A knowledge-driven Multi-Criteria Decision Making-Analytical Hierarchy Process based Geospatial Modeling for the Delineation of Fluoride Contamination Zones in Groundwater, Jamui District, Indo-Gangetic Alluvial Plains, India

Suresh Kumar  
Central Ground Water Board

Sudhakar Singha  
IIT (ISM): Indian Institute of Technology

Rambabu Singh  
CMPDIL, Bilaspur

Venkatesh Satya Akella (akellasatyavenkatesh@gmail.com)  
Indian School of Mines: Indian Institute of Technology  
https://orcid.org/0000-0002-3342-4374

Utpal Gogoi  
Central Ground Water Board, Faridabad

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A knowledge-driven Multi-Criteria Decision Making- Analytical Hierarchy Process based geospatial modeling for the delineation of fluoride contamination zones in groundwater, Jamui district, Indo-Gangetic alluvial plains, India

Suresh Kumar1,4, Sudhakar Singha2, Rambabu Singh3, A. S. Venkatesh4
1Central Ground Water Board, Patna-800001, India.
2Department of Civil Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad-826004, Jharkhand, India.
3Central Mine Planning and Design Institute Limited, Bilaspur-495006, India
4Department of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad-826004, India.
(*Corresponding author: asvenkatesh@iitism.ac.in)

Abstract
This study presents a framework to delineate the potential fluoride contamination zones within the groundwater of the study area by employing GIS coupled with Multi-Criteria Decision Making-Analytical Hierarchy Process approach (MCDM-AHP). In this context, various groundwater contamination controlling hydrogeo-meteorological factors thematic layers were prepared in the GIS environment and assigned with an appropriate rating and weights. All the selected influencing factors were overlaid using a weighted overlaid index approach after normalizing the weights and ratings of the respective layers using the AHP technique and then computed the fluoride contamination zones (FCZs). The obtained results indicate that 61.50% (1101.82 km$^2$) of the total study area was delineated as a relatively safe zone (F< 1.5 mg/L) and the remaining 38.50% (689.18 km$^2$) was demarcated under the unsafe zone (F>1.5 mg/L). The proposed FCZs model corroborates a significant agreement of 85% with the 61 observed locations and thus testify to the model reliability.

Keywords: Fluoride contamination, MCDM-AHP, Geospatial technology, Jamui, Indo-Gangetic Alluvial Plains.
1.0 Introduction

Fluoride is one of the essential and helpful elements for human health as it is associated with bone mineralization and dental enamel formation (Rahman et al., 2020; Gonçalves et al., 2020; Mondal et al., 2009). Moreover, some health issues are common, especially in children, such as deficiency in bone mineralization, dental enamel formation, dental caries, when the amount of fluoride consumed daily is less than 0.5 mg/L (Kumar et al., 2019). At the same time, the consumption of drinking water with a fluoride concentration of more than 1.5 mg/L leads to fluorosis, which is common in both adults and children (Kumar et al., 2019). Children and the younger populations in the fluoride endemic areas are highly affected by mottled enamel (Yuan et al., 2017). Consumption of fluoride enriched groundwater develops symptoms of skeletal fluorosis such as pain related to bones and joints in elderly people (Sawangjiang et al., 2019). It has been observed that these symptoms in a long run turn into permanent disability (Liu et al., 2015).

The incidence of fluorosis and its severity is due to the presence of fluoride content in water and soil. Prolonged consumption of fluoride enriched groundwater is a crucial contributor responsible for the waterborne fluorosis in human beings (Singh et al., 2017a and b, Su et al., 2019). The chemical composition of hinterland geology or lithological unit is closely related to the higher groundwater fluoride concentration (Singha et al., 2019a; Singh et al., 2018). Many scholars in their studies have highlighted that higher fluoride levels in the groundwater of granitic and metamorphic rock terrains were ascribed to the release of fluoride ion from the host rocks (Shanker et al., 2003; Thapa et al., 2017; Su et al., 2019; Narsimha et al., 2019).

Geological materials consisting of fluoride-rich minerals such as fluorite, apatite, wohlerite, tourmaline, herderite, sphene, hornblende series minerals, muscovite, actinolite and fluor-apatite
can trigger fluoride enrichment in aquifer solution through prolonged rock-water interaction (Todd and Mays, 2005; Rao., 2009, Adimalla and Venkatayogi, 2017). Several clay minerals, namely smectite, illite and chlorite also contribute significantly to fluoride concentration in solution (Tossou et al., 2017). In recent times, several researchers have opined that climate, evaporation, adsorption-desorption, ion exchange, ion competition, alkaline environmental conditions, lithology, and geomorphology of the area are the significant factors that can produce fluoride enriched groundwater (Mondal et al., 2009; Luo et al., 2018; Vithanage et al., 2014). The higher the surface drainage density more is the surface runoff of rainfall and scanty is the infiltration to groundwater storage.

