Monitoring of groundwater quality on a regular basis is essential for use in the domestic, agricultural and industrial sectors. Further, it is even more important in rural areas where people make use of groundwater for domestic purposes without prior treatment. This study was carried out with the objective of assessing the groundwater quality based on electrical conductivity (EC), fluoride, nitrate and bromide in a part of Nalgonda district, Andhra Pradesh, southern India. Groundwater samples were collected from 45 locations in January 2010. They were analysed using an ion chromatograph for fluoride, bromide and nitrate concentration in groundwater. EC was measured in the field using a portable digital probe. The groundwater samples were not suitable for drinking and domestic use based on EC, fluoride, nitrate and bromide in 6.7, 57, 22 and 11% of the locations, respectively. Overall, 31% of the locations had suitable groundwater quality. The north-eastern and south-eastern parts of this area had unsuitable groundwater. A total of 378.68 km$^2$ had unsuitable groundwater for drinking and domestic purposes. The source for the increased concentration of these parameters is varied and hence it is essential to restore the groundwater quality in this area. Of the several techniques available, artificial recharge by rainwater harvesting will help to dilute the concentration of these ions and improve the groundwater quality.

**Keywords:** Geographical Information System; rank; weightage; domestic use; granitic rocks; Nalgonda; southern India

1. **Introduction**

Assessment of groundwater quality of a region is of paramount importance to plan for proper groundwater development. Increased groundwater demand for agricultural production, industrialisation and urbanisation necessitates regular monitoring of its quality. The deterioration of groundwater quality affects its usage for drinking, agriculture and industrial activities. The causes for deterioration of groundwater quality may be natural or anthropogenic or both. After the identification of contamination sources, it is often difficult to adopt a management option to overcome the poor groundwater quality. Hence, it is essential to monitor the quality of groundwater regularly to sustainably manage the groundwater resource. Several new methods such as multivariate statistical analysis, remote sensing and Geographic Information System (GIS) are evolving to identify and explore the sources of groundwater contamination as well as to suggest mitigation measures. GIS is a proving to be a powerful tool for formulating solutions for groundwater resource management problems such as determining the water quality with respect to the inherent features of the study site such as geology, landuse (1)–(7), identifying groundwater potential zones (8)–(11), etc.

The present study was carried out in a part of Nalgonda district, Andhra Pradesh, southern India, an intensively irrigated region where people depend upon groundwater for their everyday water needs. This region is characterised by high fluoride concentration in groundwater (12, 13). A recent study by Brindha et al. (14, 15) identified the source of the high concentration of fluoride. Nitrate was found to be higher in the same area due to leaching of animal waste (14). Causes for the presence of bromide in groundwater were determined by Brindha and Elango (16). All these studies concentrated separately on the presence or absence of one or two ions and thus there is a gap in knowledge about the overall groundwater quality in this area. To manage groundwater resources sustainably, it is important to introduce an integrated approach for identification of the problem and thereby opt for a combined groundwater management strategy. With this goal in mind, the present study aims to fill the gap in previous studies of the area and to assess the groundwater quality based on electrical conductivity (EC), fluoride, bromide and nitrate in a part of Nalgonda district, Andhra Pradesh using GIS.

2. **Materials and methods**

2.1. **Description of study area**

The study area forms a part of Nalgonda district, Andhra Pradesh, India situated at a distance of 85 km ESE of...
The Survey of India toposheets (scale-1:25,000) covering the study area were used to prepare the base and drainage maps. The geological map (scale-1:50,000) was acquired from Geological Survey of India (GSI), Hyderabad. The Shuttle Radar Topography Mission (SRTM) data were used to prepare a topographic map of the study area. The method adopted for this study is shown stepwise in Figure 2.

Figure 1. Location of the study area.

Figure 2. Schematic representation of methodology.

Hyderabad (Figure 1). The Survey of India toposheets (scale-1:25,000) covering the study area were used to prepare the base and drainage maps. The geological map (scale-1:50,000) was acquired from Geological Survey of India (GSI), Hyderabad. The Shuttle Radar Topography Mission (SRTM) data were used to prepare a topographic map of the study area. The method adopted for this study is shown stepwise in Figure 2.

