Environ Geol (2007) 52:1455–1465
DOI 10.1007/s00254-006-0584-7

ORIGINAL ARTICLE

Distribution of iron in the surface and groundwaters of East Godavari district, Andhra Pradesh, India

Nagireddi Srinivasa Rao

Received: 30 May 2006 / Accepted: 14 November 2006 / Published online: 8 December 2006

Abstract With the progradation of Godavari delta in the east coast of India, increase in iron (Fe) concentrations in the groundwater was observed. High concentrations of Fe (>10 mg/l) were observed in khondalite and charnockite formations. A lower portion of the Godavari river basin, viz. East Godavari district was chosen for the study of the distribution of iron with special reference to the existing geological formations and the geomorphology of the area. The concentration of iron was observed to vary from below detection limit to 69 mg/l in the groundwater while it was less than 1 mg Fe/l in river and spring waters. The Fe of river water was reduced due to seawater mixing and the electrical conductivity (EC) was increased approximately to half of the seawater conductivity. Unlike the mixing of seawater at the surface, the same seawater mixing with groundwater yielded a water having similar order of EC with relatively high Fe. Fe was inversely related with nitrate in the groundwater. Fe was found to correlate considerably better with manganese in fluvial and coastal alluvium zones. The locations having higher Fe in delta are suspected to be related to palaeo channels. The association between Fe and Mn and their negative association with NO_3 may be due to the possible autotrophic denitrification that might have taken place in the subsurface.

Keywords Godavari delta · Groundwater pollution · Iron · Manganese · Nitrate

N. S. Rao (✉)
Department of Geography, Andhra University,
Visakhapatnam, Andhra Pradesh 530003, India
e-mail: srinagireddi@gmail.com; srinagireddi@yahoo.com

Introduction

Iron is an essential element in the metabolism of animals and plants. If it is present in water in excessive amounts, it forms red oxyhydroxide precipitates that stain laundry and plumbing fixtures and, therefore, is an objectionable impurity in domestic and industrial water supplies. A recommended upper limit for iron in public water supplies is 0.30 mg/l (WHO 1984).

The main objective of the paper is to study the occurrence and distribution of iron in the groundwater with special reference to various geological formations and geomorphology of the study area. In addition to the above study on groundwater, it is also aimed to study the distribution of iron in the river water. One hundred fifty villages from the study area were chosen for the present work.

Study area

The study area is shown in Fig. 1. The general elevation of the area varies from less than a metre near the coast to about 500 m in the hills and has a coastline of 144 km with a natural port at Kakinada. Major soil types of the district are alluvial, red soils, sandy loams and sandy clays. East Godavari district falls under Godavari river basin. The second largest river of India, Godavari, enters the district in mature stage and splits into three different rivulets thereby forming a considerably big delta before debouching into the Bay of Bengal. The Godavari delta is symmetrical in form. Alternating layers of unconsolidated sand and clay with occasional intercalations of partially decomposed vegetable matter were observed in the delta upto a maximum depth of about 110 m were observed in the

