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Remote Sensing and GIS Application for Groundwater Quality and Risk Mapping

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Abstract

The quality of water plays a prominent role in promoting both the standard of agricultural production and human health. Groundwater pollution depends on the inherent hydro geologic property of the site, agricultural land use and cultivation practices. Groundwater vulnerability maps, risk map, groundwater quality maps showing present scenario of contamination etc. can be used as a guide for future developments in an area, in order to minimize the impact of the projected developmental activities on the surrounding water resources. This study was mainly aimed at demonstrating the combined use of the DRASTIC models and geographical information system (GIS) as an effective method for groundwater pollution vulnerability and risk assessment in Kapgari catchment, West Bengal, India. IRS-1D (LISS-III) remote sensing data were used for this study along with the image processing software called Erdas Imagine and GIS software called Arc/Info. The normal DRASTIC model was applied to the study area with help of GIS and assessed the ground water pollution potentials separately. The normal risk map also prepared by integrating land use map with the corresponding vulnerability maps and compared the pollution potentials of these risk maps with vulnerability maps. The groundwater quality maps are effective tools for identifying locations which are having the threat of groundwater pollution. So groundwater quality mapping using GIS was conducted based on physiochemical characteristics of the groundwater samples collected from 30 wells of Kapgari aquifer, which helped to assess the present groundwater pollution scenario of the study area. Thus based on this analyzed ground water quality data, the temporal and spatial variations of water quality of the Kapgari catchment were analyzed. The final groundwater quality map pictorially represented the groundwater zones that are desirable and undesirable for drinking and irrigation purposes and also identified the zones where high concentration of TDS, Hardness, chloride etc are present in the study area. A complementary objective of this study was to demonstrate the GIS capabilities in exploring the full value of environmental data through spatial analysis and visual display of geographic information.

Keywords: Groundwater, Quality Maps, Vulnerability and Risk Maps, GIS

Introduction

India is a large country which supports about 1/6th of the world's population, 1/50th of the world's land and 1/25th of world's water resources (water management forum, 2003). According to the estimates adopted by NCIWRD (1999), by the year 2025, the population is expected to be 1,333 million in the high growth scenario and 1,286 million in the low growth scenario. For the year 2050, high rate of population growth is likely to result in about 1,581 million people, while the low growth projections place the number at nearly 1,346 million. Keeping in view the rapidly rising population and increasing agricultural, industrial and other requirements, the freshwater demand for 2025 would be 843 Km^3 (high demand scenario) and 784 Km^3 (low demand scenario). The requirement for 2050 would be 1180 Km^3 (high demand scenario) and 973 Km^3 (low demand scenario). Though this is the fact, unfortunately, indiscriminate use of agrochemicals, improper sewage management, inadequate water planning, lack of water awareness, and non- implementation of desired measures, have created an alarming scenario of freshwater scarcity in India. In India, groundwater plays a crucial role as a decentralized source of drinking water for millions of rural and urban families, which accounts for nearly 80 percent of the rural domestic water needs, and 50 per cent of the urban water needs in India. But the extent of ground water pollution is in alarming stage by a variety of land and water-based human activities.

Contamination of groundwater has been observed world wide, and it is becoming self evident that concentrated human activity will lead to groundwater contamination. There is need for a definite strategy and guidelines for all countries which would focus on specific part of a groundwater management, viz. the protection of ground water from contamination and land based management of the groundwater resources. Two major techniques for groundwater protection strategies are groundwater vulnerability assessment and groundwater quality mapping. Vulnerability of groundwater refers to the intrinsic characteristics that determine the sensitivity of the water to be adversely affected by an imposed contaminant load. Among the available methods to assess groundwater vulnerability, an overlay and index method namely, DRASTIC method (Aller et al., 1987), developed by the U.S. Environmental Protection Agency, is the most widely used method for identifying the areas where groundwater supplies are most susceptible to contamination. The DRASTIC hydro geologic vulnerability ranking method uses a set of seven hydro geologic parameters to classify the vulnerability or pollution potential of an aquifer. The parameters are depth of groundwater, recharge rate, the aquifer type, the soil media, and topography, impact of the vadose zone and the hydraulic conductivity of the aquifer.

In India, satellite based remote sensing inputs have been playing a key role in the management of its natural resources along with Geographic information System (GIS) over the past two decades. Remotely sensed data provides valuable and near real time spatial information on natural resources and physical terrain parameters GIS is a computer based system designed tool applied to geographical data for integration, collection, storing, retrieving, transforming and displaying spatial data for planning and management of natural resources. GIS and remote sensing derived information can be well integrated with the conventional database for assessing the actual groundwater pollution scenario and pollution vulnerability.

One can find many literatures on groundwater vulnerability assessments using DRASTIC models along with RS and GIS successively applied all around the world. Shamsuddin (2000) undertook a study on vulnerability of shallow groundwater to contamination in and around Midnapur-Kharagpur towns, West Bengal, India. Gogu and Disagrees (2000) described current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. They pointed out the new challenges for hydro-geologists as integration of results from process based numerical model in the vulnerability mapping techniques. We can find successful demonstration of DRASTIC model even in arid regions by Al-Adamant et al. (2003). In which they conducted a study on groundwater vulnerability and risk mapping for the arid Basaltic aquifer of the Azraq basin of Jordan. The study classified around 84% of the study area as being at moderate risk while the remainder was classified as low risk.

