	Relative weights
Depth to water	It is depth from ground to water table, deeper the water table the chances of pollutants to reach the ground water will be reduced	5
Net recharge	It represents the amount of water that penetrates the ground surface and reaches the water table; it facilitates the transport of contaminant vertically to the water table and horizontally within the aquifer.	4
Aquifer media	Refers to the sutured zone material properties which controls the pollutant attenuation	3
Soil media	Refers to that uppermost portion of the vadose zone characterized by significant biological activity, soil cover characteristics influence the surface and downward movement of contaminants	2
Topography	Topography refers to the slope variability of land surface. It helps to control the likelihood that a pollutant will run off or remain on the surface in one area long enough to infiltrate	1
Impact of vadose zone	It is the ground portion found between the aquifer and the soil cover in which pores or joints are unsaturated, its influence on aquifer pollution potential similar to that of soil cover, depending on its permeability and on the attenuation characteristics of the media	5
Hydraulic conductivity	It refers to the ability of the aquifer formation to transmit water, therefore it determines the flow rate of contaminant through the aquifer	3

includes Holocene phreatic water layers and Pleistocene confined aquifers and it is highly affected by ground subsidence (Changjiang *et al*., 2006).

Located in the subtropical monsoon zone, the weather in the Hang-Jia-Hu Plain is mild and humid with four seasons, with plenty of rainfall. It has fertile land and rich products hence the name land of fish and rice, because the Yangtze river delta is an important grain production base. The population of Hangzhou-Jiaxing-Huzhou plain accounted 19.35% of the total population of Zhejiang province while the corresponding gross domestic product accounted 30.64% of that of the Zhejiang province. The exploitation of groundwater for domestic and industrial water consumption in production account for 54 and 46% and in the summer from June to September peak period for the mining, it account for 40-60% (Changjiang *et al*., 2006).

The major pollutants found in that area are: Mn, nitrite, total Fe, solids, total hardness and ammonia. Mn occupy the first place with the concentration of about 55.56%, followed by nitrite and total Fe, 40%.

Contamination of groundwater has become a major concern in recent years. Since, testing of water quality of all domestic and irrigation wells within large watersheds is not economically feasible, one frequently used monitoring strategy is to develop contamination potential maps of groundwater and then prioritize those wells located in the potentially highly contaminated areas for testing of contaminants (Dixon, 2005). Therefore, in the present study the DRASTIC method, a standard system for evaluating GW pollution potential is used. DRASTIC methodology was developed in the United States under cooperative agreement between the National Water Well Association (NWWA) and the USA Environmental Protection Agency (EPA) for detailed hydro-geologic evaluation pollution potential and is a model used to spatially and comparatively display high vulnerability areas in contrast to low vulnerability areas with respect to the potential to pollute groundwater (Dixon, 2005). It is probably, the most widely used tool for vulnerability mapping. DRASTIC model incorporates the most important hydrogeologic factors that affect the potential for groundwater pollution (Rundquist *et al*., 1991). Depth to water table (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone media (I) and hydraulic Conductivity (C), hence the name DRASTIC. The data used and weights assigned to each parameter are presented in the Table 1 and 2.

As said Kim and Hamm (1999), DRASTIC model allows the designation of hydrogeologic settings within the study area, based on a composite description of all the major geologic and hydrogeologic factors for each setting. Then a scheme for relative ranking of the hydrogeologic factors is applied to evaluate the relative vulnerability to groundwater contamination of each hydrogeologic setting. DRASTIC method is composed of 2 major parts: The designation of mappable units, termed hydro-geologic setting and the application of a numerical scheme of relative ranking of hydro-geologic factors as shown in the Table 2. This model is based on 3 components (weight, range and rating) that are expressed numerically. A weight was assigned to each DRASTIC

