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Development of an Index of Aquifer Water Quality within GIS Environment

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Abstract

The changes in human population often correspond with change in land use, including expansion of urban areas, agriculture and increasing industrialization, which necessitate increasing the available amount of drinking water. As the surface water sources are under the pressure of pollution, it has become necessary to use groundwater at an increasing rate. Groundwater recharge can be abundant in the alluvial plains where the urban areas are often located. Such areas can face danger of pollution of groundwater and the changes in land use are likely to result in change in groundwater quality. Keeping these aspects in view, it was planned to development a groundwater water quality index in the Ganga-Yamuna interfluve area of northern India, The objective of the present study is to develop the Index of Aquifer Water Quality (IAWQ) inside the Geographic information system (GIS) environment, which can be used by the field investigators and modeler's in assessing the groundwater vulnerability. The formula to estimate the IAWQ index is adopted from the procedure suggested Melloul and Collin (1998). The procedure developed for this involves weights assigned to these 8 parameters as per their analytical hierarchy in violating the (drinking water) standards and not as an arbitrary means (as taken by Melloul and Collin). The suggested procedure can be extending to include more number of chemical parameters as necessitate in individual case studies. In the modified procedure presented in the present study, the number of measured chemical parameters n is taken as 8 (Cd, Mn, Pb, Fe, NO3-, Total Alkalinity, TDS and Ca2+) as against n=2 (chloride and nitrate) as taken in the Melloul and Collin's work.

Keywords: *GIS , Water Quality Index, Hydrogeology, Groundwater.*

1. Introduction

India's average annual precipitation is nearly 400 million hectare meter (mha-m) of which only 50 mha-m enters the groundwater table. Groundwater in India is used for several purposes including drinking water and agricultural municipal and industrial supplies. The changes in human population often correspond with change in land use, including expansion of urban areas, agriculture and increasing industrialization, which necessitate increasing the available amount of drinking water. As the surface water sources are under the pressure of pollution, it has become necessary to use groundwater at an increasing rate. Groundwater recharge can be abundant in the alluvial plains where the urban areas are often located. Such areas can face danger of pollution of groundwater and the changes in land use are likely to result in change in groundwater quality. Keeping these aspects in view, it was planned to development a groundwater water quality index in the Ganga-Yamuna interfluve area of northern India, in the upper part of the Ganga-Yamuna interfluve, and it is considered to be the major recharge zone for the deep aquifers.

2. The Objective

The objective of the present study is to develop the Index of Aquifer Water Quality (IAWQ) inside the Geographic information system (GIS) environment, which can be used by the field investigators and modeler's in assessing the groundwater vulnerability.

3. Study Area

The study area in which the IAWQ model was applied falls in the northern part of the vast Indo – Gangetic Plain in India and lies between latitudes 29^o 33' 51" to 30^o 19' 10" N and longitudes 77^o 06' 20" to 78^o 20' 15" E with total geographical area of approximately 5500 km2 Figure 1. The study area is bounded in its north by Siwalik Hill Range, in the east by the River Ganga and to the west by the River Yamuna (the main tributary of the river Ganga). Both the rivers are perennial in nature. The area slopes down along the north-east to the south-west direction with

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the maximum altitude of 1000m of Siwalik Hill Range in the north and the minimum altitude of 250m in the southern parts near the flood plains of the rivers Ganga and Yamuna. In addition to the rivers Ganga and Yamuna, the study area is drained by the rivers Solani (a tributary of the river Ganga) and Hindon (a tributary of the river Yamuna) and the canals emerging from the rivers Ganga and Yamuna. The flow direction of the drainage network is mainly along the north south direction. Administratively, the study area covers the districts of Hardwar in Uttaranchal and Saharanpur in Uttar Pradesh, and has a population of about 4.3 Million as per Census of 2001. The area is covered under the Survey of India Toposheets No. 53(G/1, G/2, G/5, G/6, G/9, G/10, G/13, G/14, K/1, K/2, F/8, F/11, F/12, F/15, F/16, J/4) on the scale 1:50,000. The climate of the area is humid and subtropical. The rains occur mainly during July to middle of September with annual average rainfall of about 1000 mm.