The study area was demarcated with well-defined watershed boundary covering an area of about 724 km². Nagarjuna Sagar reservoir is located at the south-eastern side of the study area and two rivers – Gudipalli Vagu and Pedda Vagu forms the northern and southern boundaries of the study area, respectively. Climate in this area is arid to semi-arid. Hot climate persists during summer (April–June) with a temperature ranging from 30 to 46.5 °C and in winter (November–January) the temperature varies between 17 and 38 °C. Average annual rainfall in this area is about 600 mm occurring usually during the south-west monsoon (June–September). There are several small hillocks in this area with elevation ranging from 100 to 200 m. The two rivers mentioned above are seasonal rivers and they flow during the south-west monsoon. The rainfall runoff has lead to the formation of a dendritic to subdendritic drainage pattern in this area (Figure 3(a)). Numerous tanks and few small reservoirs are present in the depressed parts of the undulating topography. There are also a few lined canal
networks catering to irrigation activity. In general, the ground surface slopes in the south-east direction. The forest cover in this area is thin to moderate. Most of the study area comprises of agricultural land. Rice is the principle crop grown in this area while other crops include sweet lime, castor, cotton, grams and groundnut. Drip irrigation is practiced especially for sweet lime.

Geologically this region consists of granitic rocks which forms the basement and is traversed by numerous dolerite dykes and quartz veins (Figure 3(b)) (17). Most part of the investigated area has exposures of granitic rocks belonging to late Archaen. Granites are generally medium to coarse grained. The Srisailam formation, the youngest member of the Cuddapah supergroup overlies the basement granite with a distinct unconformity. The Srisailam formation is exposed in the south-eastern part of the study area. The sediments of Srisailam formation are mainly arenaceous and include pebbly-gritty quartzite.
shale with dolomitic limestone, intercalated sequence of shale-quartzite and massive quartzite. The litho units of this formation dip at an angle ranging from 3 to 5°C towards the south-east.

2.2. Groundwater sampling and analysis

An intensive field survey was carried out and nearly 240 wells were investigated for choosing appropriate sampling locations in this area. EC was measured in all the wells and a representative well in every 15 km distance was chosen for the collection of groundwater samples. A total of 45 wells were selected as shown in Figure 3(a). Samples were collected during January 2010 in clean polyethylene bottles of 500 ml capacity. The bottles were cleaned prior to sampling by soaking them in 1:1 diluted HNO₃ for 24 h and they were washed thoroughly with distilled water. Further, these bottles were washed again before each sampling with the filtrates of the sample. EC was measured in the field using an Eutech digital portable metre. This metre was calibrated beforehand in the laboratory using 84 and 1413 μS/cm conductivity solution. These calibration solutions and the instrument were procured from Eutech. Groundwater samples collected were transported to the laboratory and filtered using 0.45 μm millipore filter paper for determination of fluoride, nitrate and bromide concentration of the groundwater samples using Metrohm 861 advanced compact ion chromatograph. Eluents, standards and blanks were run frequently to check accuracy of the procedures. The detection limit of the instrument was <2 ppb. Care was taken to avoid handling errors. Few samples were repeated to check concordant readings. All the chemicals used were of analytical grade and procured from Merck. Total dissolved solids (TDS) were calculated using the formula TDS (mg/l) = EC (μS/cm) × 0.64.

2.3. Geographic Information System

GIS was used to carry out the groundwater quality zonation mapping of the study area. Arc GIS 9.2 was used to prepare the base, drainage and geology maps. This software was also used to prepare maps of spatial variation in EC and concentration of ions in groundwater of the study area from point observations. These point observations can be converted into a spatial variation map based on several mathematical techniques. Out of the several methods available, the inverse distance weighted method is based on the assumption that points that are close to one another are more similar than those farther away. In order to predict a value for a location without a recorded value, the measured values around this location are used. The influence of the recorded values closer to the unrecorded point will have more influence than those farther away. This method assumes that each recorded value has an influence that decreases with distance, which is the case in groundwater quality observations. It weights the points closer to the prediction location greater than those farther away, hence the name inverse distance weighted method. As this method is considered suitable and widely adopted, it was used in this study.

For groundwater quality analysis using GIS, the parameters such as EC, fluoride, nitrate and bromide were assigned a rank for a particular range of recorded values depending on their suitability for domestic purposes. A weight was assigned to these parameters based on their importance. To ascertain the overall groundwater quality, the ranks and weight were used to calculate the composite suitability index (CSI) by multiplying weight by the rank of each parameter and summing up the values of all the parameters i.e.

\[ CSI = \sum_{i=1}^{N} \text{Rank}_i \times \text{Weightage} \]