Fluoride contamination commonly increases when lesser infiltration of rainwater occurs (Thapa et al., 2017). A flat ground surface leads to higher infiltration due to its less drainage density, which may result in higher leaching of fluoride in the aquifer. Besides this, the existence of fracture density in rocks is predominantly responsible for the higher propagation of fluoride values in groundwater (Kim and Jeong, 2005). Moreover, certain anthropogenic activities viz., domestic sewage, excessive utilization of phosphate fertilizers and pesticides in the crop fields and long-time irrigation practices are also accountable for higher fluoride levels in groundwater storage through leaching (Dartan et al., 2017; Srivastava and Ramanathan, 2018). The presence of excess fluoride content in the subsurface water resources has now drawn global attention as one of the most detrimental menaces to human health and geo-environmental problems in India and other parts of the world (Ando et al., 2001; Pillai and Stanley., 2002; Madhnure et al., 2007). The present study area comprises thick granitic litho-units and initially, the elevated fluoride levels in groundwater were reported in some locations of the study area by the Central Ground Water Board (CGWB, 2013) in which granitic activity is prevalent. Later on, Kumar et al., (2017...
and 2019) studied contamination of groundwater with respect to fluoride and its dynamic effects were assessed with the aid of hydro-geochemical signatures, chemometric methods and medical geological aspects. Notwithstanding, to the best of the knowledge of the authors, none of the studies have been reported on exploring and verifying the geospatial modeling for identification of fluoride contamination zones in the research area, where the study area is particularly important as it is characterized by both crystalline and alluvial aquifer units. Hence, in the current investigation, a knowledge driven Multi-Criteria Decision Making- Analytical Hierarchy Process (MCDM – AHP) approach coupled with the GIS environment has been exercised for delineating the spatial distribution of groundwater fluoride contamination regions in parts of Jamui district, Bihar, India. The main objectives of the study comprise of mapping fluoride affected hazardous zones by considering various geological features and assigning their optimized MCDM - AHP based weight/ratings for the computation of FCZ indices. Finally, the verification of the FCZ map was carried out with measured fluoride concentrations to evaluate the proposed model performance through which the prognostication of fluoride contamination zones can be planned.

2.0 Study area

The proposed study area is a part of Jamui district in the state of Bihar, India and lies between North latitude 24°40' to 25°10' and East longitude 85°50' to 86°35' with a total extent of 1791 km². The geology of the study area is composed of rocky upland, pediplain and alluvial plains. Alluvial plains in the study area were formed by continental Quaternary deposits and is a part of the Jamui Formation and is generally termed as “older alluvium” in Indian geology. The major rock types which cover the region are quartzite, quartz-mica schist, biotite-muscovite schist, granites, composite gneisses, pegmatite, amphibolite and quartz veins. The most potential
Aquifers are common in the alluvial formation. The thickness of the alluvium gradually increases towards the north and finally merges with the Gangetic alluvium, south of the River Ganga. The total thickness of the alluvium ranges from 90 m in the northern part and is finally reduced to less than 12 m in the southern part. Some other landforms like, escarpment, inselbergs and valley fills are also present in the area. Humid climate dominates the area and is the driving factor responsible for the weathering of the overlying mantle. Elevated fluoride concentration in the groundwater of the study area might have been generated due to weathering of this fluoride bearing material from granite, granite-gneiss, amphibolites and mica-schists and deposition of same over the parent rock as a weathered mantle. A tropical southwestern monsoon climate governs the area with an average annual precipitation of 1042 mm. Infiltration from monsoon rainfall contributes to the major part of the recharge of aquifers.

3.0 Materials and methods

High density polyethylene bottles (HDPE) were used for the collection of water samples for fluoride analysis. Sample bottles were cleaned several times using distilled water prior to sampling. A total of 61 groundwater samples were collected in the month of May 2014 for the estimation of fluoride. The samples were analyzed for fluoride concentration using Systronic make UV-VIS spectrophotometer (2202) within two weeks after the collection of samples. The standard procedure provided by the American Public Health Association (APHA 2012) was strictly adhered during analysis.

3.1 Development of thematic layers

In order to delineate fluoride contaminated zones, a total of 10 separate thematic layers were prepared for the investigation using conventional chemical data, remote sensing (RS) and Arc
GIS 10.3. The thematic layers include aquifer (A), geomorphology (G), soil texture (S), slope/topography (T), elevation (E), drainage density (D) and distribution of rainfall (R), depth to water table (D), land use land cover (LULC) and lineament density (L). Details of the thematic layers are given in Table 1. The methodology followed is shown in Fig. 1. Geomorphological details of the region were prepared with the help of the groundwater information booklet Jamui district, Bihar, India (CGWB, 2007). Digital elevation model (SRTM, USGS) of 30 m resolution was applied to prepare the slope and elevation map of the study region. Pre-monsoon water table depth for 31 locations was measured for the entire study area in the year 2014. The lineament and land use pattern data were collected from the National Remote Sensing Centre (NRSC), Hyderabad. The study area soil map was prepared from data obtained from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP). Rainfall data for 2013 to 2017 was compiled from Indian Meteorological Department (IMD) and the geological map used to be after the Geological Survey of India (1987).