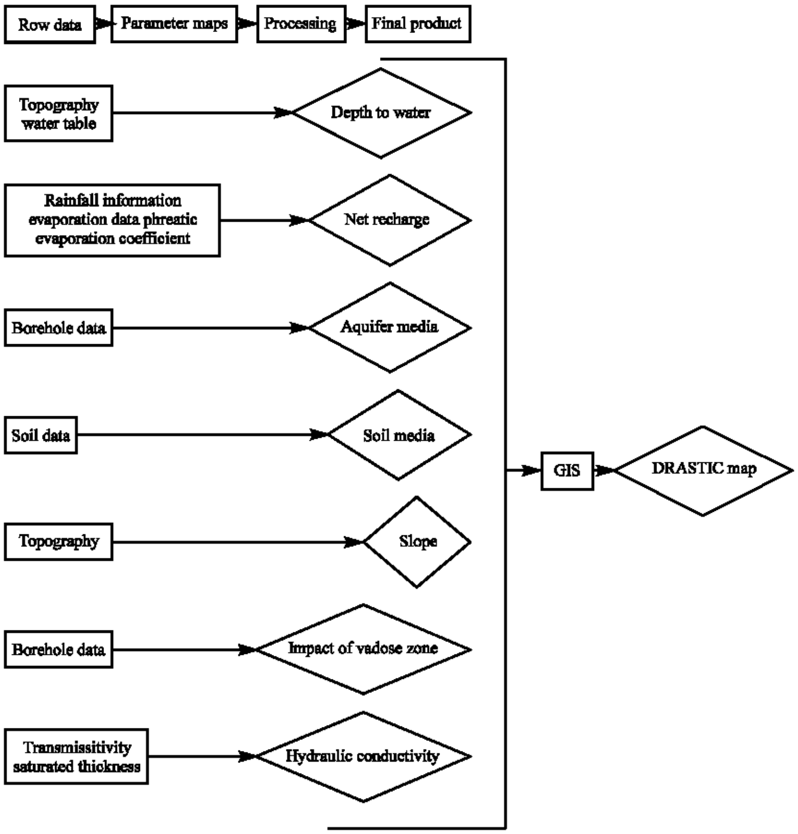

Fig. 2: Flow chart of methodology for ground water vulnerability analysis using DRASTIC model in GIS

feature in accordance with its relative importance. The weights range from 5-1 (most significant) to one (least significant). The range component divides each DRASTIC feature into several classes, or significant media types, which may affect the potential for pollution (Enrique and Dickerson, 2007). The rating assigns each class a value, based on a scale of one (least contamination potential) to 10 (high contamination potential). After assigning to each parameter the weight and rating, we determined the drastic index using the following Eq. 1:

$$D_RD_W + R_RR_W + A_RA_W + S_RS_W + T_RT_W + I_RI_W + C_RC_W = \text{DRASTIC index} \quad (1)$$

where, R is rating and W represents weight assigned to each parameter (Kalinski *et al.*, 1994). Once, a DRASTIC index has been computed, it is possible to identify areas that are more likely to be susceptible to groundwater contamination. The higher the DRASTIC index is, the greater the groundwater contamination potential (Fritch *et al.*, 2000). The flowchart methodology is shown in the Fig. 2.

Sensitivity analysis: As said by Surajit *et al.* (2007), vulnerability analysis is subjective in nature. Therefore, to avoid subjectivity sensitivity analysis was carried out. Sensitivity analysis characterizes the distribution of both individual variables and input parameter, on the resultant output of an analytical model (Surajit *et al.*, 2007). Sensitivity analysis provides valuable information about the influence of rating values and weights assigned to each parameter and helps hydro-geologists to judge the significance of subjective elements (Al-Adamat *et al.*, 2003). In that case, 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). Two sensitivity tests were carried out: The map removal sensitivity analysis and the single parameter sensitivity analysis (Lodwick *et al.*, 1990). These 2 tests have also, been used by the (Babiker *et al.*, 2005). The 1st test identifies, the sensitivity of vulnerability map by removing one or more layer maps and is worked out using the Eq. 2:

$$S = (|V/N - V'/n|/V) \times 100 \quad (2)$$

where:

S = The sensitivity measure

V and V' = The unperturbed and the perturbed vulnerability indices, respectively

N and n = The number of data layers used to compute V and V'

The unperturbed vulnerability index is the actual index obtained by using all 7 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 parameters of the model on the vulnerability measure. During this analysis, the comparison of real or effective weight of each parameter and its assigned or theoretical weight has been done. The effective weight of a parameter in a sub-area was calculated using Eq. 3:

$$W = (Pr\ Pw/V)\times 100 \qquad (3)$$

where:

W = Refers to the effective weight of a parameter in a polygon

Pr and Pw = The respective rating and weight of that parameter, respectively

V = The overall vulnerability index of that polygon

Groundwater contamination was carried out by taking water samples from 50 wells (August 2007) and tested manganese and NO_3^-. The aim of that analysis was to compare the experimental results with the contamination vulnerability levels as shown by overall vulnerability map prepared using the DRASTIC model.

