Groundwater quality in a semi-arid region of India: Suitability for drinking, agriculture and fluoride exposure risk

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Fluoride exposure through consumption of drinking water was studied in a heavily industrialised area and suitable measures were suggested to control the fluorosis risk to residents. Groundwater quality conforms to World Health Organization (WHO) criterion for drinking except for fluoride and is also suitable for irrigation. Fluoride concentration ranges from 0.1 to 4.4 mg/l and 39% of the total samples measured were found to be contaminated as per WHO limits (1.5 mg/l). The fluoride intake through drinking water was calculated to be 0.10 mg/kg/d for infants, 0.09 mg/kg/d for children and 0.05 mg/kg/d for adults with a corresponding exposure dose exceeding 2.1, 1.9 and 1.1 times for infants, children and adults, respectively, compared to the minimum risk value of 0.05 mg/kg/d. The fluorosis risk map indicates that with a few exceptions of some western and northwestern parts, the entire study area is prone to fluorosis and the highest being in the south central part. The fluoride exposure dose suggests the risk of mottled enamel among residents if untreated groundwater is provided for drinking for a long time. Considering the hydrogeological setup of this region, various amelioration methods to help mitigate the ill effects of high fluoride were evaluated and better nutrition containing calcium and vitamin C was found to be the most effective and viable option.

Keywords. Fluorosis risk zone; exposure dose; amelioration; Odisha.

1. Introduction

Groundwater is a major contributor to water supply in most rural communities in India. It is commonly believed that groundwater is a safe source of potable water as it is relatively free from microbiological and inorganic chemicals' contamination and requires minimal treatment. However, in contrast, recent reports suggest that the contamination of groundwater by both geogenic

and anthropogenic sources has been increasing significantly. Fluoride is one of the widespread inorganic contaminants impacting the health of people globally (Frencken 1992; Dean 1993; NRC 1993; Genxu and Guodong 2001; Chae *et al.* 2007; SubbaRao 2011; Jagtap *et al.* 2012). In humans, F⁻ ingestion normally is through drinking water, food (Malde *et al.* 2011) and polluted air (Batra *et al.* 1995). The F⁻ content of cultivated plants is generally low (except for tea) and contains up to

600 mg/l (Cao *et al.* 2006). However, the bioavailability of the F^- in food materials is generally influenced by the mineral content of the food, e.g., certain ions can form insoluble complexes limiting the F^- bioavailability (Malde *et al.* 2004). Studies suggest that elevated levels of fluoride in drinking water is an important factor that causes dental and skeletal fluorosis in parts of the world including India (Frencken 1992; Jacks *et al.* 2005; Rao *et al.* 2013; Bretzler and Johnson 2015; Choubisa and Choubisa 2016). It is believed that the number of persons affected by fluorosis in Asian and African countries exceeds 70 million (WHO 2006). Based on the ill effects of high fluoride on human health, the World Health Organization (WHO) has established a fluoride standard for drinking water of 1.5 mg/l (WHO 2011). Consumption of drinking water with high fluoride above the WHO limit is deemed to impact humans through dental and skeletal fluorosis. These ailments seem to be more detrimental in children as dental enamel and skeletal formation are most active during the early childhood.

There are reports that 27 out of the 30 districts of Odisha state of India are contaminated by fluoride in drinking water and this has led to acute health disorders (CGWB 2010; Nanda *et al.* 2011). Recent studies suggest that industrial and municipal pollution coupled with high F^- in drinking water led to increasing rates of tuberculosis, cancer and other ailments in habitants of Angul district of Odisha state (Dhadse *et al.* 2008; Dhakate and Rao 2010; Moharana *et al.* 2013). It is reported that children are being affected by poor mental growth and learning disabilities apart from increasing incidences of both skeletal and dental fluorosis. The residents of the study area mostly depend on groundwater resources for drinking, which are poor in quality and causes water-borne diseases (Sahu *et al.* 1991). Investigations on water quality of this region reported high fluoride content (Prasanna *et al.* 2003; Tiwary *et al.* 2009; Keesari *et al.* 2016) and some of these studies also emphasise on the need to pre-treat the water before drinking (Moharana *et al.* 2013). A hydrogeochemical study was conducted by our group on the geochemistry of groundwater and the fluoride release mechanism (Keesari *et al.* 2016). The study inferred that F^- is mostly derived from weathered rocks and that the contribution from effluents from thermal power plants is less.