“Figure 1 is about here”

3.2 Weight assignment and weight normalization factors using AHP

The Analytical Hierarchical Process (AHP), is a very effective approach for handling the complexity of real world decision-making problems, developed by Saaty (1980). A knowledge driven AHP-based multi-criteria decision analysis (MCDM) is a very much popular parameter weight prioritization approach in the prognostication of contaminants. AHP is an effective tool, which reduces the complexity associated with decision making problems into a series of pair-wise comparisons and then synthesizes the outcome of the final results (Arulbalaji et al., 2019). In addition, the AHP-based MCDM approach is also a suitable evaluation technique to evaluate the consistency of final output; accordingly, it reduces the conflict involved in the decision-
making process. Based on the above facts, in the current research work, a combined approach of AHP and GIS technique is used to delineate the fluoride contaminated zones of the area under study. The chosen ten thematic layers were supposed to be accountable for enhanced fluoride concentration in the study region. Hence, the influencing factors were weighted according to their contribution to groundwater contamination, especially with respect to fluoride, field study and keeping in mind review of past studies. A layer with a higher weight illustrates a parameter with a higher contribution towards groundwater contamination and vice versa. According to Saaty’s scales (1980) of relative importance value, assigned weights for selected factors are as follows: similar importance (scale-1), moderate importance of one over another (scale-3), strong importance (scale-5), very strong importance (scale-7), extreme importance (scale-9), intermediate values between the two adjacent judgments (scale-2, 4, 6, 8), reciprocal for inverse comparison (scale-reciprocals of the above nonzero numbers). After the weight assigned to the respective factors, the relative comparison of all the factors with each other was structured to form a pair-wise comparison matrix (Table 2).

“Table 2 is about here”

Pair-wise comparison matrix (Table 2) constructed for the thematic layers is in following accordance:

\[
M = \begin{bmatrix}
A_{11} & A_{12} & \cdots & A_{1n} \\
A_{21} & A_{22} & \cdots & A_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
A_{f1} & A_{f2} & \cdots & A_{fn}
\end{bmatrix}
\]  

(1)

Computed pair wise comparison matrix \((M = [A_{ij}])\) is demonstrated in Table 2 and has been exhibited by applying equation:
\[ A_{fn} = \frac{A_{fn}}{\sum_{j=1}^{x} A_{jn}} \]  \hspace{1cm} (2)

Where, \( n = 1, 2, 3, 4, 5, \ldots, x \), \( A_{fn} \) represents the element of \( f \) row besides \( n \) column of matrix.

(b) Computation of normalized weight (\( w_x \))

The normalized weight (\( w_x \)) was calculated utilizing Eq. 3.

\[ w_x = \frac{\sum_{n=1}^{x} A_{jn}^{-}}{x} \]  \hspace{1cm} (3)

Where, \( f = 1, 2, 3, 4, 5, \ldots, x \)

(c) Examination of uncertainty in judgment

Then to examine the uncertainty, Satty (2004) proposed the principal eigenvalue and consistency index and to examine the uniformity of judgment matrix, the consistency ratio.

Hence, for computing the consistency ratio (CR), the procedure adopted is as follows: (1) first of all, Principal Eigenvalue (\( \lambda \)) was figured out by Eigenvector technique and (2) secondly, Consistency Index (CI) was computed using the Eq. 4

\[ CI = \frac{\lambda_{\text{max}} - n}{n - 1} \]  \hspace{1cm} (4)

In the above mentioned equation, \( n \) represents no. of thematic layers (\( n = 10 \) in this case) whereas \( \lambda_{\text{max}} \) represents the maximum eigenvalue of the pair-wise comparison matrix.

Ultimately, Consistency ratio (CR) was derived by using Eq. 5.

\[ CR = \frac{CI}{RCI} \]  \hspace{1cm} (5)

Where \( CI \) represents the consistency index and \( RCI \) denotes the random consistency index, respectively. \( RCI \) values are considered from Saaty’s (1980), 1-9 point scale for the selected
number of parameters. Saaty’s ratio index (RCI) for corresponding numbers of parameters (n) is as follows: n-1 (RCI-0), n-2 (RCI-0), n-3 (RCI-0.52), n-4 (RCI-0.89), n-5 (RCI-1.11), n-6 (RCI-1.25), n-7 (RCI-1.35), n-8 (RCI-1.10), n-9 (RCI-1.45) and n-1 (RCI-1.49). Satty (1980) advocated that CR value less than 10%, defends the consistency in the pair-wise comparison. In this study, the CR value is 5.5% and thus withstands the consistency.