4. Methodology

The formula to estimate the IAWQ index is adopted from the procedure suggested Melloul and Collin [1]. In their study, Mellol and Collin examined the IAWQ for chloride and nitrate parameters to assess salinity and pollution in groundwater. The pollution weight for nitrate is taken arbitrarily as twice that of the chloride. In the present study, the scenario suggested by Mellol and Collin is extended to include major ions and heavy metals in the foothill region where groundwater is expected to be fresh. As the numbers of chemical parameters are increased from 2 to 8, the equation is appropriately modified to extend for 8 parameters. The procedure developed for this involves weights assigned to these 8 parameters as per their analytical hierarchy in violating the (drinking water) standards and not as an arbitrary means (as taken by Melloul and Collin). The suggested procedure can be extending to include more number of chemical parameters as necessitate in individual case studies. In the case of Melloul and Collin, the water standard is taken as per the WHO where as in the present study this is considered as per the Indian Standards (BIS: 10500) [4,5,6,7]

The IAWQ index estimated for the study area is analyzed using GIS based thematic map to investigate groundwater vulnerability for the pollution.

4.1 The formulation of index of aquifer water quality (IAWQ)

According to Melloul and Collin (1998), IAWQ can be expressed as a summation of weights multiplied by respective ratings of various parameters i for each cell j and is given as follows:

$$IAWQ = C/n\left[\sum_{i=1}^{n}\left(Wri.Yri\right)\right] \quad \text{............ (1)}$$

Where: C= a constant used to ensure desired range of numbers (taken as 10); i the chemical parameters and n= number of parameters. Wri= the relative value of Wi/Wmax , where Wi is a weight for any given parameter and Wmax is the maximum possible weight (taken as 5) The weight is a numerical value given to a parmeter to characterize its relative anticipated pollutant impact; lower numerical values define lower pollution potential and vice versa. Higher value of Wi indicates toxic groundwater quality. Yri = the value of Yi/Ymax; where, Yi is the rating value for the ith chemical parameter from the regression equation given by;

$$Yi = -0.712Xi^2 + 5.228Xi + 0.484 \quad \text{....... (2)}$$

$$\text{Where: } Xij = Pij / Pid \quad \text{................(3)}$$

Where: Pij is (field data value parameter i in cell j) and Pid is the standard value of this parameter as per the desired water quality (drinking or irrigation etc.)

Yi, the relative pollution level is taken in a scale range of 1-10. When Pij=Pid the Yi=5. For unacceptable groundwater quality $Pi=3.5xP_{id}$. At this value Yi = 10. Therefore, Ymax=10

Thus, from a measured parameter value Pi, Standard Limit P_{id}, parameter weight W_i, number of parameters n (and C=10) IAWQ can be estimated.

In the modified procedure presented in the present study, the number of measured chemical parameters n is taken as 8 (Cd, Mn, Pb, Fe, NO^{3-}, Total Alkalinity, TDS and Ca^{2+}) as against n=2 (chloride and nitrate) as taken in the Melloul and Collin's work. The chemical parameter pollution index, Wi is given value within a range 0 to5 using the Analytic Hierarchy Process (AHP) suggested by Saaty [2,3] as described in the Section and not in arbitrary manner.

4.2 Measurement of Chemical Parameters

The study area has been mapped using Arc View 3.2 GIS environment. Various layers related to rural, urban, forest, surface water bodies, drainage network have been prepared using the Survey of India toposheets at 1:50,000 scale and LISS-III data of India Remote Sensing (IRS) satellite imagery.