Groundwater quality mapping is one of the major techniques in any groundwater related strategy planning which provides the information about the actual quality scenario of the location. The hydro-geochemical study with GIS reveals the zones where quality of water suitable for drinking, agricultural and industrial purposes. Daniela (1997) conducted a study on groundwater contamination and prepared the groundwater contamination risk map of a sample alluvial area produced by using the ILWIS Geographical Information System (GIS) to construct and to overlay thematic maps. Hong and Chon (1999) investigated groundwater contamination and spatial relationships among groundwater quality, topography, geology, land use and pollution sources in two sites namely Asan area and Gurogu area of Seoul city, Korea. Another interesting work was done by Anbazhagan and Nair (2005). In which they conducted groundwater quality mapping using the Geographic Information System (GIS), in Panvel Basin of Raigarh district, Maharashtra, India for agricultural and drinking purposes. Ground water pollution vulnerability maps, risk maps, groundwater quality maps etc may be used to assist planners, managers, and local officials in evaluating the potential for contamination from various sources of pollution. This study was undertaken in a small agricultural watershed with very specific objectives like to assess the groundwater vulnerability status through vulnerability maps and risk maps at Kapgari watershed using GIS and DRASTIC methods and to develop Groundwater quality maps of Kapgari watershed using observed water quality parameters and GIS to assess present pollution scenario.

Materials and Methods

Study Area, Data and Systems Used

The study area used for quantitative assessment of non point source pollution of water resource is a small agricultural watershed in eastern India. The watershed is located in Jamboni block, Midnapore district of West Bengal state, India. The location map of the watershed is within $86^{0}50^{'}$ & $86^{0}55^{'}$ E longitude and $22^{0}30^{'}$ & $22^{0}35^{'}$ N latitude. On the basis of drainage channels and land topography the watershed was subdivided into three sub watersheds. The whole watershed drains water through a single well-defined outlet. Since the outlet falls in the boundary of Kapgari village, the watershed was named as Kapgari watershed. The topography of the watershed consists of uplands, medium lands, lowlands and forestland. The predominant soil of the watershed is sandy loam soil. The dominant crop in the study area is paddy, which is generally cultivated during monsoon period. The watershed topography is nearly flat. The average annual rainfall of the region is 1250 mm. Around 80% of the annual rainfall is received in between June to September. For this study well locations were obtained for 30 wells spreading all over the region by using available topographic map and other data. Based on the location information of the wells arc point coverage was prepared showing the position of the respective wells. For this we have identified 8 domestic wells and 22 agricultural wells, from which groundwater samples were collected for quality analysis. Groundwater samples were collected during June, August and December of year 2003 and 2004, and which where used for assessing special and temporal variation of groundwater quality through out the catchment. Software packages like Erdas Imagine 8.5 and Arc/Info were used for image processing application and GIS applications respectively. The major inputs required for this study are Digital Image data, Topographic Sheet, Field data, Existing data etc. The IRS 1D LISS III digital image (Path-107, Row-56) of November 2001 from National Remote Sensing Agency used for generating thematic maps. Survey of India Topographic Sheet (No: 73j/14 scale 1:50,000) and existing groundwater quality data were also used for deriving the final results.

Groundwater Vulnerability Studies Using RS and GIS

Overlay and index methods, the most common method in vulnerability assessment, which involve combining various physical attributes (e.g., geology, soils, depth to water table, well locations) been appilied for this study. In the simplest of these methods, all attributes are assigned weights based on judgment made on their relative importance and which can be accomplished very easily with help of GIS. DRASTIC Index Model is one of the most widely used models to assess groundwater vulnerability to a wide range of potential contaminants. The DRASTIC index of vulnerability was developed by Aller, et al. (1987), of US Environmental Protection Agency (US EPA) as "A Standardized System for Evaluating Ground Water Pollution Potential of Hydro-geologic Settings" for evaluating the potential for groundwater contamination at a specific site given.

The DRASTIC methodology evaluates seven measurable parameters, or factors, for each hydro-geologic setting. Hydro-geological setting is a composite description of all major geologic and hydraulic factors, which affect the groundwater movement into, through and out of the area. The equation for calculating the Drastic Index of a mapping unit is,

$$D I = D r D w + R r R w + A r A w + S r S w + T r T w + I r I w + C r C w \ldots \quad (1)$$

where:

DI = DRASTIC Index; Dr = Ratings to the depth to water table; Dw = Weights assigned to the depth to water table (value is 5); Rr = Ratings for ranges of aquifer recharge; Rw = Weights for the aquifer recharge (value is 4); Ar = Ratings assigned to aquifer media; Aw = Weights assigned to aquifer media (value is 3); Sr = Ratings for the soil media; Sw = Weights for soil media (value is 2); Tr = Ratings for topography (slope); Tw = Weights assigned to topography (value is 1); Ir = Ratings assigned to vadose zone; Iw = Weights assigned to vadose zone (value is 5); Cr = Ratings for rates of hydraulic conductivity; Cw = Weights given to hydraulic conductivity (value is 3)

Weight (w): The weighting represents an attempt to define the relative importance of each factor in its ability to affect pollutant transport to and within the aquifer. The weight is from 1 to 5 for parameters.