The normalized computed weights for all the thematic layers were finalized for further analysis. Thereafter, the subclasses of thematic layers were re-classified in the GIS platform. The ratings of subclasses of each thematic layer were allocated on a gradation of 1 to 9, according to their relative significance with respect to the contribution to the groundwater fluoride contamination.

### 3.3 Weighted overlay index-based approach (WOIA)

The WOIA method is utilized by a good number of researchers globally in different regions in varying hydro-geologic settings (Elewa and Qaddah., 2011; Ghazavi and Ebrahimi., 2015; Al-Abadi et al., 2017; Singha et al., 2017; Thapa et al., 2018). The ratings and weights of all the ten layers were multiplied and summed up together to demarcate fluoride contaminated zones (FCZ). FCZ for the study area has been computed by using the following equation:

\[ FCZ = \sum_{i=1}^{n} (P_i Q_w) \]  

Where \( P \) and \( Q \) denote the parameters and subscript \( r \) and \( w \) are the respective ratings designated to parameter subclasses and weights to each parameter class. Hence, this is the most well-known, simple and flexible method for integrating all the thematic layers in the GIS environment. Accordingly, the final fluoride contamination zone map was classified into two categories, namely, safe and unsafe zone.
4.0 Results and discussion

4.1 Role of Hydrogeo-meteorological factors and groundwater quality

Dynamic groundwater resource of the phreatic aquifer in the study area gets replenished each year, mainly by diffuse rain fed recharge apart from that managed recharge consisting of planned and unplanned recharge through various artificial recharge structures and seepage from water bodies and irrigation fields. Water that recharges the groundwater, gets altered during its course of infiltration and precipitation thereby acquire mixed quality depending on the source and passing media (i.e. Hydrogeo-meteorological parameters). Therefore, groundwater quality and its occurrence is dependent upon various hydrogeo-meteorological factors viz., aquifer media, geomorphology, soil texture, slope, elevation, drainage density, rainfall distribution, depth to the water table, land use land cover and lineament density. On the basis of each parameter characteristics and significance in terms of potential groundwater contamination with respect to fluoride, relative rating and weights have been assigned and fluoride contaminated zones (FCZ) were demarcated after building of each thematic layer as mentioned in the following section.

Aquifer media imparts a vital role in absorption, storage, the transmission of water and the residence time of groundwater. The coarser the aquifer material, the lesser is the residence time and lesser the chances of groundwater contamination and vice versa. Based on the aquifer characteristics (media), the study area was categorized into four classes, viz., alluvial, biotite-muscovite-chloride schist, granite gneiss, quartzite, quartz schist and phyllite extending over an area of around 113 km², 818 km², 506 km² and 353 km² respectively. The aquifer map of the study region is shown in Fig. 2a.

Geomorphologic patterns are generally known as the surface indicators revealing the conditions for groundwater occurrence of a region (Preeza et al., 2011). Moreover, it also reflects the
underlying geological formation that is responsible for groundwater occurrence, storage, transmission and its residence time. Hence, the geomorphology of the study area plays an important role in groundwater studies (Machiwal et al., 2011; Singha et al., 2019b). In the study area, Quaternary alluvial plains occupy an area of about 463 km$^2$, denudational hills and piedmont covers an area of about 730 km$^2$ and pediplain covers an area of about 598 km$^2$ respectively. The geomorphological pattern of the study area is shown in Fig. 2b.

Soil texture is one of the influencing factors considered for any groundwater-related studies as it exhibits the infiltration rate of the soil media through which water flows and reaches the aquifer. The coarser the soil media, the lesser will be the holding capacity and more will be the chances of contaminants to reach the aquifer and vice versa. In the study area, coarse loamy soil extends over an area of about 458 km$^2$ approximately, whereas fine loamy soil extends over an area of about 1333 km$^2$. Coarse loamy soil has been assigned higher weightage due to its high infiltration rate. The soil texture map of the study area is shown in Fig. 2c.

The slope is another important factor in groundwater studies, that greatly influences the recharge of groundwater, i.e., gentle to flat slopes will contribute to less runoff, thereby increases the infiltration rate and groundwater contamination. On the contrary, segments of the study area, with higher slope (steep slope) results in a higher runoff, lower infiltration rate and consequently reduces the chances of groundwater contamination. According to the slope, the study area was categorized into five classes such as 0-3%, 3-6%, 6-9%, 9-12% and more than 12% encompassing over an area of approximately, 654 km$^2$, 626 km$^2$, 210 km$^2$, 65 km$^2$ and 236.99 km$^2$ respectively. The slope map of the study area is shown in Fig. 2d.

"Figure 2 is about here"

Elevation and slope of a region signify the storage of groundwater, i.e., a lower slope tends to higher groundwater storage in comparison to the areas with steeper slope (Thapa et al., 2017). In
the study area, around 1415 km² area falls in an elevation varying from 42-167 m, 297 km² falls in between 167-292 m, 70 km² falls within 292 to 417 m and 9 km² area falls in between 417-542 m respectively. The elevation map of the study area is shown in Fig. 2e.