Several studies addressing water quality issues in this region were conducted; however, there

are no detailed studies on the estimation of fluoride exposure to the residents through drinking water and the potential fluorosis risk zones have also not demarcated. This information is very critical to strategise effective plans for controlling the negative impacts of consumption of high fluoride on human health. The suitability of the water for irrigation was also not attempted. The major objectives of this paper are to: (i) estimate the fluoride exposure through drinking water and compare this with the allowed limits, (ii) demarcate the fluorosis risk zones and (iii) assess the water quality for drinking and irrigation in the Talchir industrial area of Angul District, Odisha.

2. Materials and methods

The study site falls between $20^{\circ}52'30''$ – $20^{\circ}57'30''$ N latitudes and $85^{\circ}08'30''$ – $85^{\circ}14'30''$ E longitudes covering an area of 150 km² (figure 1). Water level depth varies from 1.26 to 13.69 m below ground level (bgl) and the seasonal fluctuation is 0.6 to 1.5 m bgl (Tiwary *et al.* 2009). The river Mahanadi flows towards the east–southeast direction and the river Brahmani flows towards the southeast direction. The area has an average annual rainfall of 1370 mm and falls under the sub-tropical monsoon climate. The temperature typically varies between 11.9° and 44.4°C with an average of 26.9°C. The groundwater is extracted from the recent alluvium deposited along the river courses and at few places from deeper depths tapping weathered and fractured rocks. Dug wells extend up to 10 m bgl while the tube wells and bore wells tap deeper groundwater (up to 300 m bgl) and mostly concentrated in the Gondwana formation.

Twenty-eight groundwater samples were collected from available sources (bore wells, hand pumps and dug wells) as shown in figure 1. The sample details are given in table 1. Water samples were filtered through 0.45 µm pore size membrane filters before storing in a clean polythene bottle. Samples were acidified using conc. HNO_3 to pH = 2 for cation measurements while unacidified samples were used for anion measurements. *In situ* parameters (temperature, pH, dissolved oxygen (DO) and electrical conductivity (EC)) were measured by water quality kits (Corning model 313 and Orion model 130). Alkalinity was measured by Gran titration. Chemical species [anions (Cl^- , SO_4^{2-} , NO_3^-]

Figure 1. Sample location map.

and F^-) and cations (Na^+ , Ca^{2+} , Mg^{2+} and K^+)] were measured by ion chromatography system (Dionex DX-500). The accuracy of the chemical ion data was calculated using the charge balance equation given below and the charge balance error (CBE) values were within the accepted limits of $\pm 5\%$ (Hounslow 1995):

$$CBE = \frac{\text{meq}(\text{cations}) - \text{meq}(\text{anions})}{\text{meq}(\text{cations}) + \text{meq}(\text{anions})} \times 100. \quad (1)$$

3. Results and discussion

3.1 Fluoride exposure dose

The dissolved fluoride concentration in the study area ranges from 0.1 to 4.4 mg/l with an average of 1.2 mg/l. A histogram of the fluoride distribution is shown in figure 2. About 39% of the total samples measured (11 out of 28 samples) show F^- concentration above the maximum permissible limit of 1.5 mg/l set by WHO (2011) and Bureau of Indian

Table 1. Field parameters and chemical data of groundwater samples.