Rating (r): Each range for each DRASTIC factor has been evaluated with respect to the others to determine the relative significance of each range with respect to pollution potential. The ratings are from 1 to 10. Adopted range values in this study can be found in Remesan and Panda (2008).

As the DRASTIC vulnerability index is a linear combination of several hydro geological factors, which can be computed using GIS. The methodology adopted for groundwater vulnerability studies of Kapgari catchment using remote sensing data and GIS is shown in the Figure 1

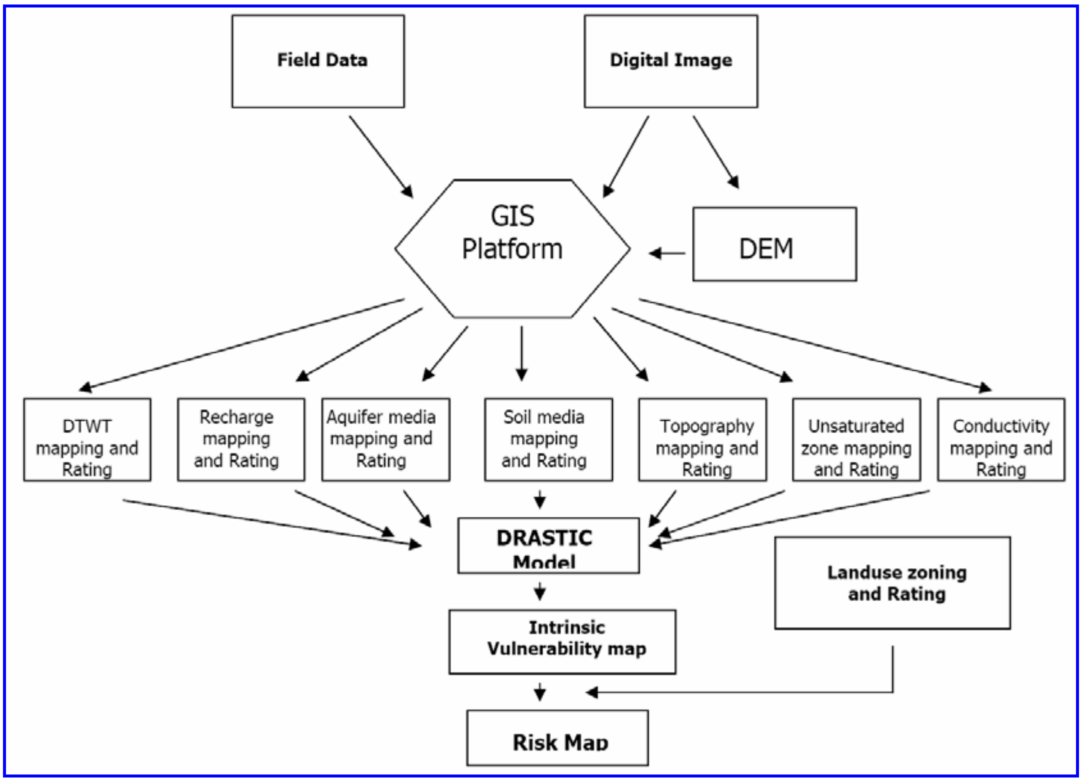

Fig 1. Flow chart showing methodology adopted for groundwater vulnerability assessment and risk mapping

Risk Assessment and Mapping

The resulting vulnerability map obtained from DRASTIC model (in Figure 1) is then integrated with a land use map as an additional parameter in the DRASTIC model to assess the potential risk of groundwater to pollution in the study area Modified DRASTIC index value is calculated using the Equation 2 and classifying the area based on this modified index value. This classification gives an idea of combined effect of the intrinsic characteristics of aquifer and the effect of land use on groundwater pollution

$$MDI = DI + Lr \times Lw \quad \text{……………………………………………......(2)}$$

where

MDI = Modified DRASTIC Index value
DI = DRASTIC Index value
Lr = Land use rating
Lw = land use weight

Groundwater Quality Assessment and Water Quality Mapping Using RS and GIS

The quality of the groundwater samples has been analyzed separately for drinking and irrigation purposes. As there is no major industry in the study area, quality analysis for industry is not significant. Groundwater quality for drinking water purposes was analyzed by considering the WHO standards. It was found that some samples had chloride, hardness and TDS values above desirable limits. The values were plotted corresponding to respective sample locations and surfaces were interpolated using Kriging interpolation technique. Water quality maps were generated for chloride, TDS and hardness in the study area showing areas falling under desirable limits and areas falling under undesirable limits. A salinity hazard map was also prepared as per recommendations of water quality for agricultural purposes. The salinity hazard map shows regions with low, medium and high salinity hazards. The study was carried out with the help of four major components: input from remote sensing data, topographic sheets, groundwater quality data and data collected during field visits. The three thematic maps with parameters such as chloride concentration, hardness and TDS having desirable and undesirable classes were integrated using the addition function available in Arc/Info software. Thus the final groundwater quality map for drinking purpose was prepared by overlying the above mentioned three grid data. Finally the study area was delineated into two classes on the basis of groundwater quality for drinking purposes: desirable and undesirable. The methodology adopted for groundwater quality mapping using water quality data in the GIS environment is shown in the Figure 2.