The water sampling for the present study was done during November-December 2003 through extensive field surveys. The water samples (136 Nos.) were procured from various sites well distributed all over the study area covering all the land use parts. In the field inventory, shallow hand pumps were used in sampling the top aquifer as these are expected to be the first to get affected for any surface pollution and therefore easy to assess the effectiveness of the area for the groundwater pollution. EC and pH were measured on site during the sample collection. The EC in the area varies from 175μS/cm to 1530μS/cm with the median

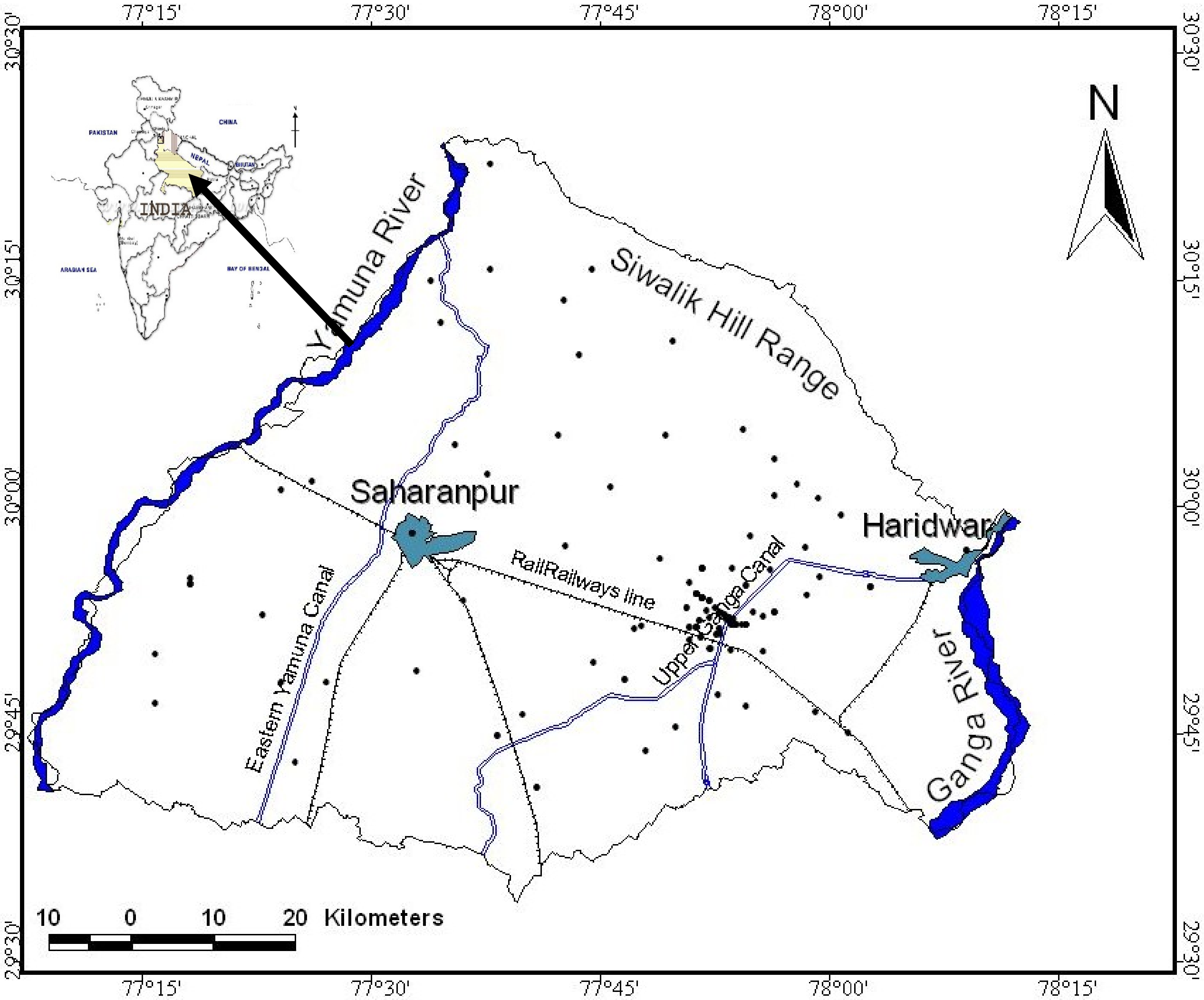

Fig.1. Index map of the study area.