Drainage density is known as the proximity of the spacing of the flow channels. The drainage density is inversely correlated to the permeability factor. Drainage density is inversely related to the permeability of aquifers (Arulbalaji et al., 2019). The higher drainage density of an area indicates the presence of a less permeable lithological unit resulting in more runoff within the region (Rashid et al., 2012). Hence, higher drainage density indicates low recharge and lower chances of subsurface water contamination and vice versa (Bagyaraj et al., 2013). In the study area, drainage density was classified into five categories such as 0-3 km/km² encompassing over an area of around 1264 km², 3-6 km/km² extending over an area of about 369 km², 6-9 km/km² with 104 km², 9-12 km/km² with 45 km² and more than 12 km/km² accounts for 9 km² approximately in the study area respectively. The drainage density map of the study region in the Jamui district is shown in Fig. 2f.

Intensity, duration, and distribution of rainfall in a region also impart a vital role in respect to infiltration and contamination rate. Higher intensity and shorter duration infer the higher rate of runoff and lower infiltration, hence lower chances of groundwater contamination and conversely (Ibrahim-Bathis and Ahmed, 2016). The study area experiences an annual rainfall varying from 718 mm/year to 1071 mm/year and was classified accordingly into three subclasses such as 718-835 mm (around 117 km² of total area), 835-952 mm (1225 km²) and more than 952 mm (449 km²) respectively. The rainfall distribution map of the study area is shown in Fig. 2g.

Depth to the water table is one of the most significant parameters amongst other selected parameters as it depicts the thickness (band) of material through which contaminant travels from
the surface to the groundwater table before reaching an aquifer. The deeper the water table depth, the lesser the possibilities of contaminants to reach within subsurface water (Senthilkumar et al., 2014). Pre-monsoon water table depth has been considered for the study and was classified into four categories, i.e., 0-3 m, 3-6 m, 6-9 m, more than 9 m which encompasses over an area of around 5 km², 1138 km², 634 km², and 15 km² respectively. The range of depth to water table varies in the study area from 1.93 m to 12.06 m. The depth to water table map is shown in Fig. 2h.

Land Use Land Cover (LULC) is considered as one of the important parameters as it is intimately associated with the groundwater quality of an area and also refers to all the activities that occur on the land surface (Wu et al., 2016). In the present study, LULC was classified into six categories, namely, barren rocky land with occasional scrubs, cropland, fallow land, forest and plantation, rural and urban settlements and water bodies, which covers an area of about 287 km², 611 km², 359 km², 407 km², 66 km², and 61 km² respectively. The LULC map is shown in Fig. 2i.

The lineaments in the geological units are mainly the linear fractures detected on satellite images and aerial photographs. Several researchers have advocated the positive relationship between groundwater flow and yield with respect to the lineament density. Thus, detailed information on the presence of lineaments in sub-surface lithological units are very important for groundwater development and management studies (Al-Rawabdeh et al., 2015). The possibility of groundwater pollution is increased due to the availability of higher lineament density that promotes the infiltration of contaminants into groundwater. In the present study, lineament density was classified into six subclasses i.e., 0-0.5 km/km², which encompasses over an area of about 1391 km², 0.5-1 km/km², 1-1.5 km/km², 1.5-2.0 km/km², 2-2.5 km/km² and more than 2.5
km/km² extends over an area around 157 km², 61 km², 51 km², 33 km² and 91 km² respectively. The prepared lineament density map is shown as Fig. 2j.

4.2 Delineation of potential fluoride contaminated zones (FCZ)

As discussed earlier in section 3.2, factors weight and rating were assigned based on a knowledge based AHP-based multi-criteria decision analysis (MCDM) and then potential fluoride contaminated zones (FCZ) map was obtained by overlaying all the ten thematic layers in Arc GIS 10.3 software. Figure 3(a) illustrates the distribution of potential fluoride contaminated zones in the study area that implied the maximum and minimum indices values of the final output within a range of 4.05 to 8.29. Thereafter, by using the “jenks natural breaks”, the FCZ map was classified into two categories namely, safe and unsafe zones with respect to fluoride contamination. The safe zone means an area having fluoride concentration less than 1.5 mg/L, whereas, the unsafe zone indicates the area with fluoride concentration higher than the permissible limit, i.e., above 1.5 mg/L (BIS, 2012).