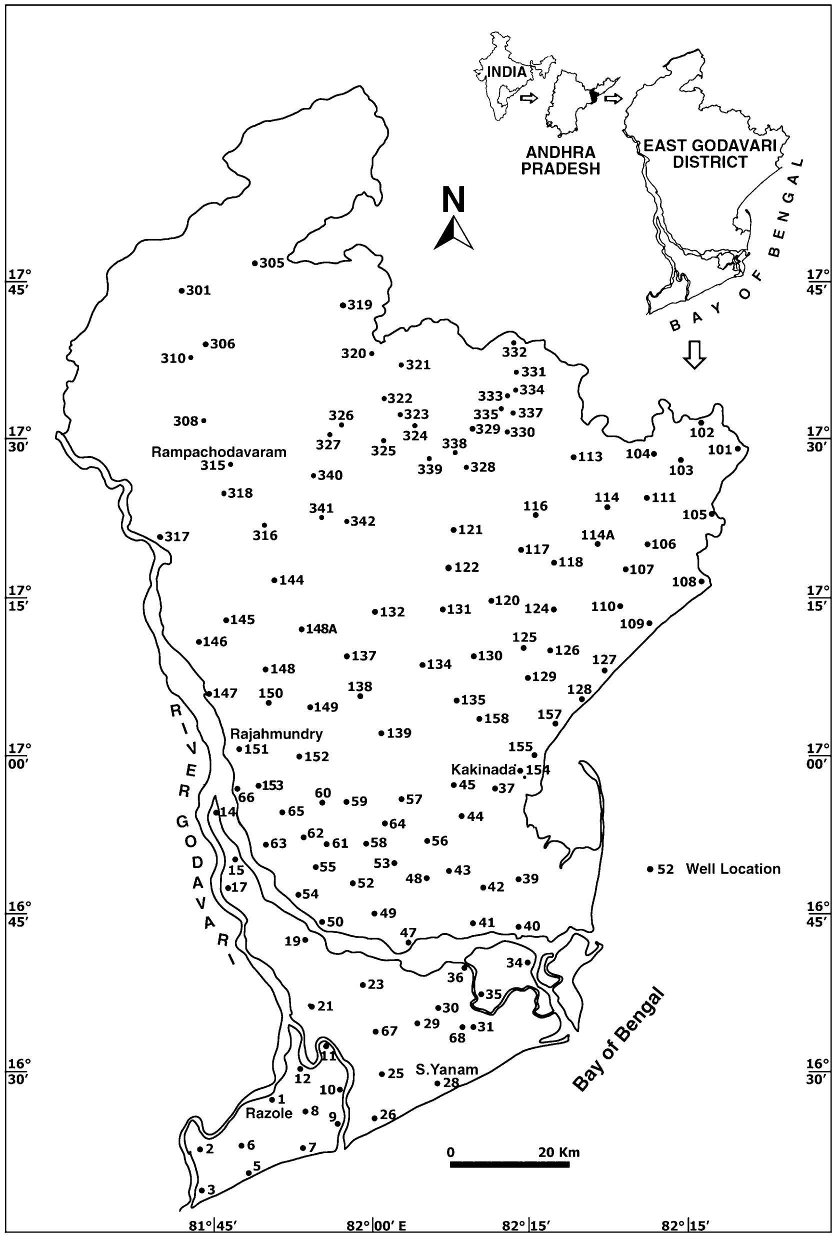

Fig. 1 Map showing sampling locations

delta (Sagar and Sarma 1956). Blackish-brown fragments of low specific gravity (lighter than ordinary black clay) resembling lignitic material were obtained at depths of 82 and 85 m at a village nearer to sampling site No. 50 (Fig. 1) (Sagar and Sarma 1956).

The Geology of the study area is shown in Fig. 2. The major rock types occurring in the district are Khondalites, Charnockites, Gondwana (Tirupathi) sandstones, Deccan trap, Rajahmundry sandstone and alluvium in deltaic and coastal region (NRSA 1994). The Khondalite suits of rocks are the oldest, high-grade metamorphic rocks, exposed in the northern, central and northeastern parts of the district. Charnockites are dark coloured, metamorphic rocks which are similar in composition to granite. They occur in close association with Khondalites and shows intrusive relationship. The upper Gondwana rocks (Tirupathi) are represented by sandstones and clays. The basaltic flows of Deccan Traps overlie the Tirupathi sandstone. Rajahmundry sandstone lies over the Deccan traps. Lateritic residual cappings have developed over sandstone. Clay is also found in association with Rajahmundry sandstone. Alluvial deposits mainly occupy the major part of the southern half of the district. They consists of clay, silt, sand and gravel in various proportions to form unconsolidated to semi-consolidated sediments. These deposits occur along the major rivers/streams in the form of alluvial plains and