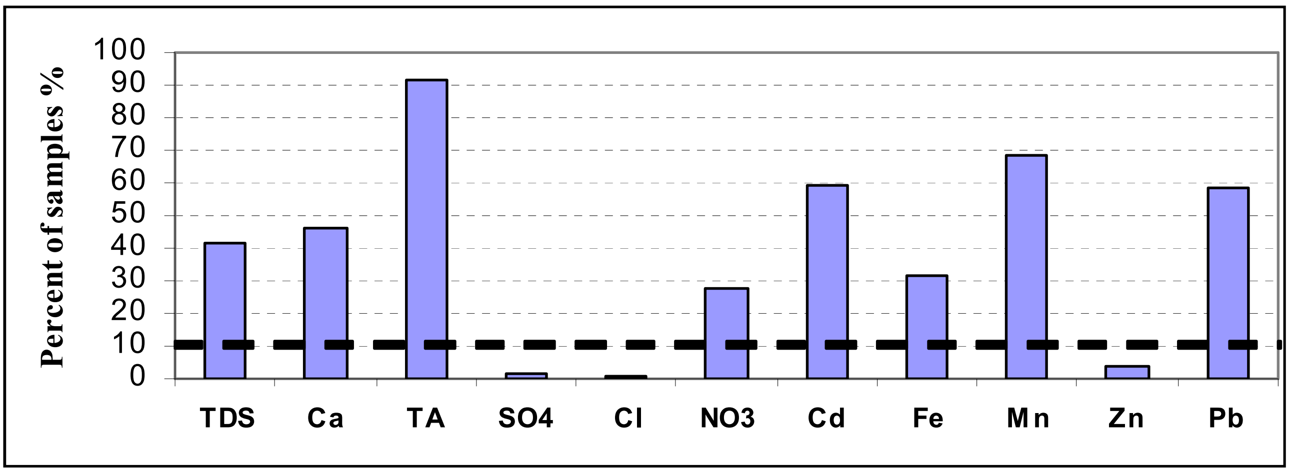

Fig. 2 Comparison against water quality standard.

Table 1. Statistical summary for the water quality data.

Characteristics	No of sample	Min	Max	Mean	Median	STD.
Physical properties						
pH, (standard units)	136	7.01	8.90	7.75	7.71	0.47
Specific conductance, (mS/cm)	136	175	1530	751	677	302
Total dissolved Solid, (mg/L)	136	117	1002	491	437	199
Major ions (Dissolved) (mg/L)						
Calcium (Ca^{2+})	136	7.6	180.0	79.8	71.7	35.5
Magnesium (Mg^{2+})	136	2.4	86.0	27.4	24.3	14.3
Potassium (K^+)	136	0.4	38.8	5.0	4.0	5.0
Sodium (Na^+)	136	3.0	189.0	37.0	29.8	29.8
Biocarbonate (HCO_3^-)	136	74.0	695.5	348.5	330.0	121.0
Carbonate (CO_3^{2-})	136	0.0	19.2	0.6	0.0	1.7
Sulphate (SO_4^{2-})	136	2.9	380.6	43.5	29.2	46.3
Chloride (Cl^-)	136	1.0	259.9	46.5	29.5	51.8
Flouride (F^-)	136	0.0	1.6	0.3	0.3	0.2
Nutrients (mg/L)						
Nitrate(NO_3^-)	136	2.07	335.00	34.11	11.65	47.88
Phosphate (PO_4)	136	0.0001	0.0744	0.0058	0.0040	0.0084
Organic (mg/L)						
Total organic carbon (TOC)	136	0.0000	69.3500	1.3967	0.0000	8.5361
Metals (Total) (µg/L)						
Cadmium (Cd)	136	ND	157.0	49.2	28.0	51.4
Iron (Fe)	136	ND	1233.0	248.1	166.0	265.4
Manganese (Mn)	136	ND	1898.0	357.9	247.0	385.8
Nickel (Ni)	136	ND	ND	ND	ND	ND
Zinc (Zn)	136	ND	16030.0	1080.0	418.5	2076.7
Lead (Pb)	136	ND	599.0	109.0	96.0	113.9
Chromium (Cr)	136	ND	ND	ND	ND	ND
Copper (Cu)	136	ND	ND	ND	ND	ND