Based on the FCZ map (Fig. 3a), some parts of the study region belong to the safe category covering an area of 1101.82 km² (61.52% of the total area). Groundwater from these zones is suitable for drinking and other uses whereas, mostly the southeastern, southwestern parts and a few stretches in the upper central northern portions were reflected as higher fluoride contamination zones/ unsafe zones, covering an area of about 689.18 Km² (38.48% of the total area) was unsuitable for drinking. Afterward, the reported unsafe zones were compared with the geology of the area which indicates that these regions were underlain by granite-gneiss/ granites with intensely fractured basement rocks. The relatively higher ratings assigned to the existing litho-units and structural features, including faults during the model computation process and are forming the basis for assigning these areas as responsible as unsafe zones.
Furthermore, the results of the present study are in concurrence with the earlier studies conducted by Kumar et al., (2017 and 2019) with the aid of hydro-geochemical signatures that the elevated fluoride values are reported in the study area were of the geogenic source (granite gneiss). Additionally, barren rocky land with occasional scrubs and the existence of cropland may also contribute to elevated fluoride in groundwater being one of the prime anthropogenic sources in a few places albeit to the lower extent. Similarly, the presence of pediplains and relatively high rainfall distribution were also one of the leading factors responsible for the contribution of high fluoride concentration which in turn results in an unsafe zone.

“Figure 3 is about here”

4.3 Validation of the proposed fluoride contamination zone (FCZ) map

In general, the AHP-based MCDM approach works with certain assumptions while assigning ratings and weights purely based on the inputs provided by the modeler. Any error or imprecise invoking of input parameters into the model may lead to erroneous results and thereby by the failure of the approach. Therefore, it is imperative to validate the results obtained through the knowledge based AHP-based MCDM approach model with the real ground conditions, in order to avoid the uncertainties, if any. This will also ensure the accuracy and precision of the model.

For this sake, sixty-one groundwater samples covering the entire study area were collected during May 2014 and analyzed for fluoride concentrations were overlaid on the final FCZ map. Figure 3b shows the superimposition of on-site fluoride sampling locations with the prepared fluoride contamination zone map. Thereafter, an agreement between predicted FCZ (pixel with FCZ values) and the measured fluoride concentration of respective locations have been checked (Table 3). Overall, 52 wells out of 61 wells with fluoride concentrations are having an agreement
concerning the respective fluoride contaminated zones. Therefore, it is prudent to conclude that the map of FCZ zones predicts the occurrence of fluoride contamination with 85.24% accuracy.

“Table 3 is about here”

5.0 Conclusions

In the present work, a knowledge based MCDM based model coupled with the application of remote sensing and GIS techniques has been proven to be an efficient tool for mapping fluoride contamination zones (FCZ) using selected hydro-geo-meteorological parameters. The findings were confirmed with a real fluoride concentration in wells obtained from 61 locations. The validation of actual fluoride concentration with the proposed model exhibited an agreement of around 85%, signifying the accuracy of the final model output. The results of the study revealed that 61.52% of the total area appeared as a safe zone, whereas 38.48% of the total area emerged as unsafe zones i.e., areas with more than 1.5 mg/L fluoride concentration in groundwater.

The main advantage of the current study was the integration of a number of the hydro-geo-meteorological thematic layers on a regional scale that can be successfully adapted to delineate fluoride contaminated zones. In addition to this, the preciseness of model output to measure the authenticity and reliability level can also be taken into consideration by cross checking the generated output map with measured fluoride concentrations. Similarly, the major constraint of this approach is the absence of comprehensive information on a regional scale, especially for uneven distribution of reported fluoride point data and mineralogical composition of the rocks. In spite of this limitation, such type of FCZ mapping has been attempted first time in the study area in order to provide an insight into the potential fluoride contaminated zones. The FCZ map will
be very much helpful for the researchers, planners, and administrators in assessing the severity of contamination of fluoride concentration in groundwater. The FCZ map will also be helpful for evaluating the regions of the study area in the need of drinking water free from fluoride contamination. The unsafe zones can be identified for the construction of artificial recharge structures for diluting the concentration of fluoride in groundwater along with other remedial measures.