RESULTS AND DISCUSSION

Depth to water: Depth to water is an important factor because it determines the depth of material through, which a contaminant must travel before reaching the water table in an aquifer. In general, the aquifer potential protection increases with depth to water. Depth to water was calculated using: Land-surface topography and water-table-surface topography both available at the scale of 1:250,000. During that process, the subtraction of the groundwater level from the elevation map was performed.

As indicated in Table 1, the elevation of the well and the mean water level table from 1970-2007 is available and has been used in that computation. The Raster calculator from analyst tool was used to perform the above operation.

Table 3: Depth to water

Ranges (m)	Rating	Index
<1.5	10	50
1.5-5	9	45
>5	7	35

Weight = 5

The point data were contoured by interpolating and divided into 3 categories i.e., <1.5, 1.5-5 and >5 m. Thereafter, it was converted into grid to make it raster data for GIS operation.

The depth to water table map was then assigned rates ranging from 1 (minimum impact on vulnerability) to 10 (maximum impact on vulnerability), i.e., the deeper the groundwater implies the smaller rating value, because the pollutants have a long distance to travel before reaching groundwater. This means that areas with high water tables are more vulnerable. The depth-to-water table interval range, DRASTIC rating, weight and resulting index are shown in Table 3.

Net recharge: Net recharge is the amount of water from precipitation and artificial sources available to migrate down to the groundwater. Recharge water is, therefore, a significant vehicle for percolating and transporting contaminants within the vadose zone to the saturated zone. It carries the solid and liquid contaminants to the water table and also increases the water table. Hangzhou-Jiaxing-Huzhou plain is located in the subtropical monsoon climate zone latitude, mild climate, 4 seasons with abundant rainfall; hence, the net recharge is a very important factor in this study. Net recharge results were obtained using the Eq. 4:

$$N = (R-E)\times r \qquad (4)$$

where:

N = The net recharge

R = Rainfall

E = Evaporation

r = Recharge rate

Net recharge ranges, DRASTIC rating, weight and resulting index are shown in Table 4.

Aquifer media: Aquifer media is the potential area for water storage, the contaminant attenuation of aquifer depends on the amount and sorting of fine grains, higher the grain size, lower the attenuation capacity of aquifer media and consequently, the greater the pollution potential. An aquifer media map was prepared from the well log data and topographical maps. Ranges, rating and resulting index are presented in Table 5.

Table 4: Net recharge

Ranges (mm year^{-1})	Rating	Index
0-50	1	4
50-100	3	12
100-180	6	24
180-250	8	32
>250	9	36

Weight = 4

Table 5: Aquifer media

Aquifer	Rating	Index
Fine sand	4	12
Middle sand	6	16
Coarse sand	8	24
Gravel	9	27

Weight = 3

Table 6: Soil

Soil media	Rating	Index
Clay	1	2
Clay loan	5	10
Sand loan	6	12
Coarse sand	9	18

Weight = 2

Soil: Soil media refers to that uppermost portion of the vadose zone characterized by significant biological activity. Soil has a significant impact on the amount of recharge that will infiltrate into the ground and hence on the ability of a contaminant to move vertically into the vadose zone. The soil grain size and macro-pores, which are controlled by the amount of clay which is present in soil affect mainly the soil pollution potential of any place. This means that the presence of fine grain size materials and the percentage of organic matter within the soil cover can decrease intrinsic permeability and retard or prevent contaminant migration via physico-chemical processes (Table 6).

Topography: Refers to the slope variability of land surface. Topography helps to control the likelihood that a pollutant will run off or remain on the surface in one area long enough to infiltrate.

Steep terrain will help to control runoff of pollutants and their infiltration into the groundwater, hence, the less vulnerability to groundwater contamination, while areas with low slope tend to retain water for longer period of time, which allows a greater infiltration or recharge of water and a greater potential for contaminant migration. In this research, slope percentages have been calculated using arcGIS and grouped into 5 classes as shown in the Table 7.