Sample IID	Source	Temp. (°C)	pH	EC (μS/cm)	mg/L										HCO ₃ ⁻		
					TDS	DO	Li	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	F ⁻	Cl ⁻	NO ₃ ⁻		SO ₄ ²⁻	
1	HP	29.4	7	1545	1081	4.35	0.05	ND	ND	ND	ND	ND	1.7	229	6.2	95.4	363.5
2	HP	29.2	6.4	183	129	5.67	0.02	16.4	5	4.7	24	0.13	7.14	1.6	2.8	146.4	
3	HP	29.1	6.3	253	178	6.08	ND	ND	ND	ND	ND	ND	0.8	54.3	4.5	10.1	44
4	HP	29.7	6.8	614	430	4.64	BDL	65	6.6	21.7	51.5	0.15	25	2.3	25	295.2	
5	HP	28.6	6.7	1852	1297	5.05	ND	ND	ND	ND	ND	ND	1.2	507	147	207	354
6	HP	ND	ND	ND	ND	ND	BDL	15.3	8.3	3.1	12.1	0.6	21.1	3	1.2	133	
7	DW	28.8	7.3	450	317	5.81	ND	ND	ND	ND	ND	ND	0.32	27.6	18.4	52.8	313.5
8	HP	29.3	7.5	800	561	4.9	BDL	63.5	15.3	57.2	97	0.4	53	27	82	500	
9	HP	29.7	7.5	817	572	5.26	BDL	117	4.6	56.5	58.5	0.5	136	27	59	318.4	
10	HP	29.6	7.1	377	264	4.18	BDL	53.8		39	121	1.4	61.5	67.6	61.9	380	
11	HP	29.5	7	1257	878	5.17	0.02	139	1.3	28.4	14.9	1.1	7.8	0.9	13.7	450.2	
12	HP	28.9	6.4	1291	903	5.28	BDL	123	1.5	23	99	4.4	149	28.5	105	465	
13	HP	29.9	7.4	996	696	4.28	BDL	137	0.67	6.7	25.9	1.8	17.1	0.5	14.5	475.8	
14	HP	29.8	7.1	960	672	4.4	0.02	73.5	2.1	18.4	55.5	0.75	23.7	1	13.9	352.5	
15	HP	30.7	7.1	1508	1056	4.81	BDL	102	ND	19.6	30.3	1.7	37.9	3.9	12.4	447.7	
16	HP	29.1	7.4	579	406	7.4	BDL	16.9	0.9	12.1	45.5	0.4	11	19	12.5	220	
17	HP	30.4	7.6	709	496	6.8	BDL	59.6	0.64	26	97.8	0.48	40	11.7	28.6	470.9	
18	HP	29.3	7.2	1910	1340	4.75	0.02	119	15.1	28.7	102	1.3	139	4.7	73.5	399	
19	HP	28.8	6.6	2160	1510	6.45	BDL	316	3.2	108	91	3.7	685	26	174	78.8	
20	DW	27.76	7.61	674	472	4.97	BDL	53	ND	36	25	1.5	55	20.4	106	490	
21	HP	29.6	6.6	306	215	5.45	ND	ND	ND	ND	ND	1.7	346	33.8	199	190	
22	HP	29.2	7.6	1061	744	4.29	BDL	191	1.6	40	20.9	1.5	76.7	29.7	88	632	
23	HP	29.2	7.1	1411	987	5.17	BDL	16.6	4.3	2.9	24	0.3	14.5	4.8	13.6	114.2	
24	DW	26.8	7.8	1515	1061	5.3	BDL	168	4.2	14.3	64.5	0.5	113	38.7	118	405	
25	HP	28.1	7.2	2195	1534	4.89	BDL	161	4.9	83.5	114	1.6	195	81	127	527	
26	HP	29.5	7.4	94	66	6.9	BDL	5.4	2	3.3	11.6	1.1	0.8	0.1	5	68.3	
27	HP	29.1	7.1	1956	1371	4.77	BDL	27.5	5.9	45	86.3	0.9	217	43	51	248	
28	HP	29.7	7	287	202	5.22	ND	ND	ND	ND	ND	1.8	112	8.2	13	163.5	

Note: EC, electrical conductivity; DO, dissolved oxygen; ND, not determined; BDL, below detection limit; sample ID is same as shown in figure 1.