at 697µS/cm suggesting that the groundwater is suitable for drinking purpose as per the Indian Standards (IBS: 10500) [4,5,6,7]. The pH in the study area varies from 7.01 to 9.00 with a median at 7.71 suggesting semi-alkaline nature of the groundwater.

The pollution in groundwater can be due to major cations/anions or due to metals ions. In the present study, the chemical parameters that were considered to assess the pollution in groundwater are; TDS, major caions/anions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, CO_3^{2-}, F^-), pollution from excessive use of fertilizers (NO_3^-, PO_4^{3-}), and heavy metals (Cd, Fe, Mn, Ni, Zn, Pb, Cr, Cu). In the measurement of chemical parameters, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-} and Cl- were measured by titration method; Na^+ and K^+ using flame photometer; F^- and NO_3^- by Selective Ion Analysis; PO_4 using spectrophotometer and heavy metals using ICP-MS technique. The statistical summary of the water quality data is shown in table 1. It may be noted that for the purpose of the model analysis, the data for the entire sample set along with its spatial distribution is considered.

4.3 Application of AHP: Calculation of the IAWQ Parameter Weights

The eight water quality parameters selected for computing the IAWQ index were classified in five groups on the basis of the human health significance of these parameters Table 3. The first group was considered relatively the most important, whereas the last group, the least important on the basis of available reports and references. As per the relative importance scheme of the AHP the criteria of these parameters were transferred as input values for the AHP matrix Table 4.

The eigenvalue (column 9 of the Table 4) were normalized to obtain the priority (pollution impact) vector or relative unit vector. The highest priority vector was given a weight 5 (due to the need of rescaling as per the 0-5 scale of IAWQ) and weights of the other chemical parameters were deduced accordingly. The final weights, Wi, to be used in IAWQ model are given in the column 11 of the Table 4.

4.4 Calculation of the Final IAWQ Map Using GIS

The process of calculation of IAWQ index has been explained below:

- The geographic distribution (under GIS) of the aforementioned eight parameters was prepared.
- The Xj values were calculated for each cell (j) based upon equation 1 and using the geographic distribution of the parameters by using the spatial analyst extension in software ArcView GIS; where Cd_d, Mn_d, Pb_d, Fe_d, $NO^{3-}{}_d$, TA_d, TDS_d and $Ca^{2+}{}_d$ are desired Indian standards for drinking water Table 2.
- All the cells having values of Xij equal or more than 3.5 were given a value 3.5 using the map query tool in ArcView GIS and the final map for each parameter was prepared Figure 3.

Table 2. Normalized data.

Parameter	Percent of samples exceeding the Indian standard	Indian water quality standard
TDS	41.2	500
Ca^{+2}	46.3	75
TA	91.2	200
SO_4^{-2}	1.5	200
Cl^-	0.7	250
NO^{3-}	27.9	45
Cd	59.6	10
Fe	31.6	300
Mn	68.4	100
Zn	3.7	5000
Pb	58.8	50

- The Yi values were calculated for each cell based upon equation 2 and the Yi maps were prepared for each parameter. Subsequently, maps of Yri cell values for each parameter were prepared by dividing the Yi values by the values 10 (Ymax).
- Wri values in cells for each parameter were calculated based upon the weight values (from column 11 of Table 4) divided by 5 (Wmax). New maps were prepared for each parameter by multiplying the Yri values by the values of Wri.
- The final values of the IAWQ were calculated by employing equation 1, whereas the values arrived at after summation of the eight maps (Yri x Wri) were multiplied by the value 1.25 (C/N; where C=10 and N=8).
The final IAWQ map is shown in the Figure 4.