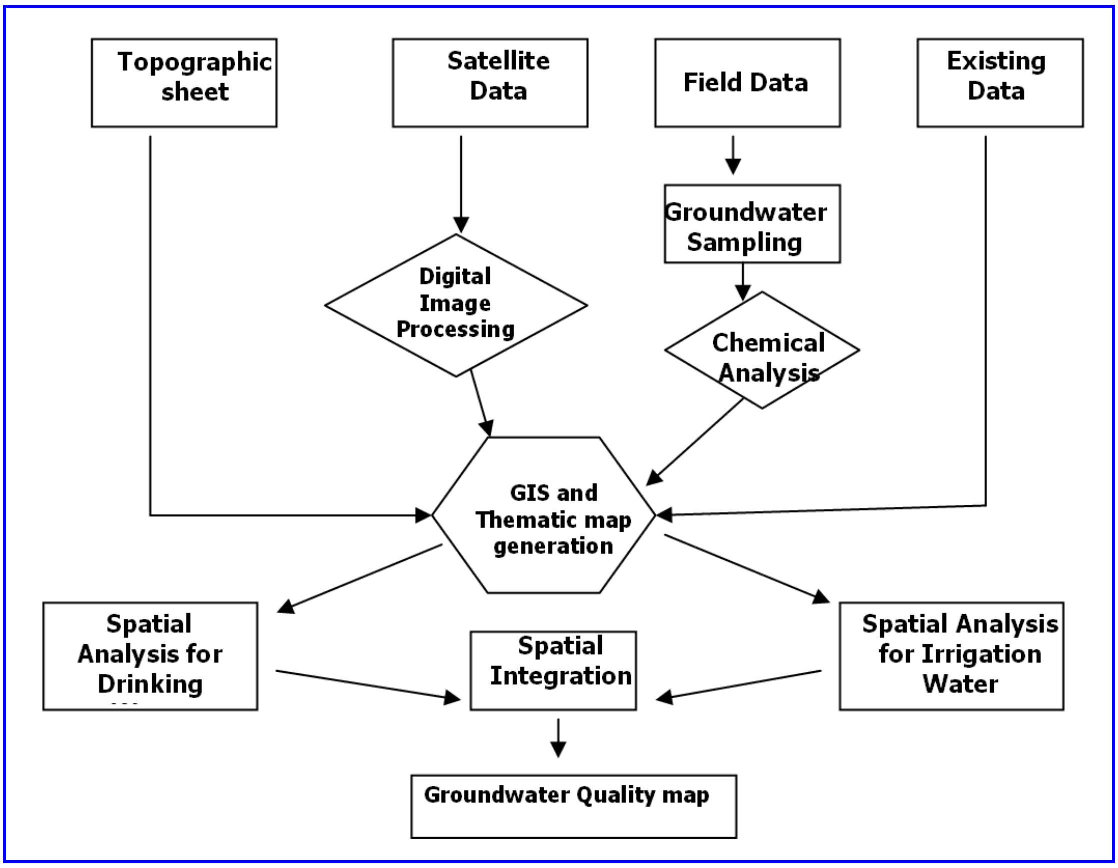

Figure 2. Flow chart showing methodology adopted for integrated quality mapping

Results and Discussions

The section deals with the results obtained from aspects like groundwater vulnerability studies and risk mapping of Kapgari watershed. Alone with that the results of spatial and temporal analysis of groundwater quality of watershed are presented and discussed

Aquifer vulnerability assessment in Kapgari catchment

Groundwater Vulnerability Mapping

The DRASTIC vulnerability index was computed according to Equation 1 using the seven hydro geological maps. In order to understand the vulnerability index, it is necessary to choose a representation method which can expose the aquifer vulnerability in an appropriate fashion and simultaneously allows comparability between different areas. For preparation of different vulnerability classes of Kapgari area, the vulnerability index values were first arranged in a descending form and then the vulnerability indices corresponding to each 25% of the total number of pixels in the study area were taken as thresholds for the classification. Thus four DRASTIC vulnerability classes were prepared for Kapgari namely; very high, high, intermediate and low. Colours were then assigned to the ranges of the subsequent percentages of pixels. The cool colours (shades of blue) indicate Low vulnerability, the shades of green indicates “Moderate” vulnerability while the warm colours (shades of red) indicate “High” vulnerability. The normal DRASTIC vulnerability map of Kapgari watershed is shown in the Figure 3. It is seen from the interpolated map that the normal DRASTIC index ranges from 92 to 216. The normal DRASTIC index ranges from 150 to 216 in the major part of the area, indicating a high to very high index of aquifer vulnerability. Relatively small part of the area shows an index value less than 150; thus it can be considered as an area, which is less likely to be vulnerable to pollution. The very high vulnerable class have an area of 567.52 ha (58.3 %) and high vulnerable class have 285.42 ha (29.32%) area. The other two low DI classes, intermediate and low together sharing 12.4% of total Kapgari area with 107.77 ha and 12.79 ha respectively.