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

Table 7: Topography

Slope (%)	Rating	Index
0-2	10	10
2-6	9	9
6-12	5	5
12-18	3	3
>18	1	1

Weight = 1

Table 8: Impact of vadose zone

Range	Rating	Index
Hard clay	1	5
Medium sand	6	30
Coarse sand	8	40
Gravel	9	45

Weight = 5

Table 9: Hydrologic conductivity

Range	Rating	Index
>20	2	6
20-40	4	12
40-60	6	18
60-80	8	24
>80	10	30

Weight = 3

The vadose zone has a high impact on water movement if it is composed with permeable material i.e., the impact of vadose zone implies that less permeable confining layers improve ground water protection. The weight, ratings and resulting index for the vadose zone are shown in Table 8.

Hydrologic conductivity: Refers to the aquifer's ability to transmit water; an aquifer with high conductivity is more vulnerable to contamination because contaminants can move easily through the aquifer. Hydraulic conductivity values were obtained from published hydrologic reports and have been classified in 5 classes as shown in the Table 9.

Based on the results presented in the Table 10 and sensitivity map (Fig. 3), of the total of 6490 km^2 an area of 488.05 km^2 is in the low vulnerable zone with a DRASTIC index range between 80-109, about 4028.99 km^2 are in the moderately vulnerable zone with a DRASTIC index ranging between 110 and 139 and about 1972.96 km^2 are in the high vulnerability zone with a DRASTIC index ranging between 140-190, it means that more than half of the Hangzhou-Jiaxing-Huzhou groundwater is at moderate risk in terms of pollution potential; this is mainly the result of moderate net recharge, hydraulic conductivity and lithology of that area.

Sensitivity analysis: The analysis of the means of the parameters shows that the highest contribution to the vulnerability index is made by net recharge (mean = 9)

Table 10: Area under different vulnerability to groundwater pollution in Hangzhou-Jiaxing-Huzhou

DRASTIC index value	Area (km^2)	Area (%)	Vulnerability zones
80-109	488.05	7.52	Low
110-139	4028.99	62.08	Moderate
140-190	1972.96	30.40	High
Total	6490.00	100.00	

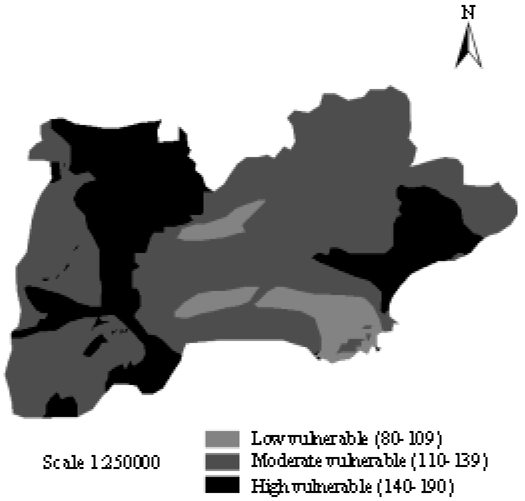

Fig. 3: Groundwater vulnerable zones in Hangzhou-Jiaxing-Huzhou

closely followed by depth to water (mean = 8). The 3rd place is occupied by topography (mean = 7.5). Soil media whose mean value of 5.5 and impact of vadose zone, which has the mean of 6, contribute moderately to the vulnerability index, while the contribution of aquifer media and hydraulic conductivity to the contamination of GW, having, respectively mean values of 4.5 and 4.2 is low. The coefficient of variations reveals that a high contribution to the variation of vulnerability index is made by aquifer media (64.4%) and hydraulic conductivity (61.9%), moderate contribution is made by impact of vadose zone (53.3%), topography (50.6), soil media (47.2%), while the lowest contribution is made by depth to water (31.2%) and net recharge (23.3%) (Table 11).