Figure 2. Histogram of the F^- concentration (inset pie chart of % sample exceeding WHO limit).

Standards (BIS 2012) as shown in figure 2 (inset). Fluoride concentration up to 1.0 mg/l in potable water is considered good for skeletal and dental growth, but higher amount beyond 1.5 mg/l can result in health ailments (WHO 2011). The concentration of fluoride between 1.5 and 3.0 mg/l in drinking water results in browning and mottling of teeth, which is an initial manifestation of dental fluorosis and this further leads to hard and brittle teeth. F^- level between 4 and 8 mg/l results in skeletal fluorosis, which further develops into crippling fluorosis when the F^- level rises above 10 mg/l. Excessive F^- ingestion has other health effects such as urinary tract malfunction, muscle fibre degeneration, gastrointestinal problems, red blood cell deformities, reduced immunity and neurological manifestations (Lian-Fang and Jian-Zhong 1995; Fordyce *et al.* 2007; Shailaja and Johnson 2007; Davies 2008; WHO 2011; Chen *et al.* 2012).

The fluoride exposure dose was calculated for humans (infants, children and adults) based on the following equation (Jha *et al.* 2009):

$$\text{Exposure dose} = \frac{C \times WI}{BW}, \quad (2)$$

where C is the total bioavailable fluoride concentration (mg/l) in groundwater, WI is the water intake (l/d) and BW is the body weight (kg). In this case, the dose was calculated by assuming exposure is chronic and the total dissolved fluoride represents the total bioavailable fluoride (Jackson *et al.* 2002). It was also assumed that groundwater is the only

Figure 3. Fluoride exposure dose to residents of this region.

source of drinking for the residents of this area; however, packaged water is also used for drinking in some instances. Water intake for different ages of humans was taken as 0.25, 1.5 and 3 l/d for infants (6 kg body weight), children (20 kg body weight) and adults (70 kg body weight), respectively (Brindha *et al.* 2016). The concentration of fluoride was doubled in the case of infants taking into account boiling of water for milk preparation (Grimaldo *et al.* 1995).

A Box-Whisker plot of the exposure doses of fluoride for three age groups, adults, children and infants, is given in figure 3. An estimated level for minimum risk (0.05 mg/kg/d) by Agency for Toxic Substances and Diseases Registry (Levy 1994; ATSDR 2003) was also given in figure 3. The median value of the exposure dose for adults was at par with the minimum risk level while for children and infants the median values exceed that of the minimum risk level. Even though the daily ingested total F^- through food is not considered in this study, the exposure dose of F^- based on water intake alone shows that groundwater consumption by residents in this area can lead to fluorosis. The risk exposure is found to be about two times higher for infant and children compared to the adults (table 2). The true estimate considering the fluoride ingestion through vegetables, fruits and prepared food would be higher than the calculated one. On the other hand, other sources of drinking water such as packaged water or treated groundwater by conventional techniques such as osmosis or filtration reduce the fluoride exposure.

The maximum values of exposure doses for different age groups in this area are comparable to other fluorosis affected regions such as Nalgonda, India

Table 2. Exposure dose and risk exposure in different ages.

	Infant	Child	Adult
Body weight (kg) (Jha <i>et al.</i> 2009)	6	20	70
F ⁻ in water (average; figure 3)	1.2	1.2	1.2
Water intake (l/d) (Brindha <i>et al.</i> 2016)	0.25	1.5	3
Exposure dose (ED) (mg/kg/d)	0.10	0.09	0.05
Standard (STD) (mg/kg/d) (Levy 1994)	0.05	0.05	0.05
Risk exposure (ED/STD)	2.1	1.9	1.1

Figure 4. Spatial distribution of (a) fluoride exposure to the public through drinking water, (b) nitrate concentration (mg/l), (c) total hardness (mg/l) and (d) sodium percent of groundwater samples.