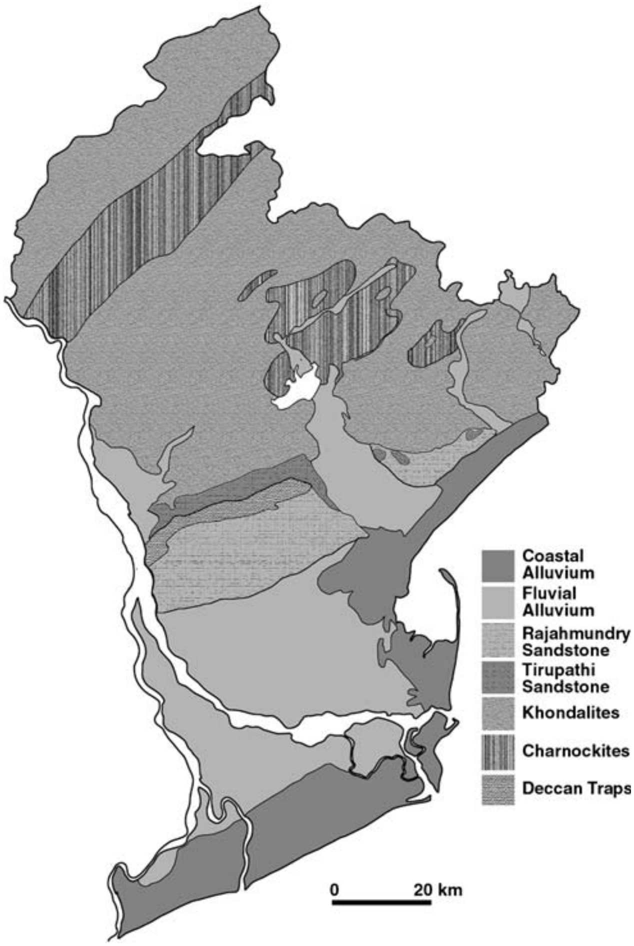

Fig. 2 Geology of East Godavari district

deltaic plains. The coastal sediments occur widely in the southern part. Mineralogically, the Godavari delta sediments have higher percentage of pyroxenes, amphiboles and magnetite in addition to the other heavy minerals like ilmenite, rutile, leucoxene, zircon, monzite and lesser amounts of sillimanite and garnet indicating their derivation from more basic rocks (Rao et al. 1989).

Materials and methods

One open/bore well water was sampled from each village. At a few places, additional samples from the same village were also collected. The water levels in open wells were measured. The sampling locations are shown in Fig. 1. The samples were collected in polyethylene bottles (TARSONS make) of 500 and 125 ml capacity. The sample was collected in three bottles from each well site. A sample of 500 ml capacity was collected for the determination of chloride, sulphate, fluoride and phosphate in the laboratory. The remaining two samples were collected in 125 ml bottles and were preserved with concentrated HCl and concentrated HNO_3 1 ml each immediately after drawing water for the determination of iron and manganese, respectively, in the laboratory. The samples were filtered before acidification. The samples (Nos. 301, 305 and 306 of Fig. 1) with very high iron concentrations (>50 mg/l) observed in three are not shown in any statistics presented in this paper since these could not be filtered before preservation with HCl due to some technical problems. It was observed that fine suspended matter in these three samples was already found dissolved at the time of chemical analysis.

The pH of the sample was measured at the well site using 2-decimal hand held digital pH meter (Systronics make, Guntype). Water temperatures were measured using Zeal thermometer. On-site determinations were carried out for calcium, magnesium and bicarbonate. The nitrate determination and electrical conductivity (EC) of the sample were measured on the same day. The APHA (1989) standard methods were followed for the determination of all the constituents mentioned above (Table 1). Iron was determined using phenanthroline method. Nitrate was determined by cadmium reduction method (method 8039 of HACH (2002) at 500 nm) using HACH chemicals. Fluoride was determined by both Alizarin Red S (visual method) (APHA 1976) and SPADNS (spectrophotometric) methods (APHA 1989). Almost similar values were obtained from both methods. SPADNS solution was imported from HACH (USA). The standard solutions for fluoride, nitrate, iron and manganese were obtained from HACH (USA) and SISCO laboratories (India). The sample numbers starting with digit '3' shown in Fig. 1 represent the upper reaches of the area while those starting with digit '1' represented the middle portion of the study area. The remaining numbers belong to delta portion of the area. The samples were collected during the summer months of April and May 2004.