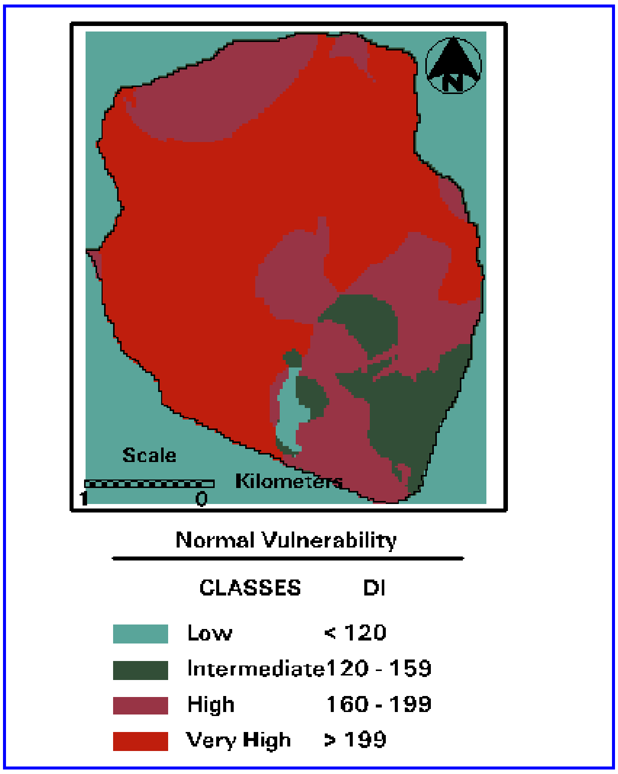

Figure 3. Normal vulnerability map of the study area

Normal risk mapping

The normal risk map of Kapgari catchment was prepared by integrating the corresponding DRASTIC vulnerability map with land use map. The normal risk map of the Kapgari is shown in the Figure 4 The risk map also classified in to four classes namely very high, high, medium and low based on the pixel value ranges of MDI. The MDI values of normal risk map ranged from 121 to 148, and thereby these values classified in to above mentioned four classes with MDI ranges >209, 180 - 209, 150 – 179 and < 150 respectively. From the risk map, we could understand that very high risk class has an area of 802.2 ha which is 82.4 % of total area of Kapgari catchment. The other classes like high, medium and low zones have areas of 127.6 ha (13.1%), 33.3 ha (3.4%) and 10.4 ha (1.1%). The normal vulnerability map and normal risk maps were compared to study the effect of land use on the pollution potential. The graphical distribution of pollution potential of normal vulnerability map is shown in Figure 5. The graph showed that the very high class of normal risk map covers more area than that of normal vulnerability map. This change shows that incorporation of land use to DRASTIC model gives more accurate mapping of pollution risk. The introduction of land use into the normal DRASTIC rating has increased the areas that have very high vulnerability by nearly 24% (234.68 ha) of the total study area.