(Brindha and Elango 2013), Pambar basin, Tamil Nadu (Kalpana and Elango 2013), Vaniyar basin, Tamil Nadu (Jagadeshan *et al.* 2015), Dindigul district of Tamil Nadu (Viswanathan *et al.* 2009), Bushehr province in southern Iran (Battaleb-Looie *et al.* 2013) and others. A fluoride risk map is shown in figure 4(a). An average value of F⁻ exposure to different age groups was used for contouring purpose. It can be seen from the figure that the southern part of the study area has the maximum fluoride exposure risk to the residents of this region.

However, with the exception of some western and northwestern parts, the entire study area is prone to fluorosis.

3.2 Suitability of other parameters to drinking purpose

The major ion and physical parameter data of groundwater samples is shown by Box-Whisker plots (figure 5a-l). Most of the parameters showed a narrow distribution in groundwater. No extreme

Figure 5. Box-Whisker plot of physicochemical and chemical parameters: (a) temperature ($^{\circ}\text{C}$), (b) pH, (c) EC, (d) DO, (e) sodium, (f) potassium, (g) magnesium, (h) calcium, (i) chloride, (j) nitrate, (k) sulphate and (l) bicarbonate. All concentrations are expressed in mg/l except temperature, pH and EC ($\mu\text{S}/\text{cm}$).

values for physical or chemical parameters were noticed in this region indicating that the overall chemistry of the groundwater is uniform throughout the study region. The basic water types were found to be Na-Ca- HCO_3 , Na-Mg- HCO_3 , Ca-Mg- HCO_3 and Ca-Na- HCO_3 . A detailed hydrochemical interpretation on facies variation and fluoride release mechanism has been given in Keesari *et al.* (2016).

The hydrochemical parameters of groundwater were checked for suitability for domestic purposes based on the recommendations by WHO (2011) and BIS (2012). The average values of different water quality parameters are within the permissible limits as per WHO and BIS, whereas individual samples have shown higher concentrations than the prescribed limits (table 3). Most of the samples show ion concentration within the WHO guideline values (figure 5a-l). Only a few samples show pH, total dissolved solids (TDS), Mg^{2+} , Cl^- and NO_3^- concentrations above the WHO guideline values (figure 5b, c, g, i and j).

Potassium is an essential nutrient that is critical to the functioning of nerve and muscle cells, which if taken in excess may cause hyperkalaemia or hypokalaemia if one is deficient in K^+ . No permissible limit has been suggested for this ion in groundwater by WHO; however, the European Community (EU 1980) has issued a guideline value of 10 mg/l and maximum admissible level of 12 mg/l. Two samples showed K^+ concentration above prescribed drinking water limits (figure 5f). Nitrate is soluble and leaches through soil along with the infiltrating water. Common sources for high nitrate are decaying organic matter, domestic wastes (David and Gentry 2000) and fertilisers (Tripathi *et al.* 2000). Consumption of water with high nitrate in potable water can lead to methemoglobinemia (blue baby syndrome) in infants. Groundwater of this area contains nitrate in the range of 0.5–147 mg/l and 11% of the samples show contamination (table 3 and figure 5j). The contour diagram of nitrate in groundwater suggests that the nitrate contamination (>45 mg/l) was noticed only at a few locations (figure 4b).

Table 3. Percentage of water samples suitability for drinking purposes based on BIS (2012) and WHO (2011).