Results

Groundwater occurs at shallow depths over most of the study area. Groundwater levels in the deltaic region were observed to vary from 1.2 to 8.2 m depth to groundwater (mean 2.98 ± 0.24, median 2.54 m) while the water levels in the middle region varied from 0.7 to 10.2 m depth to groundwater (mean 4.43 ± 0.41, median 4.50 m). The water temperatures during the sampling varied from 29.5 to 33.5°C. The statistical summary on the groundwater quality in East Godavari district is presented in Table 2. The iron (Fe) concentrations in

Table 1 Standard methods (APHA 1989) used for the study

Sl. No.	Name of the parameter	Standard method used	Wave length (nm)	Reference No. of the method
1	Calcium	EDTA titrimetric method		D of 3500-Ca
2	Hardness	EDTA titrimetric method		2340 C
3	Magnesium	By calculation method		E of 3500-Mg
4	Chloride	Argentometric method		B of 4500-Cl
5	Bicarbonate	Standard acid method		2320 B
6	Sulphate	Turbidimetric method	420	E of 4500-SO_4
7	Fluoride	Alizarin Red-S method		414 D (APHA 1976)
		SPADNS method	570	D of 4500-F
8	Phosphate	Vanadomolybdophosphoric Acid	400	C of 4500-P
9	Iron	Phenanthroline method	510	D of 3500-Fe
10	Manganese	Persulfate method	525	D of 3500-Mn

Table 2 Statistical summary of groundwater (all concentrations in mg/l)

Parameter	*N*	Min	Max	Median	Mean	SE	SD
Iron	137	BDL	69[a]	0.21	0.72	0.12	1.4
pH	154	5.5	8.1	7.06	7.03	0.04	0.46
EC (μS/cm)	142	30	23000	1,695	2,274.27	209.33	2,494.48
Nitrate (as NO_3)	131	BDL	870	35	78.44	10.34	118.38
Fluoride	147	BDL	2.5	0.25	0.35	0.04	0.44
Calcium	153	BDL	400	72	80.48	4.9	60.56
Hardness (as $CaCO_3$)	153	35	3,200	410	490.65	30.55	377.88
Bicarbonate	152	49	1,293	408.9	445.05	20.99	258.76
Magnesium	153	4	593	50.4	69.14	5.29	65.42
Chloride	154	BDL	7,600	190	359.88	57.49	713.42
Manganese	140	BDL	2.2		0.23	0.03	0.4
Phosphate (as PO_4)	131	0.12	5.4	2	1.89	0.09	1.02
Sulphate	32	1	80	10.5	18.88	3.47	19.65

SE Standard error for mean, *SD* standard deviation, *Min* minimum, *Max* maximum

[a] The maximum concentrations of three samples (51, 61 and 69 mg/l) were not used for any statistical calculation

the groundwater were observed to vary from below detection limit (BDL) to 69 mg/l with a mean concentration of 0.72 ± 0.12 mg/l (median 0.21). It has been observed that the Fe concentrations exceed the WHO guideline of 0.30 mg Fe/l in about 39% of the samples. Of the 140 groundwater samples analyzed for Fe, 79 samples were from open wells and 61 samples were from borewells. The depth of sampling in most of the open wells was less than 7 m and that in the borewells was above 20 m. Almost all the sampling wells in the upper reaches were borewells. The water column in the open wells was observed to vary between 2.0 and 5.0 m. Considering the delta region alone, the mean iron concentrations in both open and bore wells is more or less the same (i.e. about 0.4 mg/l). However, the high concentration reaching 5.6 mg Fe/l was observed in an open well (well No.35, Fig. 1). If the entire area is taken into consideration, the Fe concentrations dominate (i.e. Mean 1.0 mg/l) in the bore well water in the upper reaches due to the dissolution of iron bearing minerals which are abundant in the upper reaches.