A low CSI indicates that groundwater quality is suitable whereas the highest CSI is unsuitable with regard to all the parameters. The influence of topography on the groundwater composition of EC, fluoride, nitrate and bromide was studied with the help of slope map and geology of this area. From the topographic map derived from SRTM data, a triangulated irregular network (TIN) was created. TIN is a digital data structure used for the representation of a surface. It is a vector based representation of a surface made up of irregularly distributed nodes and lines with three-dimensional coordinates (x, y and z) that are arranged in a network of non-overlapping triangles. In regions where there is little variation in surface height, the points may be widely spaced whereas in areas of more intense variation in height the point density is increased. From the TIN generated, the slope of this area was arrived. Thus the spatial variation in slope of the area which reflects the topography was prepared and this was compared with the GIS derived groundwater zonation map. Similarly, areas of different geological features were grouped to study their relation with groundwater quality.

3. Results and discussion

Groundwater quality in any area depends on the concentration of major ions, minor ions, trace elements and the biological constituents. In the study area, groundwater quality investigation carried out indicates that the quality of groundwater is not affected with regard to major ions. No other studies carried out from this area have reported adverse effect of major ions on groundwater quality. However, this area is known for the presence of fluoride greater than the recommended limits. Similarly high nitrate and bromide concentration in groundwater is reported. This section discusses the groundwater quality assessment made for this area with respect to EC, fluoride, nitrate and bromide. Even though major ions are not a cause of great concern, the groundwater EC measured during this study was considered since it represents the total dissolved constituents and is of interest.
3.1. Electrical conductivity

EC is a measure of the ability of water to conduct an electric current and it depends on concentration of all ions. EC in the study area ranges from 450 to 4080 μS/cm with an average of 1002 μS/cm. Groundwater with EC less than 750 μS/cm is considered desirable for drinking (19) and 31.1% of the total samples were within this limit. About 62.2% of groundwater samples had EC ranging between 750 and 1500 μS/cm and were permissible for drinking purpose. EC is above 2500 μS/cm in the south-eastern and south-western part of the study area whereas about 71% of the groundwater samples in the study area have EC between 500 and 1000 μS/cm (71%) which indicates that the groundwater is suitable for drinking purposes (Figure 4). TDS was calculated based on EC as mentioned under methodology. Samples were divided to ascertain their use for various activities according to widely used classifications. Fresh groundwater occurs in 93.3% (<1000 mg/l of TDS) of the area which can be used for drinking needs whereas 6.7% of groundwater is of brackish water type (1000–10,000 mg/l of TDS) (20). According to David and DeWeist (21) classification 31.1% of the samples were desirable for drinking (<500 mg/l) and 62.2% were permissible for drinking (500–1000 mg/l) based on TDS. Groundwater with higher TDS when consumed decreases its palatability, may cause gastrointestinal irritation in humans and may have laxative effect. (22, 23).

3.2. Fluoride

Fluoride concentration in drinking water can range between 0.6 and 1.5 mg/l as per Bureau of Indian Standards (BIS) (24) standard. Intake of fluoride concentration above this limit into the human body may lead to dental and skeletal fluorosis. This is a serious problem in nearly 25 countries with around 200 million people at risk (25). Andezhath and Gosh (26) reported that in India 62 million people including six million children are estimated to have serious health problems due to consumption of fluoride contaminated water. Siddiqui (27) reported first on the prevalence of fluorosis in Nalgonda district in 1955. Since then, Nalgonda district is widely known for its fluoride occurrence in groundwater, and hence a removal (of fluoride) method is named after this district (Nalgonda technique). But this method also has limitations. Hence, it is important to adopt a suitable method for the removal of fluoride from groundwater, at the same time taking into account the current status of other ions and also the side effects of the method adopted. Fluoride concentration in groundwater in this area is at an average of 1.4 mg/l. The minimum concentration of fluoride recorded in the groundwater is 0.13 mg/l while the maximum concentration is 2.9 mg/l. The 42% of the groundwater samples is suitable for consumption. Thus, 57% do not fall within the desirable range for drinking. The spatial variation in fluoride concentration in this area is shown in Figure 5. Water in the central and south-eastern part of the study area is suitable for drinking with respect to fluoride. The source for high concentration of fluoride in groundwater is the host rocks such as granites and granitic gneiss that are rich in fluoride (14, 15). Wedepohl (28) put forth that the granitic rocks of Nalgonda district contain fluoride content ranging from 325 to 3200 ppm whereas the world average is 810 ppm. These fluoride rich granitic rocks occur throughout this area (Figure 3(b)) contributing fluoride ion to groundwater through the weathering process and rock–water interaction.