Spearman's rank order correlations were computed using the following formula n (n-1)/2 (where, n is the number of parameters = 7), i.e., 7(7-1)/2 = 21, for testing the interdependence of rated seven parameters of the DRASTIC model. According to Rosen (2005), the independency of DRASTIC parameters decreases the probability of misjudgment. Correlation is a measure of the relationship between 2 or more variables and when r is closer to 0, it means that the dispersion is large and the variables are uncorrelated. Our research showed that the relationship between the parameters was very poor and in some cases is almost uncorrelated. Out of the 21 correlations, only 3 (Table 12) are significant at or >95% confidence level and these correlations may be due to chance that means that the parameters were largely independent and there was very little risk of misadjustment in the final index.

Table 11: Statistical summary of the DRASTIC parameters' map

	D	R	A	S	T	I	C
Min	2	6	4	5	1	4	1.0
Max	16	12	9	8	8	10	9.0
Mean	8	9	4.5	5.5	7.5	6	4.2
SD	2.5	2.1	2.9	3	3.8	3.2	2.6
CV (%)	31.2	23.3	64.4	47.7	50.6	53.3	61.9

SD: Standard Deviation; CV: Coefficient of Variation

Table 12: Summary of rank-order correlation analysis result between seven DRASTIC parameters

Correlated parameters	Correlation coefficient r	Significance level p
D and S	0.81	<0.0050
D and T	0.91	<0.0001
S and T	0.81	<0.0050

Table 13: Map removal sensitivity analysis

Parameters removed	Variation index (%) Min.	Max.	Mean	SD
D	0	15	9	2.3
R	0	20.4	10.6	3.2
A	1	8.5	4.2	2.4
S	6	11	5.5	2.1
T	2	16.1	8.9	1.2
I	1	14.3	4.8	1.3
C	2	14.2	6.1	2.5

Table 14: Statistics of single parameter sensitivity analysis

Parameters	Theoretical weight	Theoretical weight (%)	Effective weigh Mean (%)	SD
D	5	21.7	23.4	4.6
R	4	17.4	25.1	5.7
A	3	13.0	9.2	7.2
S	2	8.7	5.9	3.1
T	1	4.3	9.4	2.8
I	5	21.7	18.5	5.4
C	3	13.0	8.5	4.6

Table 13 shows that the most sensitive parameters to contamination were net recharge, depth to water, topography, hydraulic conductivity, soil media followed by impact of vadose zone. The impact of aquifer media shows the lowest sensitivity value. The map removal analysis shows that there is a clear variation in vulnerability index because of removing a layer at a time. This can be because of high theoretical weight assigned to the removed layer.

Single parameter sensitivity analysis: The single parameter sensitivity analysis is normally used to compare theoretical weights with effective weights. The effective weights of the DRASTIC parameters obtained in this research exhibited some deviation from that of the theoretical weights. This analysis shows that net recharge and depth to water layer tend to be the most effective parameters in the vulnerability assessment because their mean effective weights, 25.1 and 23.4%, respectively, are