The spatial distribution of Fe in the groundwater is shown in Fig. 3. It may be observed from the figure that the well waters which are adjacent to the river courses have relatively higher concentrations of Fe. High concentration of Fe were also observed in the groundwater of known sandy formations at three locations (Nos. 6, 34 and 36 in Fig. 1) in the delta region. Fe concentrations with respect to geological formations of the area are presented in Table 3. The concentrations of iron in the groundwater of coastal alluvium, fluvial alluvium and khondalite zones are higher (>0.3 mg/l). However, very high concentrations exceeding 10 mg/l of iron were observed in the khondalites and charnockite zones situated in the upper reaches.

The Fe concentrations in the spring water at three locations are shown in Fig. 4. The Fe concentration in the spring water at Bodduluru (S1; Fig. 4) in the upper reaches was 0.17 mg Fe/l. At the remaining two locations (S2 and S3), the Fe concentrations have been found to be similar (0.3 mg/l). The Fe concentrations in the river water along with other quality parameters are shown in Fig. 4.

Discussion

The iron in the groundwater is contributed by geological formations. No external source for Fe in the

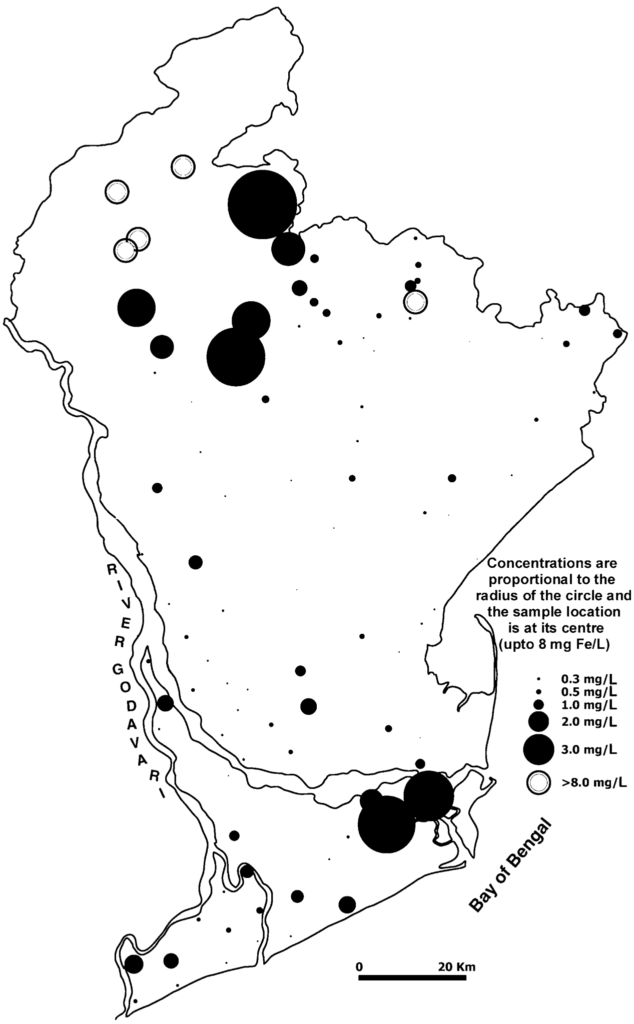

Fig. 3 Spatial distribution of Fe in the groundwater

groundwater was observed. In view of the observations of relatively high Fe near river courses and sandy zones in the delta region, an attempt has been made to find the association if any between the geomorphology of Godavari delta and the occurrence of high Fe concentrations in the delta region.