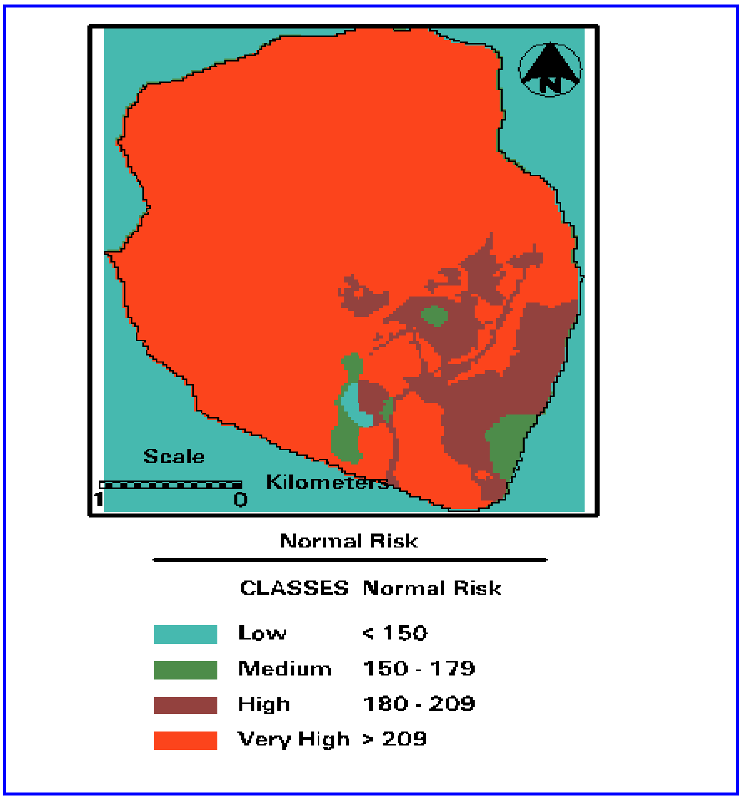

Figure 4. Normal risk map of the study area

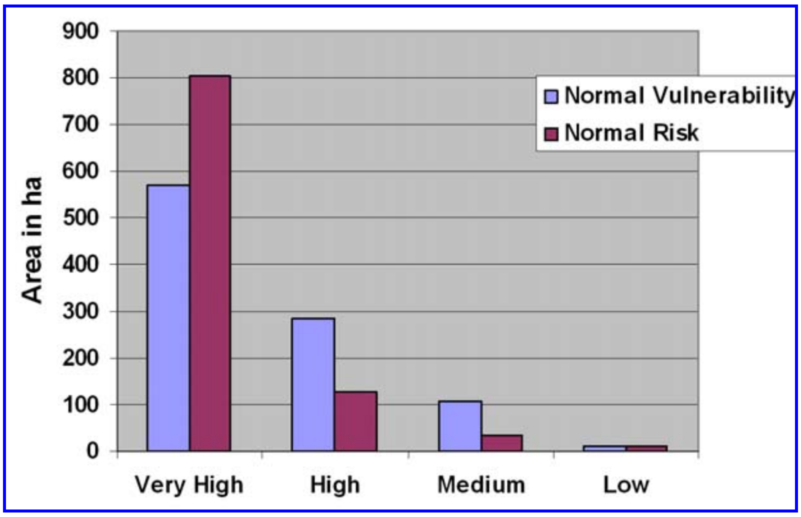

Figure 5. Graphical representation of pollution potential in normal vulnerability and normal risk map

Temporal Variation of Quality Parameters at Kapgari catchment

For analyzing the temporal variation of water quality, groundwater samples were collected from 10 selected wells of the Kapgari catchment during year 2003 and 2004. Water sample were collected in three different seasons, viz. pre-monsoon season, during monsoon and post monsoon season during these two year. The water quality of well samples for these three seasons were compared to determine any changes in the concentration of various constituents due to evaporation and precipitation. The temporal analysis was conducted for concentration of agricultural derived ions like nitrate, potassium, phosphorous etc. and other parameters like DO, pH, electrical conductivity and turbidity. The temporal variations of concentration of nitrate in three selected wells are shown in the Figure 6. Chemical analyses were carried out for the major ion concentrations of the water samples collected from 30 different well locations in the catchment. Turbidity is one of the major water quality parameter and the recommended turbidity value is less than 5 NTU for drinking water. The analyzed turbidity values range between the minimum value of 3.1 and maximum value of 7.8 and the mean value observed as 5.86. In the case of electrical conductivity, some samples showed values higher than 3 dS/m which is even not suitable for agricultural purposes. But the mean conductivity value of the catchment, 0.495 dS/m was within the acceptable limit. Total dissolved solids (TDS) is the measure of various types of minerals like carbonates, bicarbonates, chlorides, sulfate, phosphate, silica, calcium, magnesium, sodium potassium etc. present in water in the dissolved form. TDS value of the Kapgari watershed ranged between 40 to 2115 ppm. Even though some samples have shown very high TDS values, than the WHO recommended value, the mean TDS value of the kapgari watershed was within very acceptable limit. In the case of pH, more than 30% of the samples have shown acidic nature compared to the prescribed limit, so the mean pH value of the catchment observed slightly below the WHO standard. The calculation of hardness is based on the presence of calcium carbonate in the sample. Thus the hardness depends on the concentration of calcium and magnesium. Because of extreme values of calcium concentration in some locations, the hardness values were very high. Still the mean hardness value of the catchment was with in the acceptable limit, 500 ppm. Since coefficient of variation of all these parameters are comparatively small values, these six parameters showed the least variability compared to the anions and cations.

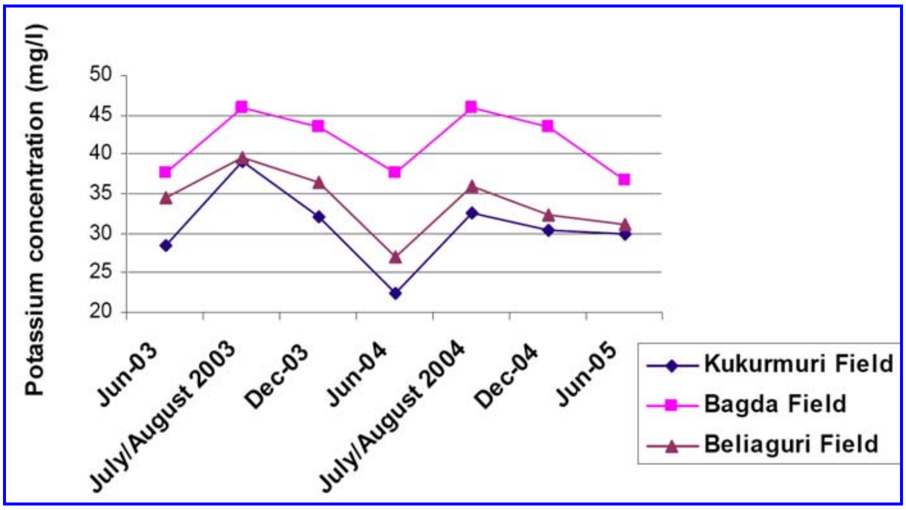

Figure 6. Temporal variation of potassium concentration in Kapgari watershed

Spatially integrated drinking water quality map

The final spatially integrated map of groundwater quality for drinking purposes in the Kapgari basin is shown in Figure 7. This drinking water quality map was prepared by spatially integrating the three thematic grid maps of chloride concentration, hardness and TDS using the Arc/Info grid addition. This map also delineated the area in to two groups, namely the areas where the groundwater is desirable for drinking purpose and undesirable for drinking purpose. The map shows that nearly one fifth of the area is covered by groundwater with a decent quality and remaining area of the basin falls in the undesirable category. In the integrated map groundwater of 783.17 ha area was zoned as undesirable for drinking purposes which is nearly 80 % of the area of the catchment