5. Discussion

The IAWQ model calculated for eight parameters Cd, Mn, Pb, Fe, TA, NO3-, TDS and Ca is shown in the figure 4. The figure is classified into 0 to 3.5 regions into 14 divisions with 0.25 division width. The index 0 indicates the lowest pollution effect and 3.5 as the maximum pollution affected groundwater. The IAWQ index map it can be seen that groundwater starts deteriorating on moving towards southern direction and more intensely on mowing towards south-west direction in the study area. The north-northwest region appears to be fresh pure water much within the drinking standard limits. Hydrologically, the groundwater movement in the study area is also in the north-south direction in the eastern part of the study area and in the south-west direction in the western part of the study area.

The north -north-east region is hilly terrain with no urbanization whereas urbanization increases on moving south, south-west direction. Therefore, groundwater is expected to get deteriorated along the south and south-west region with the incorporation of the pollutants discharged from urbanized/industrial/agricultural west and increasing the IAWQ index.

6. Conclusions

1. The study has indicated that shallow groundwater is polluted at many places in Ganga-Yamuna Interfluve area. Generally, the ionic concentrations have been found to increase from northern to southern part except that of NO3-, which shows higher concentration in the northern part.
2. The groundwater is alkaline in nature. In most of the area, TDS and concentration of major ions is suitable for drinking purpose as per Indian standards.
3. The tolerance limits for concentration of the heavy metals (Cd, Pb and Mn) in shallow groundwater is violated in more than 60% of the samples with the higher concentration being found in urban and rural land use categories probably due to increased human activity. In these areas, shallow groundwater can however, be used for irrigation and domestic purposes, barring drinking.
4. The Index of Aquifer Water Quality (IAWQ) indicates increasing pollution in the southern part of the study area where human activity is more.
5. The IAWQ modeling can be used as a tool to map the groundwater quality (with an) considering the weights of an ensemble of chemical parameters together to decipher the area affected by the pollution and where special attention may be required to improve the groundwater quality.

Table 3. Classification of water quality parameters on the basis of human health significance.

Group	Parameter	Water quality criteria
I	Cd	• Biologically, Cadmium is a nonessential, non beneficial element recognized to be of high toxic potential. • It is deposited and accumulated in various body tissues and is found in varying concentration throughout all areas where man lives. • The cadmium is toxic to man when ingested or inhaled. It is stored largely in the kidneys and liver and is excreted at an extremely slow rate (Train, 1979).
	Pb	• Most Lead salts are of low solubility and stable complexs result also from the interaction of Lead with the sulfhydryle group. • It has no beneficial or desirable nutritional effects. • It is a toxic metal that tends to accumulate in the tissues of man and other animals. Although seldom seen in the adult population, irreversible damage to the brain is a frequent result of lead intoxication in children. Such lead intoxication most commonly results from ingestion of lead-containing paint still found in older homes. The major toxic effects of lead include anemia, neurological dysfunction, and renal impairment (EPA, 1973).
II	NO_3^-	• It becomes toxic only under conditions in which they are high nitrates concentration. Otherwise, at “reasonable” concentrations, nitrates are rapidly excreted in the urine. • High intake of nitrates constitutes a hazard primarily to warm blooded animals (Specially the younger ones) under conditions that are favorable to their reduction to nitrite (Train, 1979).
III	Mn	• Manganese is a vital micro – nutrient for both plants and animals. • Very large doses of ingested manganese can cause some disease and liver damage but these are not still documented. • Few Manganese toxicity problems have been found throughout the world and these have occurred under unique circumstances, i.e. a well in Japan near a deposit of buried batteries (McKee and Wolf, 1963).
	Fe	• Iron is an essential trace element required by both plants and animals. • In some waters, it may be limiting factor for the growth of algae and other plants; this is especially true in some marl lakes where it is precipitated in high alkaline conditions (Train, 1979). • The human body has the ability to naturally store Iron. • Too much Iron in the body may be linked to heart disease, cancer, diabetes and other diseases (Joseph, 2004).
IV	TDS	• Excess dissolved solids are objectionable in drinking water because of possible physiological effects, unpalatable mineral tastes. • The physiological effects directly related to dissolved solids include laxative effects principally from sodium sulfate and magnesium sulfate and the adverse effect of sodium on certain patients afflicted with cardiac disease and women with toxemia associated with pregnancy (Train, 1979).
V	TA	• There are no direct effects on the human health.
	Ca^{+2}	• There are no direct effects on the human health.