Sambasivarao and Vaidyanadhan (1979) have studied the morphology and evolution of Godavari delta. ^{14}C dating suggested that there was a lower sea level than today off the east coast of India around 10,800 ± 155 years B.P. (Naidu 1968). The growth of the modern delta might have started through successive deposits of detrital material brought by the river Godavari after the restoration of sea level around 10,800 ± 155 B.P. Four stages in the growth of delta fronts have been recognised from the disposition of the ancient beach ridges in each strandline (I, II, III and IV; Fig. 5) (Sambasivarao and Vaidyanadhan 1979). The rate of progradation of modern delta for 1000 years would be about 3.5 km, the distance from the first strandline to present major shifts in the river courses as the delta prograded (Sambasivarao 1979). The gradual shift in the strandlines towards the coast without any regressive trend is indicative of the gradual growth of the delta with continuous influx of fluviatile sediments. The available geomorphology map of Godavari delta published by Sambasivarao and Vaidyanadhan (1979) was very small in size. The well locations superimposed on this map are shown in Fig. 5. Since the well locations were not measured using GPS and the published map was very small, it is doubtful indeed whether the observation wells were located in a palaeochannel region. However, there may be a possibility of some of the observation wells falling in the palaeochannel regions. It can be observed from the Fig. 6 that the Fe concentrations in the wells located along the four strand lines (marked in Fig. 6 as I–IV), are low as compared to the Fe concentrations of the wells located in between the strandlines. From this observation, it may be mentioned that the Fe is low along the present and paleo coastlines. The Fe concentrations with reference to the strandlines are given in Fig. 7 and Table 4. From the Table 4, it may be observed that the mean iron concentrations are increasing from strandline I to strandline IV. A decreasing trend has been observed in the number of samples having low concentrations of Fe (<0.50 mg/l) from strandline I towards strandline IV (Fig. 7). Further, It may be observed that number of samples having iron concentrations in the range of 0.50–1.00 mg/l is increasing towards Strandline IV (Fig. 6, 7). If delta area alone is considered, higher Fe was observed be-

Table 3 Fe concentration (mg/l) in the groundwater of different geological formations

Formation	*N*	Mean	SE	Median	Min	Max	SD
Coastal Alluvium	26	0.45	0.11	0.20	0.03	2.29	0.58
Fluvial Alluvium	43	0.64	0.17	0.22	0.01	5.57	1.14
Rajahmundry sandstones	13	0.09	0.03	0.06	0.00	0.39	0.12
Khondalites	39	1.01	0.25	0.36	0.00	69[a]	1.56
Charnockites	4	4.06	2.10	4.02	0.12	61[a]	4.19

[a] The maximum concentrations of three samples (51, 61 and 69 mg/l) were not used for any statistical calculation