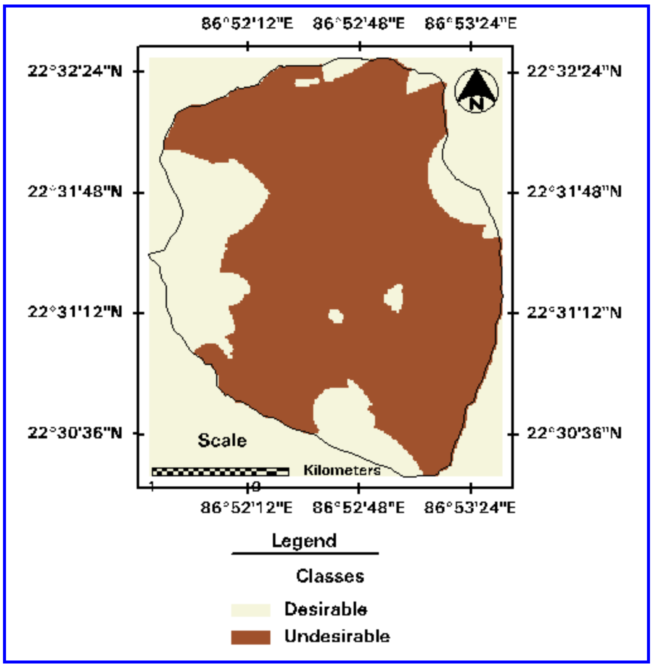

Figure 7 Groundwater quality map for drinking purposes of the Kapgari catchment

Groundwater quality mapping for agricultural purposes

The quality of water for irrigation purposes depends on the salinity and alkalinity. The EC value for the samples gives the extent of salinity for the area. The groundwater quality map was prepared on the basis of salinity hazard classes which are given in Table 1. Most of the groundwater samples fall in the medium salinity hazard (C2) as per the salinity hazard classification in the basin. Eleven samples falls in the low salinity hazard category (C1) while a few of the samples fall in the high salinity hazard category (C4). Groundwater samples that fall in the low salinity hazard class (C1) can be used for irrigation of most crops and the majority of soils. The groundwater quality map for agricultural purposes is shown in the Figure 8. The whole area is divided into four classes on the basis of EC. The classes are the groundwater from area excellent for irrigation (C1), good for irrigation (C2), doubtful about the quality (C3) and unsuitable for irrigation (C4). The map has shown that 742.09 ha (76.22%) of area falls in the C2 category that means in that much area the water quality is good for irrigation. The area of Excellent category (C1) is 169.46 ha and the corresponding area of Doubtful category (C3) and Unsuitable category (C4 and C5) are 57.02 ha and 4.92 ha.

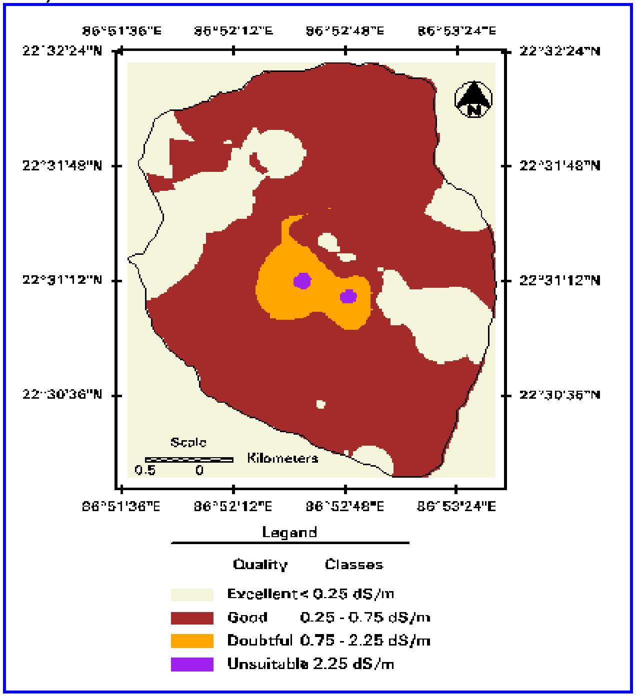

Figure 8 Groundwater quality map for irrigation purposes or Salinity hazard map of Kapgari catchment

Table 1 Salinity hazard classes

Salinity hazard class	EC in dS/m	Remark on water quality
C1	0.1 – 0.25	Excellent
C2	0.25 – 0.75	Good
C3	0.75 – 2.25	Doubtable
C4 and C5	> 2.25	Unsuitable