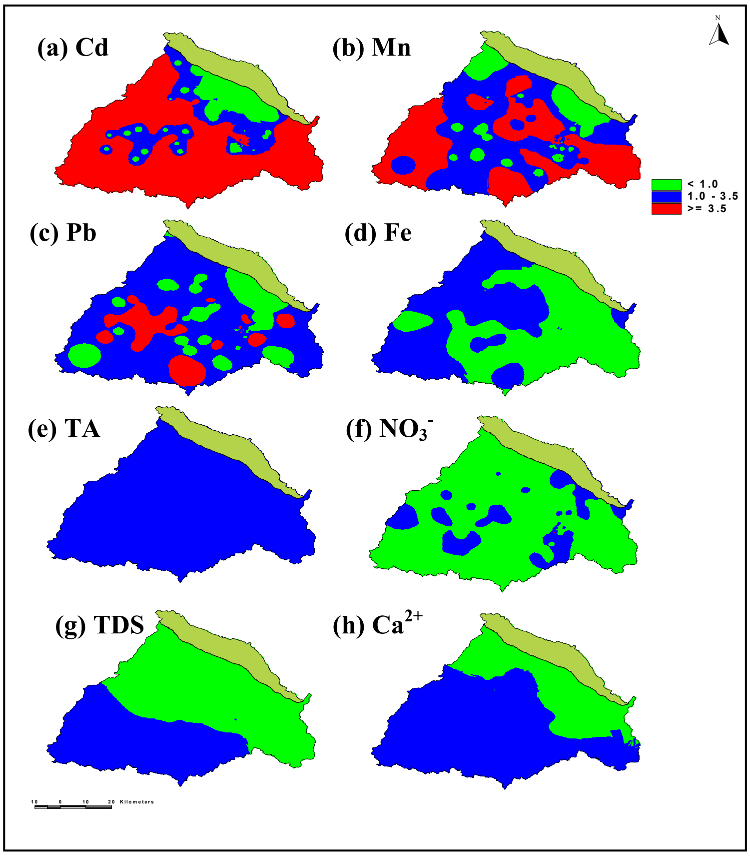

Fig.3. Xi map for the eight parameters.