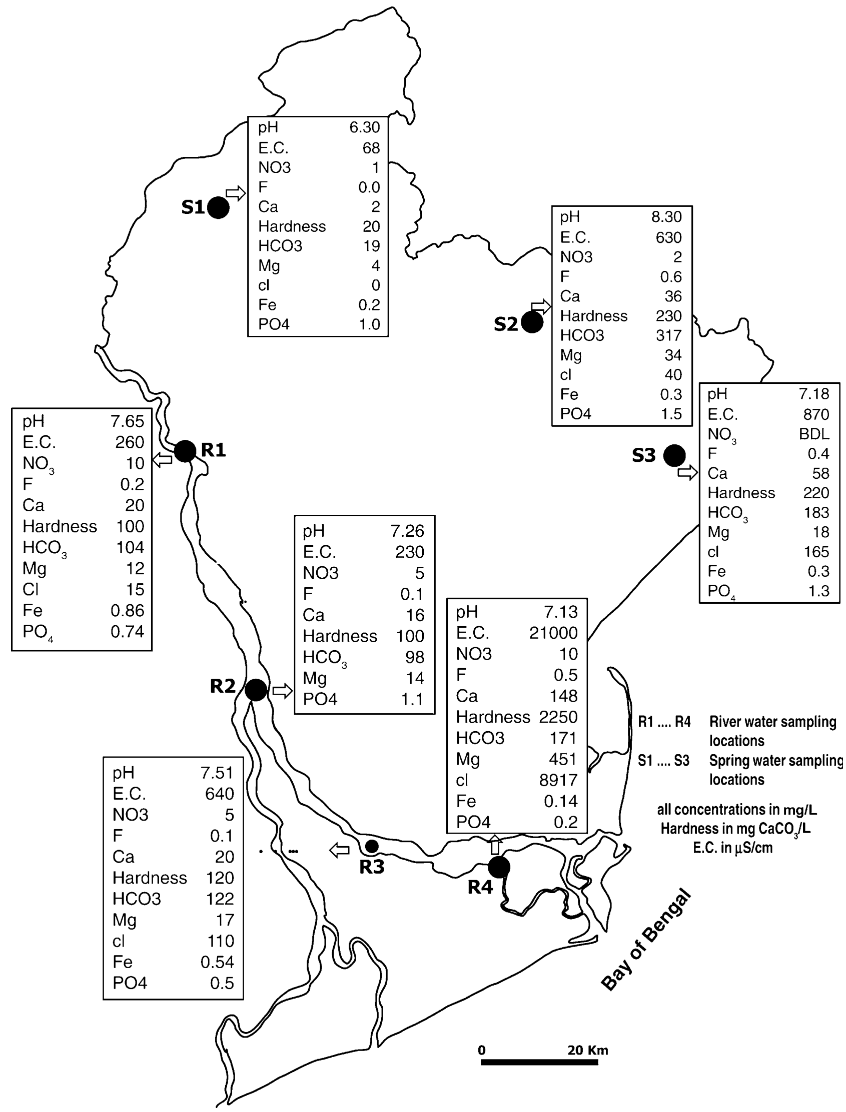

Fig. 4 Location of spring and river water samples and their quality

tween strandlines III and IV. From the above observations, it is interesting to note that the iron concentrations are also increasing with the progradation of delta.

As a result of the complex depositional pattern of sediments in the delta region, two types of groundwaters were observed in the delta region. When the groundwater occurs in the clayey formations, the water is saline while the sandy formations yield freshwater. There is a four to tenfold difference in the TDS of groundwater of sandy and clayey formations. The Fe in the clayey formations is less as compared to the same in the sandy formation. The complex depositional pattern of sand and clay was responsible for abnormal quality of groundwater within short distances. The author (Rao 1997) obtained similar results on variation of water quality within short distances in the complex depositional environment of Vamsadara river basin. A detailed study of the groundwater quality variations due to progradation of delta can be made only by sampling all the existing wells in all the villages in the Godavari delta. However, at this stage of investigation, it can only be mentioned that the groundwater located in the sandy zones of paleochannels in the Godavari delta have relatively high Fe. To find a link between palaeo channels, sedimentation and occurrence of Fe, further study using recent high-resolution satellite imageries and digital techniques, the GPS measurements of well locations and determination of Fe at different water level conditions is required.

In most oxygenated groundwaters, iron is not present or is detectable only in minor amounts (Matthess 1982). Dissolved oxygen (DO) was determined only at 31 locations in the delta. The DO concentrations were