3.3. Nitrate

Nitrate is a common surface and groundwater pollutant in agricultural areas. Apart from health issues to humans due to high concentration of nitrates, it also causes eutrophication of water bodies where the amount of oxygen available to the flora and fauna in the water bodies decreases and results in death and decay of these organisms. Thus the surface water becomes unusable. Concentration of nitrate in this area ranged between 2.3 and 790 mg/l with an average of 44.4 mg/l. Maximum permissible limit for nitrate is 45 mg/l as per BIS (24). Very
high concentration of 790 mg/l is a concern in this area. About 22% of groundwater samples exceed the limit for nitrate in drinking water. Prolonged exposure to high concentration of nitrate may cause serious disorders in humans like shortness of breath, heart attack or even death as nitrate binds with red blood cells and limits their ability to carry oxygen. This disease called methemoglobinemia or blue baby syndrome results in blueness of the skin. Several researchers have reported on methemoglobinemia in humans due to nitrates (29)-(33). Hence, it is essential to take appropriate measures to reduce nitrate concentration in groundwater. The major source behind the presence of nitrate is the inappropriate disposal of animal waste (14). Animal waste contains high concentrations of nitrate and is cast away in heaps along the roads, near the houses and even near drinking water wells. During monsoon, nitrate gets leached through the soil along with rainwater and reaches the water table, thus polluting the groundwater. As most parts of the study area are under irrigation, application of fertilisers may also contribute for nitrate in groundwater. The spatial variation of nitrate (Figure 6) shows that its concentration is within the permissible limits in the central parts of this area. However, the south-eastern part is exceeding the BIS limits.

3.4. Bromide

Bromine is one of the halogen elements found in trace amounts in all groundwater (34). The concentration of bromide in this area varies from <0.002 to 1.64 mg/l with an average of 0.56 mg/l. BIS (24) or WHO (23) does not have any maximum permissible limit for bromide. Flury and Papritz (35) have put forth a limit of 1 mg/l of bromide in drinking water based on literature on toxicity data. Bromide depresses the central nervous system when 1 to 2 mg/day is consumed (36). Its concentration was above 1 mg/l in 11.1% of the groundwater samples i.e. five samples were above the limit. Bromine naturally occurs in groundwater due to seawater intrusion and from dissolution of rocks (37). The reason for higher concentration of bromide in this area may be due to marine origin of the formations of nearby Cuddapah basin (38). It may also be due to application of fertilizers or may be naturally present in groundwater (16). The spatial variation of bromide in groundwater (Figure 7) in this area shows that only small patches in the area has bromide above 1 mg/l. Overall, bromide occurs in trace amounts in groundwater of this area and is not a major problem when compared with other ions.

3.5. Integrated groundwater quality mapping

The parameters such as EC, fluoride, nitrate and bromide were used to assess the overall quality of groundwater in this area. The groundwater quality mapping of this area was achieved by assigning ranks and weightage to these four parameters (Table 1). As given in Table 1, a rank of 1 indicates that groundwater is suitable for domestic use whereas a rank of 2 indicates unsuitability. An equal weightage of 0.25 was assigned to all parameters. This is because even if one parameter exceeds the desirable limit, then the groundwater is not suitable for domestic use. Based on this rank and weightage as given in Table 1, the CSI was calculated and ranges from a minimum of 1 to a maximum of 2 with an increment of 0.25. A CSI of 1 means the groundwater is suitable with respect to all four parameters. Index values of 1.25, 1.50 and 1.75 indicate that the groundwater is not suitable with respect to one, two and three parameters, respectively. An index of 2 will indicate that all the four parameters are not within the desirable limits. Based on this, overlay analysis was carried out. The spatial variation of overall groundwater quality based on EC, fluoride, nitrate and bromide is shown in Figure 8. The figure shows that groundwater is not suitable in most parts of the area i.e. at least one of the parameter exceeds the desirable limit for drinking purpose. Groundwater quality is poor in the north-eastern and south-eastern parts of this area, where it is not suitable with respect to all four parameters. Thus, the groundwater quality of this area is unfit for domestic purposes. Overall, 31% of the 45 well groundwater samples are suitable.
for drinking purpose while rest of the samples could not be utilized (Table 1). Of the total area of 724.09 km² considered in this study, 378.68 km² had unsuitable groundwater for drinking and domestic needs.