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### List of Tables

#### Table 1: Details of the ten thematic layers along with their areal extents.

| Parameter                  | Subclass                                    | Rating | Normalized weight | Area (km²) | Percentage area (%) |
|----------------------------|----------------------------------------------|--------|-------------------|------------|---------------------|
| Aquifer                    | Alluvial                                     | 4      | 0.195             | 113.67     | 6.35                |
|                            | Biotite-muscovite-chloride schist            | 8      | 0.187             | 818.47     | 45.70               |
|                            | Granite gneiss                               | 10     | 0.098             | 505.75     | 28.24               |
|                            | Quartzite, quartz schist and phyllite        | 5      | 0.093             | 353.11     | 19.72               |
| Geomorphology              | Alluvial plain                               | 4      | 0.096             | 463.2      | 25.86               |
|                            | Denudational hill and Piedmont               | 3      | 0.069             | 729.7      | 40.74               |
|                            | Pediplain                                    | 9      |                   | 598.1      | 33.39               |
| Soil texture               | Coarse loamy soil                           | 9      | 0.166             | 457.60     | 25.55               |
|                            | Fine loamy soil                             | 5      |                   | 1333.40    | 74.45               |
| Slope (%)                  | 0-3%                                         | 9      | 0.021             | 653.67     | 36.50               |
|                            | 3-6%                                         | 7      |                   | 625.73     | 34.94               |
|                            | 6-9%                                         | 5      |                   | 210.02     | 11.73               |
|                            | 9-12%                                        | 3      |                   | 64.59      | 3.61                |
|                            | >12%                                         | 1      |                   | 236.99     | 13.23               |
| Elevation                  | 42-167                                       | 9      | 0.021             | 1414.77    | 78.99               |
|                            | 167-292                                      | 6      |                   | 297.35     | 16.60               |
|                            | 292-417                                      | 3      |                   | 69.71      | 3.89                |
|                            | 417-542                                      | 1      |                   | 9.17       | 0.51                |
| Drainage density           | 0-3 km/km²                                   | 9      | 0.100             | 1264.49    | 70.60               |
|                            | 3 to 6 km/km²                                | 7      |                   | 369.23     | 20.62               |
|                            | 6 to 9 km/km²                                | 5      |                   | 103.7      | 5.79                |
|                            | 9 to 12 km/km²                               | 2      |                   | 44.71      | 2.50                |
|                            | >12 km/km²                                   | 1      |                   | 8.87       | 0.50                |
| Rainfall (mm/year)         | 718-835                                      | 4      | 0.120             | 116.85     | 6.52                |
|                            | 835-952                                      | 6      |                   | 1224.71    | 68.38               |
|                            | >952                                         | 8      |                   | 449.44     | 25.09               |
| Depth to water table (m)   | 0 to 3                                       | 3      | 0.170             | 4.63       | 0.26                |
|                            | 3 to 6                                       | 5      |                   | 1137.98    | 63.54               |
|                            | 6 to 9                                       | 7      |                   | 633.77     | 35.39               |
|                            | > 9                                          | 9      |                   | 14.62      | 0.82                |
| Land use land cover        | Barren rocky land with occasional scrub      | 9      | 0.077             | 287.39     | 16.05               |
|                            | Crop land                                    | 7      |                   | 611.32     | 34.13               |
|                            | Fallow land                                  | 3      |                   | 358.83     | 20.04               |
|                            | Forrest and plantation                       | 4      |                   | 406.72     | 22.71               |
|                            | Rural and urban settlement                   | 1      |                   | 65.82      | 3.68                |
|                            | Water body                                   | 2      |                   | 60.92      | 3.40                |
| Lineament density (km/km²) | 0-0.5 km/km²                                  | 2      | 0.034             | 1390.87    | 77.66               |
|                            | 0.5-1.0 km/km²                               | 3      |                   | 156.77     | 8.75                |
|                            | 1.0-1.5 km/km²                               | 4      |                   | 60.82      | 3.40                |
|                            | 1.5-2.0 km/km²                               | 5      |                   | 50.81      | 2.84                |
Table 2: Pair wise comparison matrix established amidst ten thematic layers.

| Parameter | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|-----------|----|----|----|----|----|----|----|----|----|-----|
| P1 | 1.00 | 2.00 | 1.00 | 3.00 | 3.00 | 2.00 | 2.00 | 4.00 | 6.00 | 6.00 |
| P2 | 0.50 | 1.00 | 1.00 | 3.00 | 3.00 | 2.00 | 3.00 | 3.00 | 5.00 | 5.00 |
| P3 | 1.00 | 1.00 | 1.00 | 2.00 | 2.00 | 2.00 | 3.00 | 4.00 | 6.00 | 6.00 |
| P4 | 0.33 | 0.33 | 0.50 | 1.00 | 2.00 | 2.00 | 3.00 | 4.00 | 5.00 | 5.00 |
| P5 | 0.33 | 0.33 | 0.50 | 0.50 | 1.00 | 1.00 | 3.00 | 4.00 | 6.00 | 6.00 |
| P6 | 0.50 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 | 2.00 | 3.00 | 6.00 | 6.00 |
| P7 | 0.50 | 0.33 | 0.33 | 0.33 | 0.33 | 0.50 | 1.00 | 5.00 | 6.00 | 6.00 |
| P8 | 0.25 | 0.33 | 0.25 | 0.25 | 0.25 | 0.33 | 0.20 | 1.00 | 2.00 | 2.00 |
| P9 | 0.17 | 0.20 | 0.17 | 0.20 | 0.17 | 0.17 | 0.17 | 0.50 | 1.00 | 1.00 |
| P10 | 0.17 | 0.20 | 0.17 | 0.20 | 0.17 | 0.17 | 0.17 | 0.50 | 1.00 | 1.00 |

Table 3: Agreement details of measured fluoride concentration with fluoride contamination zones.