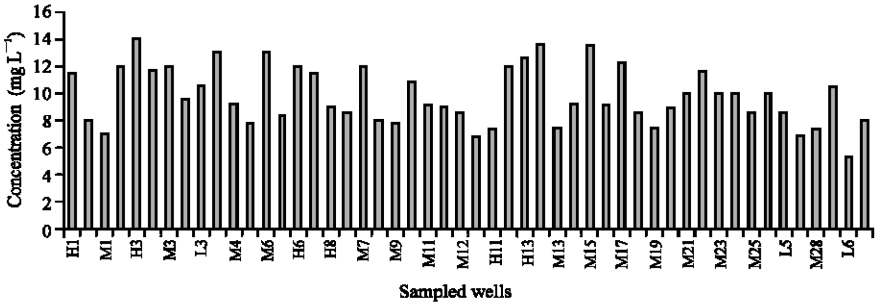

Fig. 4: NO_3^- concentration in different wells

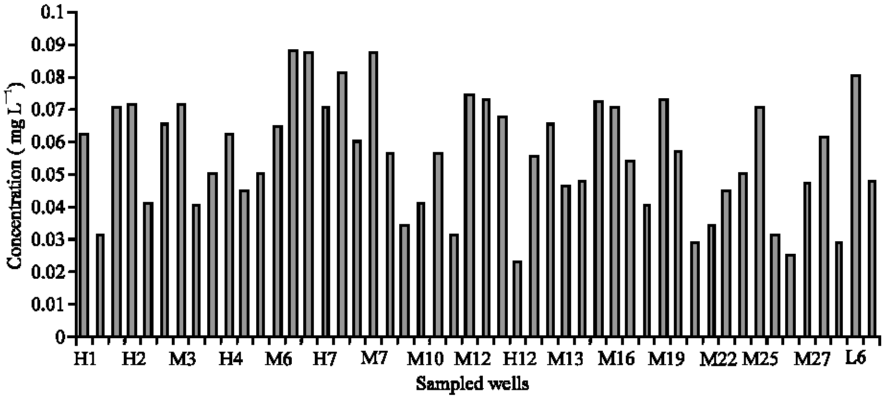

Fig. 5: Mn concentration in different wells

higher than their respective theoretical weights 17.4 and 21.7%. Also, Topography 9.4% has higher effective weight when compared to its theoretical weight, which is 4.3%. The remaining layers show lower effective weights when compared with their theoretical weights. This shows the importance of net recharge, depth to water and topography layers in the DRASTIC model (Table 14).

Contamination analysis: As shown in Fig. 4, out of 50 wells 21 wells have high concentration of NO_3^- and 10 of them are located in the high vulnerable zones, 9 are located in the moderate vulnerable zones and 2 are located in the low vulnerable zone. For manganese, 28 wells have concentrations above the accepted level of EPA >0.05 L^{-1}. Among those wells 12 are located in the high vulnerable zones and 16 remaining are located in moderate vulnerable zones (Fig. 5). Hence, these experiments supplement the results obtained by the DRASTIC model.

CONCLUSION

As described by Al-Adamat *et al.* (2003), vulnerability maps are designed to show areas of greatest potential for groundwater contamination on the basis of hydro-geological conditions and human impacts. In this study, output map has been created using the DRASTIC model and GIS in order to determine the vulnerability of GW pollution in shallow aquifers in Hangzhou-Jiaxing-Huzhou plain.

The results revealed that a large part of the groundwater in Hangzhou-Jiaxing-Huzhou plain is under moderate vulnerable zones. In this plain, the vulnerable zones were classified into 3 zones namely low, moderate and high vulnerable zones.

The study shows that 30.4% of the total study area is under high vulnerable zone, which is mainly as a result of the low slope, short depth to water table and plenty recharge from rainfall, Tiaoxi River, great channel and Tai lake. The high vulnerable zone is mainly in Huzhou and Hangzhou cities, where chemicals and other wastes are discharged into open drains from the lock, brass, household and industries, which has led to the pollution of shallow aquifers. For the high, vulnerable part which is in Haiyan, it may be caused by the fertilizers used in agriculture because that region is an important grain production bases hence the name land of fish and rice. Also, this study showed that the major part, 62.08% of the total area was under the moderate vulnerable zone, which is mainly the result of moderate net recharge in the major part of the plain, hydraulic conductivity and lithology of that area. In the Hangzhou-Jiaxing-Huzhou, this research showed that about 7.52% is under low vulnerability.

This study provides, a very valuable tool for environmental managers in Hangzhou-Jiaxing-Huzhou region, because it gives a very comprehensive indication of vulnerability to GW contamination. The high vulnerable zones call local authorities for managing GW resources, monitoring this problem closely and to act accordingly. The vulnerability map produced in this study shows clearly areas that need to be closely monitored, as well as those areas, which are less likely to become contaminated and require less intensive monitoring.

In this study, we found that DRASTIC model map is correlated with contaminant analysis data and sensitivity analysis was performed in order to validate and evaluate the consistency of parameters used in the DRASTIC model. Based on the sensitivity analysis, the parameters were found to follow the order net recharge, depth to water, topography, impact of vadose zone, soil media, aquifer media and hydraulic conductivity. The single parameter sensitivity analysis showed that net recharge, depth to water and Topography tend to be the most effective parameters in the vulnerability assessment because their mean effective weights are higher than their respective theoretical weights. Others showed the inverse.

Our study suggests, the prioritization of vulnerable areas in order to prevent the further pollution to already more polluted areas. Also, there is a need to carry out a detailed and frequent monitoring in high and moderate vulnerable zones in order to monitor the changing level of pollutants.

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