Parameter	BIS (2012)		WHO (2011)	Samples exceeding (%)		Undesirable effect produced beyond the MPL
	DL	MPL	Guideline value	As per BIS (2012) MPL	As per WHO (2011)	
pH	6.5–8.5	No relaxation	6.5–8.5	11	11	Taste effects, mucus membrane and water supply system
TH (as CaCO ₃) (mg/l)	200	600	500	9	9	Calcification of arteries. It may cause urinary concretions, diseases of kidney and stomach disorders
TDS (mg/l)	500	2000	1000	0	3	Palatability decreases and may cause gastrointestinal irritation in humans
Magnesium (Mg ²⁺) (mg/l)	30	100	100	4.5	4.5	Its salts are cathartics and diuretic. High conc. may have a laxative effect particularly on new users
Chloride (Cl ⁻) (mg/l)	250	1000	250	0	11	May be injurious to some people suffering from diseases of heart or kidneys. Taste, indigestion, and palatability are affected
Nitrate (NO ₃ ⁻) (mg/l)	45	No relaxation	50	11	11	Methaemoglobinaemia in bottle-fed infants
Fluoride (F ⁻) (mg/l)	1	1.5	1.5	36	36	Risk of dental caries above 1.5 mg/l, very high concentration may cause crippling skeletal fluorosis

TDS and total hardness (TH) are common indicators to determine the suitability of water for drinking. High TDS in drinking water causes gastrointestinal irritation and laxative effects in humans while high TH may raise the risk of calcification in arteries and also kidney or bladder or stomach disorders. The TDS values in ground-water of this region range between 129 and 1534 mg/l. The water classification based on TDS values (Davies and DeWiest 1966) is given in table 3. It can be seen from the table that 43% of the samples are desirable, 29% of samples are permissible and the rest is unfit for drinking.

Total hardness is caused by dissolved salts of Ca²⁺, Mg²⁺ or Fe and is expressed as mg/l of CaCO₃. It is calculated by the equation given by Todd (1980):

$$TH = 2.497 \times Ca^{2+} + 4.115 \times Mg^{2+}, \quad (3)$$

where Mg²⁺ and Ca²⁺ concentrations are in equivalents per million. The TH values in ground-water samples are in the range of 43–672 mg/l. Based on the classification suggested by Durfor and Becker (1964), 9% fall in soft category, 13% each for moderately hard and hard types whereas the remaining 65% samples fall under the very hard type of water (table 4). The TH contour map is shown in figure 4(c).

3.3 Suitability to irrigation

To evaluate the irrigation suitability of ground-water EC, sodium adsorption ratio (SAR), per cent of sodium (Na%), residual sodium carbonate (RSC), Wilcox diagram and United States Salinity Laboratory (USSL) classification were commonly employed. The high amount of sodium in water used for irrigation impacts the soil permeability and its texture in such a way that soil becomes hard to plough and seedling emergence becomes difficult (Trivedy and Goel 1984). SAR is normally used to quantify the sodium/alkali hazard in a given water sample. Another major concern with high Na⁺ in irrigation water is ion exchange with the alkaline earth metals in soil/clay material. This eventually results in soil with poor internal drainage (Karanth 1987).

The SAR value of a given water sample is calculated using the equation given by Richards (1954):

$$SAR = \frac{Na^+}{\sqrt{Ca^{+2} + Mg^{+2}/2}}, \quad (4)$$

Table 4. Water classification based on TDS and TH.

TDS	Water classification	Samples (%)	Total hardness	Water classification	Samples (%)
Up to 500	Desirable for drinking	43	Up to 60	Soft	9
500–1000	Permissible for drinking	29	60–120	Moderately hard	13
1000–3000	Useful for irrigation	29	120–180	Hard	13
>3000	Unfit for drinking and irrigation	0	>180	Very hard	65

Table 5. Water class based on irrigation suitability.

EC ($\mu\text{S}/\text{cm}$)	Water class	Samples (%)
<250	Excellent	6.90
250–750	Good	37.93
750–2000	Permissible	48.28
2000–3000	Doubtful	6.90
>3000	Unsuitable	0.00
Alkalinity hazard (SAR)		
<10	Excellent	100
10–18	Good	—
18–26	Doubtful	—
>26	Unsuitable	—
Per cent sodium		
<20	Excellent	13.79
20–40	Good	37.93
40–60	Permissible	34.48
60–80	Doubtful	13.79
>80	Unsafe	—
Residual sodium carbonate		
<1.25	Good	51.72
1.25–2.5	Doubtful	24.14
>2.5	Unsuitable	24.14

where the concentrations are in equivalents per million. The SAR values of the groundwater samples of the study area range from 0.5 to 6.2 and belong to low sodium hazard class (table 5).