The groundwater quality of a region depends on several factors including topography, slope, geology, land use, etc. In this research, the suitability of water for drinking purposes was assessed directly based on the measurement of concentration of minor ions in the groundwater. In order to understand whether there is any influence of ground slope and geology of the region, a comparison was made between these parameters and groundwater quality map. It is generally assumed that, ground slope controls the groundwater recharge processes which will affect the groundwater quality. Such a relation however was not observed in this site. This is due to the absence of large spatial variation in the quantum of rainfall recharge in this area. As the rainfall recharge in this area is less than 10%, the control of the ground slope on altering this low percentage of recharge is negligible. Hence, variation in the slope of this area is not controlling the groundwater quality. This can be understood from Figure 9 showing that the area of distribution of suitable and unsuitable groundwater quality is more or less the same for various ranges of slope. This confirms that the ground slope does not play a major role in areal distribution of suitable and unsuitable zones.

Similarly, a comparison was made between the groundwater quality map and the geology of the region. As most of the area is comprised of only granites and gneisses the role of geology in controlling the suitability or otherwise of groundwater is not significant. As the groundwater flow is from north-west to south-east through different geological formations, suitable or unsuitable groundwater quality zones are not related to the geological formations. This is evident from Figure 10 which shows a comparatively high proportion of area of unsuitable groundwater quality in regions of migmatite granite and quartzite. However, this is not significant as the total area covered by these rock groups is much less

| Parameter | Range  | Classification | Rank | Weightage |
|-----------|--------|----------------|------|-----------|
| EC (µS/cm) | <750   | Desirable      | 1    | 0.25      |
|           | 750–1500 | Permissible   | 1    |           |
|           | 1500–3000 | Not permissible  | 2    |           |
|           | >3000   | Hazardous      | 2    |           |
| Fluoride (mg/l) | <0.6    | Unsuitable     | 2    | 0.25      |
|           | 0.6–1.5 | Suitable       | 1    |           |
|           | >1.5    | Unsuitable     | 2    |           |
| Nitrate (mg/l) | <45     | Suitable       | 1    | 0.25      |
|           | >45     | Unsuitable     | 2    |           |
| Bromide (mg/l) | <1      | Suitable       | 1    | 0.25      |
|           | >1      | Unsuitable     | 2    |           |

Figure 8. Integrated groundwater quality map.

Figure 9. Groundwater quality based on ground slope.
as compared to the granitic gneiss. Thus, no direct relationship between geology and groundwater quality zones was observed.

This study was based on the observations made of 45 wells located in an area of 724 km². The extrapolation of these point values were made by inverse distance weighted method. However, the method is developed and the final map will serve the purpose of planning and locating regions that need immediate attention.

3.6. Management measures

Groundwater of this area is of poor quality and not suitable for domestic use. Groundwater can be treated by physical and chemical methods to remove these ions. But, these methods will be specific for a particular ion and each has its disadvantages. For example, the Nalgonda technique well known for removal of fluoride uses alum, lime and bleaching powder (39). The National Environmental Engineering Research Institute in India developed this technique for household removal of fluoride. However, the major disadvantage in this method is the disposal of sludge, which contains aluminium and the removed fluoride. If disposed inappropriately on a land surface, these contaminants would again reach the groundwater by leaching through the soil during precipitation. This method is also inappropriate for the removal of nitrate or bromide. Thus, one removal method may not be so suitable for the complete treatment of groundwater for this area. It is important to identify a common method to improve the groundwater quality. Considering the diversity of sources such as inherent rocks, animal waste, fertilisers, etc. artificial recharge may be a suitable method to dilute the concentration of ions in groundwater. Rainwater harvesting will increase the groundwater recharge and thereby decrease the ionic concentration. This method is also cost effective as compared to either in situ or ex situ large-scale chemical or biological treatment. It is important to educate the people of this area regarding the quality of water they have been consuming. Awareness must be created and rainwater harvesting pits should be installed in all houses.

4. Conclusion

This study was carried out as an integrated approach for managing the groundwater quality problem in a part of Nalgonda district, Andhra Pradesh, India. GIS was used as a tool to distinguish areas with groundwater pollution and determine suitable single measure for improving the groundwater quality. Interpretation of groundwater quality of 45 groundwater samples collected during January 2010 for this study shows that 345.41 km² of the area had groundwater suitable for drinking. The north-eastern and south-eastern parts of the area had very poor groundwater quality. The source of these ions in groundwater is diversified. So, the chemical methods for the removal of one ion may not be a suitable management measure for this area. Adopting artificial recharge may help to dilute the overall concentration of all ions in groundwater and improve the quality. Thus, this study filled a gap in the knowledge about the management of overall groundwater quality in this area and suggested a suitable measure for mitigation at the appropriate time.

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