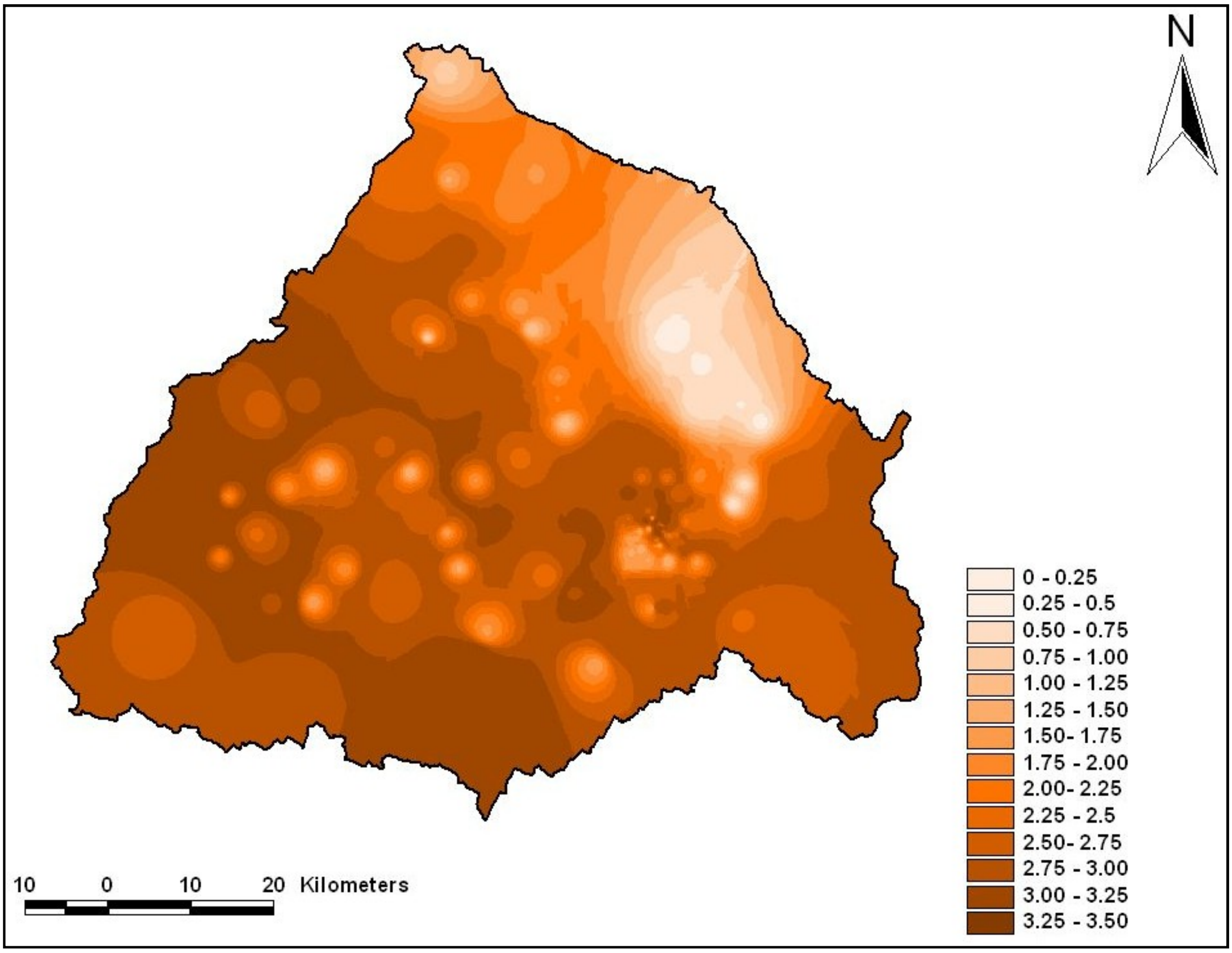

Fig.4. Final IAWQ map for the study area.

Table 4. The Analytic Hierarachy Process matrix.

	1	2	3	4	5	6	7	8	9	10	11
	Cd	Pb	NO_3^-	Mn	Fe	TDS	TA	Ca^{+2}	Eigenvalue	Priority Vector	Weight
Cd	1.00	1.00	5.00	7.00	7.00	8.00	9.00	9.00	4.468	0.323	5.00
Pb	1.00	1.00	5.00	7.00	7.00	8.00	9.00	9.00	4.468	0.323	5.00
NO_3^-	0.20	0.20	1.00	3.00	3.00	7.00	8.00	8.00	1.888	0.137	2.11
Mn	0.14	0.14	0.33	1.00	1.00	5.00	7.00	7.00	1.066	0.077	1.19
Fe	0.14	0.14	0.33	1.00	1.00	5.00	7.00	7.00	1.066	0.077	1.19
TDS	0.13	0.13	0.14	0.20	0.20	1.00	2.00	2.00	0.371	0.027	0.41
TA	0.11	0.11	0.13	0.14	0.14	0.50	1.00	1.00	0.251	0.018	0.28
Ca^{+2}	0.11	0.11	0.13	0.14	0.14	0.50	1.00	1.00	0.251	0.018	0.28

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