Na% is another parameter used for assessing the suitability of water for irrigation (Wilcox 1948). Sodium ions present in water samples complexes with HCO_3^- and CO_3^{2-} to form alkaline soils, and combine with chloride to form saline soils. Both these soils are not favourable for plant growth. Na% is calculated using the following equation:

$$\text{Na}\% = \frac{(\text{Na}^+ + \text{K}^+) \times 100}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+}. \quad (5)$$

All the concentrations are in milliequivalents per litre. Na% up to 60 is allowed for agricultural purposes (Ramakrishna 1998). Groundwater of this

Figure 6. Irrigational suitability of groundwater in the study area (Wilcox diagram).

study area has Na% in the range of 14.3–76.3% and four samples show Na% above 60% value (table 5). The spatial distribution of Na% is shown in figure 4(d). In addition to poor drainage of the soils, high Na% in water along with high EC renders reduction in the osmotic activity of plants and limits the absorption of water and nutrients from the soil. In order to visualize the combined effect of both EC and Na%, a diagram proposed by Wilcox (1955) is constructed and shown in figure 6. The majority of the groundwater samples are suitable for irrigation purposes whereas some samples fall in under permissible to doubtful (5) and doubtful to unsuitable (2) categories (figure 6).

The high alkalinity of groundwater (HCO_3^- and CO_3^{2-}) allows the formation of precipitates with Ca^{2+} and Mg^{2+} and makes the water unsuitable

Figure 7. USSSL classification of groundwater in the study area.

for irrigation. RSC is used to quantify this effect and is calculated by the equation given by Eaton (1950):

$$\text{RSC} = (\text{HCO}_3^- + \text{CO}_3^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+}). \quad (6)$$

Water containing RSC less than 1.25 is suitable for irrigation whereas marginally suitable with RSC up to 2.5 and not suitable for irrigation above 2.5 (Lloyd and Heathcote 1985). The RSC values of the groundwater samples of this area range from -12.3 to 6.0 . Groundwater samples fall under good category (51%) and an equal per cent of samples (49%) also fall in doubtful and unsuitable categories (table 5). USSSL diagram (USSL 1954) was employed to further evaluate the irrigational suitability of the groundwater. As per USSSL classification, low-salinity water ($<250 \mu\text{S/cm}$) can be used for all types of soils. In the study area, the majority of the groundwater samples fall into two zones, C2S1 and C3S1, representing medium-to-high salinity and low alkalinity water, respectively (figure 7). These zones indicate that water can be used for irrigation on almost all types of soils with little danger of exchangeable sodium.

3.4 Possible remedial measures

Inorganic ions such as arsenic, fluoride, lead, nitrate, selenium and uranium are considered as the key chemicals responsible for large-scale health effects through drinking water exposure, therefore

providing guidance on identifying local priorities and implementing proper management is very essential for tackling these chemicals in drinking water (WHO 2004, 2011). There are four broad approaches suggested by WHO to limit the negative effects of F^- on public health (WHO 2002). These approaches were evaluated for the current study area considering the hydrogeological constraints (figure 8).

The first approach is the identification of an alternative source of potable water with low fluoride content. In this area, the groundwater is being pumped from the semi-consolidated and consolidated formations and the well yields are less than $100 \text{ m}^3/\text{d}$ signifying moderate-to-low yielding wells (<http://www.indiawaterportal.org>) and the fluoride content is also higher in these formations (up to $1.5\text{--}5 \text{ mg/l}$) (Nanda *et al.* 2011; NEERI 2016). Nearby river and other surface water bodies are also moderately contaminated by fluoride (Keesari *et al.* 2016), hence providing an alternate water source for drinking is not a viable option in this case.