| Sr | Location | Longitude | Latitude | Type of Sample | Catchment Area (Lithology) | Fluoride concentration (mg/L) | Zone | Agreement |
|----|----------|-----------|----------|----------------|---------------------------|-------------------------------|------|------------|
| 1  | Bhimbandh| 86.3750   | 25.0620  | HP             |                           | 0.09                          | 2.0-2.5 | Agree      |
| 2  | Sikandara| 86.0500   | 24.9333  | HP             | Alluvium                  | 0.08                          | 2.0-2.5 | Agree      |
| 3  | Maniadda | 86.2109   | 24.9580  | HP             | Alluvium                  | 0.14                          | 2.0-2.5 | Agree      |
| 4  | Nawadi   | 86.0000   | 24.9202  | HP             | Alluvium                  | 0.14                          | 2.0-2.5 | Agree      |
| 5  | Corporation Bank | 86.1569 | 24.9267  | HP             | Alluvium                  | 0.18                          | 2.0-2.5 | Agree      |
| 6  | Kala     | 86.4085   | 24.9654  | HP             | Hard rock                 | 0.20                          | 2.0-2.5 | Agree      |
| 7  | Manjhos  | 86.1043   | 24.9600  | HP             | Alluvium                  | 0.21                          | 2.0-2.5 | Agree      |
| 8  | Bhemain  | 86.2176   | 24.7882  | HP             | Alluvium                  | 0.22                          | 2.0-2.5 | Agree      |
| 9  | Domachak | 86.4108   | 24.9980  | HP             | Hard rock                 | 0.23                          | 2.0-2.5 | Agree      |
| 10 | Amaratah | 86.1883   | 24.9536  | HP             | Alluvium                  | 0.26                          | 2.0-2.5 | Agree      |
| 11 | Lakshimpur| 86.4031  | 25.0069  | HP             | Alluvium                  | 0.26                          | 2.0-2.5 | Agree      |
| 12 | Ratanpur | 86.2868   | 24.8992  | HP             | Alluvium                  | 0.36                          | 2.0-2.5 | Agree      |
| 13 | Jogiya   | 86.4032   | 25.0249  | HP             | Hard rock                 | 0.38                          | 2.0-2.5 | Agree      |
| 14 | Fathpur  | 86.1879   | 24.8085  | HP             | Hard rock                 | 0.44                          | 2.0-2.5 | Agree      |
| 15 | Kamat    | 86.2525   | 24.7503  | DW             | Alluvium                  | 0.51                          | 2.0-2.5 | Agree      |
| 16 | Dighi    | 86.4309   | 24.9356  | HP             | Alluvium                  | 0.52                          | 2.0-2.5 | Agree      |
| 17 | jaijha   | 86.3628   | 24.7890  | HP             | Hard rock                 | 0.53                          | 2.0-2.5 | Agree      |
| 18 | Purnakha | 86.1921   | 24.8768  | HP             | Alluvium                  | 0.53                          | 2.0-2.5 | Agree      |
| 19 | Gidhour  | 86.3064   | 24.8564  | HP             | Hard rock                 | 0.54                          | 2.0-2.5 | Agree      |
| 20 | Sonai    | 86.1900   | 24.9954  | HP             | Alluvium                  | 0.55                          | 2.0-2.5 | Agree      |
| 21 | Gugudih  | 86.3181   | 24.9150  | HP             | Alluvium                  | 0.61                          | 2.0-2.5 | Agree      |
| 22 | Jhajab   | 86.3640   | 24.7890  | DW             | Hard rock                 | 0.66                          | 2.0-2.5 | Agree      |
| 23 | Middle School, Barahat | 86.2939 | 25.0200  | HP             | Hard rock                 | 0.67                          | 2.0-2.5 | Agree      |
| 24 | Nawadi   | 86.0000   | 24.9000  | DW             | Alluvium                  | 0.68                          | 2.0-2.5 | Agree      |
| 25 | Lakhuar  | 86.0375   | 24.9611  | DTW            | Alluvium                  | 0.70                          | 2.0-2.5 | Agree      |
| 26 | Patneshwar Temple | 86.2407 | 24.9637  | HP             | Hard rock                 | 0.78                          | 2.0-2.5 | Agree      |
| 27 | Dighoi   | 86.2139   | 24.9794  | HP             | Alluvium                  | 0.83                          | 2.0-2.5 | Agree      |
| 28 | Dehuridih| 86.3000   | 24.7600  | HP             | Alluvium                  | 0.88                          | 2.0-2.5 | Agree      |
| No. | Location          | Latitude  | Longitude | Type   | Depth | Disagree-Mean | Disagree-Median | Disagree-Mean | Disagree-Median | Disagree-Mean | Disagree-Median |
|-----|------------------|-----------|-----------|--------|-------|---------------|----------------|---------------|----------------|---------------|----------------|
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Figure 1: Methodology adopted for portraying fluoride contamination zones (FCZ) in the research area.

Figure 2: Spatial distribution of different thematic layers (a) Aquifer map (b) Geomorphological pattern (c) Soil texture map (d) Slope map (e) Elevation map (f) Drainage density (g) Rainfall distribution (h) Depth to water table (i) Land use land cover pattern (j) Lineament density map of the study area.

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