Integrated quality mapping

Groundwater quality for irrigation can be known from the salinity map. The groundwater quality map for drinking purposes was integrated with the groundwater quality map for irrigation. Integrating groundwater quality map for drinking purposes and that of irrigation purposes, one can pictorially represent groundwater zones favorable for drinking purposes, irrigation purposes, zones for both drinking and irrigation purposes and zones not favorable for either drinking or irrigation purposes. The integrated quality map which shows the suitability of zones for irrigation purposes and drinking purposes is shown in the Figure 9. The figure shows four categories namely, groundwater from the area desirable for both irrigation and drinking, desirable for irrigation only, moderately suitable for irrigation and undesirable for both irrigation and drinking purposes. There was no region where ground water is good for irrigation and undesirable for drinking purposes. Most of the region falls in moderately good for irrigation category and having an area of 615.08 ha. The corresponding areas for other three categories like desirable for both irrigation and drinking, desirable for irrigation only and undesirable for irrigation are 205.62 ha, 90.98 ha and 61.82 ha respectively. So groundwater from nearly 21 % of the Kapgari catchment is suitable for both irrigation and drinking purposes, and 6.35 % area is undesirable for both irrigation and drinking purposes.

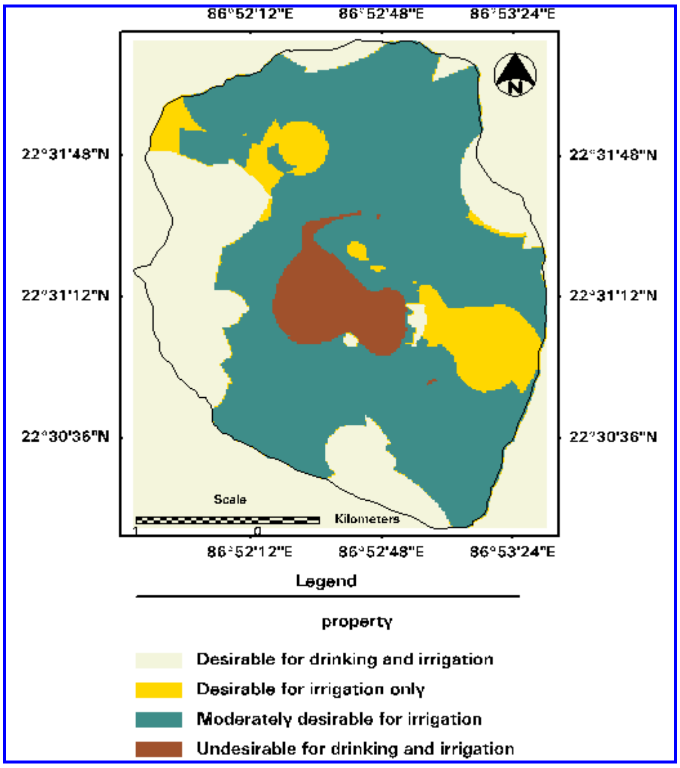

Figure 9. Integrated water quality map of Kapgari watershed

Conclusions

Groundwater resources degradation is an issue of significant societal and environmental concern In India, where which plays a crucial role as a decentralized source of drinking. In order to prevent groundwater pollution before it occurs and avoid the future need for costly remediation efforts, "DRASTIC Index" models can be used to assess the groundwater pollution potential with the help of GIS. The normal DRASTIC models have been used to investigate potential groundwater vulnerability and risk in the Kapgari catchment within a GIS environment. The normal DRASTIC index varied between 92 and 216, which were divided into four groups of low, intermediate, high and very high vulnerability. Very high vulnerability ranked groundwater areas dominated the study area in normal DRASTIC vulnerability maps with area proportion 58.55 %. A modified DRASTIC index (vulnerability plus risk) was developed by integrating land use with the normal and pesticide DRASTIC models. It was found that the introduction of land use only increased the potential for very high groundwater vulnerability class by 24% in case of normal DRASTIC. In the present study, the GIS technique has successfully been demonstrated its capability in groundwater quality mapping of the Kapgari basin. The final output has given the pictorial representation of groundwater quality suitable or unsuitable for drinking and irrigation purposes in the basin. The final spatially integrated drinking water quality map grouped 80% of the area as undesirable for drinking purpose. The irrigation water quality map showed that groundwater from 93.6% of the area is confidently desirable for irrigation (i.e. EC < 0.75 dS/m). A final integrated map was prepared from these drinking water quality map and irrigation quality map which is showing region where groundwater suited for both irrigation and drinking purposes. From the hydro-geochemical analysis, it is inferred that the excess concentration of chloride, TDS and hardness at some locations has an undesirable quality of water for drinking purposes. Similarly, considerable areas in the basin are having high salinity hazards. Such zones require special care and an alternative salt tolerance cropping pattern.

A complementary objective of this study was to demonstrate the GIS capabilities in exploring the full value of environmental data through spatial analysis and visual display of geographic information. Through this study, it was demonstrated that the combined use of DRASTIC and geographical information system (GIS) as an effective method for groundwater pollution risk assessment and water resource management. The present pollution scenario also assessed using the drinking water quality map, irrigation quality map, nitrate concentration map etc. which are prepared using the GIS technique. Although GIS is recently being recognized as a powerful tool in environmental studies and modelling, they are certainly subject to error and uncertainty introduced at almost every step of the spatial information generation and processing, from the data collection to the interpretation of the results. However, the high value of GIS products in the evaluation, communication, and management of environmental problems is unambiguous.

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