The second approach is to dilute high fluoride water with low fluoride water to attain a mass balance of within 1.5 mg/l . The groundwater resources capacity in the study area fell below 3000 HaM , which is very low (<http://www.indiawaterportal.org>); in addition, the amount of the low F^- groundwater available is not sufficient and also contains high nitrate concentration (figure 4b). The overall groundwater yields are quite low ($\sim 5 \text{ lps}$). The rainfall in the study area is low

Figure 8. Flowchart depicting the suitable strategies for amelioration of fluoride toxicity.

and erratic and therefore frequently results in drought conditions (http://www.angul.nic.in/atlas_of_development_trends_angul.pdf). Due to complex subsurface and geomorphological constraints, the rainfall recharge to groundwater is also low (<http://www.indiawaterportal.org>). These factors reflect that dilution of high F^- waters would be a challenging and difficult task.

The third approach involves improving the dietary condition of the residents. This aspect mostly takes into consideration the socioeconomic status of the residents. Good nutrition is suggested to combat the impact of fluorosis on the residents as it helps in reducing the absorption of F^- in the body tissues (<http://www.medindia.net/patients/patientinfo/fluorosis.htm>). Studies on nutritional interventions for fluorosis mitigation have shown that a diet containing low Ca^{2+} increases the retention of F^- in the body (<http://www.inrem.in/fluorosis/pdf/nutrition.pdf>). On the other hand, Mg^{2+} helps in the excretion of F^- through urine. Consumption of vitamin C was found to increase the ejection of F^- and reduce the severity of fluorosis. A closer examination of the total hardness contour ($Ca^{2+} + Mg^{2+}$) of this region (figure 4c) shows that high fluorosis risk zones typically coincide with the high TH zones. This can be a positive indication, as nutritional studies have shown that Ca^{2+} and Mg^{2+} help in reducing the risk of fluorosis to the residents. Supplementing the diet with vitamin C, which is very widely available

in the area, can further help in reducing the incidences of fluorosis (Mehta Dhaval and Shah 2013). The fourth approach is fluoride removal using various ion exchange and adsorption techniques. This needs initiation from the governmental and non-governmental institutions so that households are supplied with F^- removal filters depending on the amount of the F^- present in the groundwater at a location. A combination of proper nutrition and installation of fluoride removal kits can together effectively improve the health condition of the residents of this region and other similar regions elsewhere.

4. Summary and conclusions

Groundwater quality and its suitability for drinking with a special emphasis on F^- exposure to humans was evaluated in the Talcher Area, Odisha. An assessment of groundwater suitability for irrigation purposes was also presented in this paper. This study is significant as the water resources are being polluted by mining and other industrial activities in this region and groundwater is impacted by geogenic contamination like high fluoride concentration. Results indicate that most of the hydrochemical parameters are well within the WHO guideline values except fluoride. Indicators such as SAR, RSC and $Na\%$ that qualify the water for irrigation suitability are found to be

under low sodium hazard and permissible category. There are also cases of water samples falling under doubtful to unfit category due to the presence of high sodium concentrations.

The F^- concentration in the study is found to be in the range of 0.1–4.4 mg/l. About 39% of the samples show fluoride concentration above the WHO and BIS permissible limit of 1.5 mg/l. The exposure dose for F^- due to drinking water was found to be in the range of 0.01–0.37, 0.01–0.33 and 0.01–0.19 mg/kg/d for infants, children and adults, respectively. The F^- exposure values fall close to or above the minimum risk level for fluorosis. The spatial trends of the F^- exposure estimates indicate that the western and northwestern parts of the study area show no or less risk of fluorosis, while in rest of the study area, the fluorosis risk is moderate to high. The presence of higher concentrations of dissolved Ca^{2+} and Mg^{2+} in zones of high fluoride risk present a favourable case to prevent the severity of the fluorosis. However, incorporation of vitamin C in the diet as well as use of F^- removal kits can effectively reduce the risk of fluorosis among the residents of this area.

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