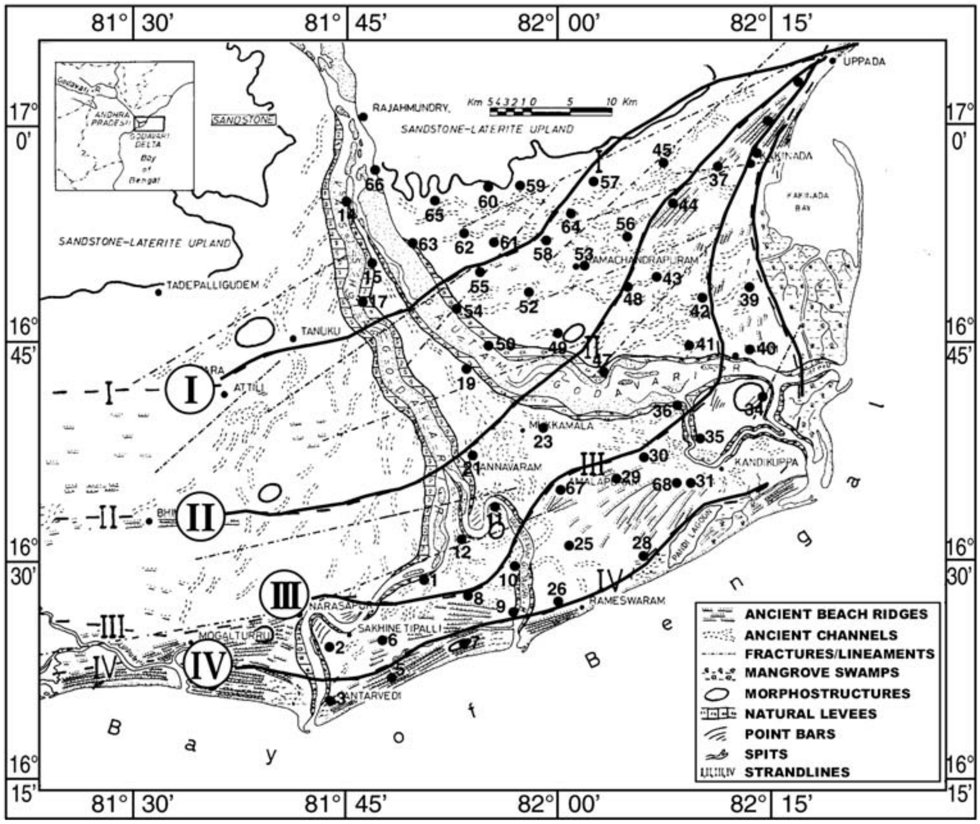

Fig. 5 Well locations on the geomorphic map of Godavari delta

observed to vary between 2.2 and 6.2 mg/l with a mean of 4 mg/l. In about 70% of the samples, the DO ranges between 3.0 and 5.0 mg/l. However, no relation was observed between DO and iron in the area. For example, the DO in sample Nos. 15 and 17 was 4.4 mg/l while iron concentrations were 1.6 and 0.2 mg/l, respectively. Groundwater having a pH between 6 and 8 can be sufficiently reducing to retain as much as 50 mg/l of ferrous iron at equilibrium, when bicarbonate activity does not exceed 61 mg/l (Hem 1986). Incidentally, at Kuduru village (No. 306, Fig. 1), the bicarbonate in groundwater was 60 mg/l and the pH and Fe concentrations in the groundwater were 6.26 and 61 mg/l, respectively. The calcium, chloride and sulphate concentrations at this place were below detectable limit. However, at two other locations, where the Fe concentrations were determined as 55 and 69 mg/l, the pH values were less in the groundwater but the bicarbonate concentrations reached upto 110 mg/l.

The very high concentrations of Fe in the groundwater were associated with low EC (low salinity) and low pH (Table 5). Relatively high Fe was also observed with the higher EC at wells numbered 25, 28, 34 and 35 (Table 5). All the four wells are located in the delta. However, at many places, relatively higher Fe concentrations are associated with low EC and vice-versa. The reason for this association is that most of the low EC waters were observed in the recharge zones of upper reaches where iron bearing minerals are abundant.

An attempt has been made to correlate Fe with other chemical constituents in all samples. In general, in the groundwater of East Godavari District, Fe is positively correlated with manganese and negatively related with nitrate. Better correlations could not be observed between iron and other chemical constituents. In addition, correlation analysis between Fe and other constituents was also done for all geological formations and considerable correlation coefficients are given in Table 6. The Fe and Mn data of **Ayotte et al.'s (2000) and Fe, Mn and NO_3–N of Woo et al. (2000) were collected and correlation coefficients were calculated by the author. Their correlation coefficients for Fe and Mn are presented in Table 6. The relation between iron, manganese and nitrate is shown in Fig. 8. The samples having below detectable concentrations of Mn, Fe and NO_3 are not plotted in Fig. 8. Hence, the number of data points varies in each plot of Fig. 8. The negative association of NO_3 with Fe and Mn may be explained by the autotrophic denitrification that might have taken place in the aquifer.

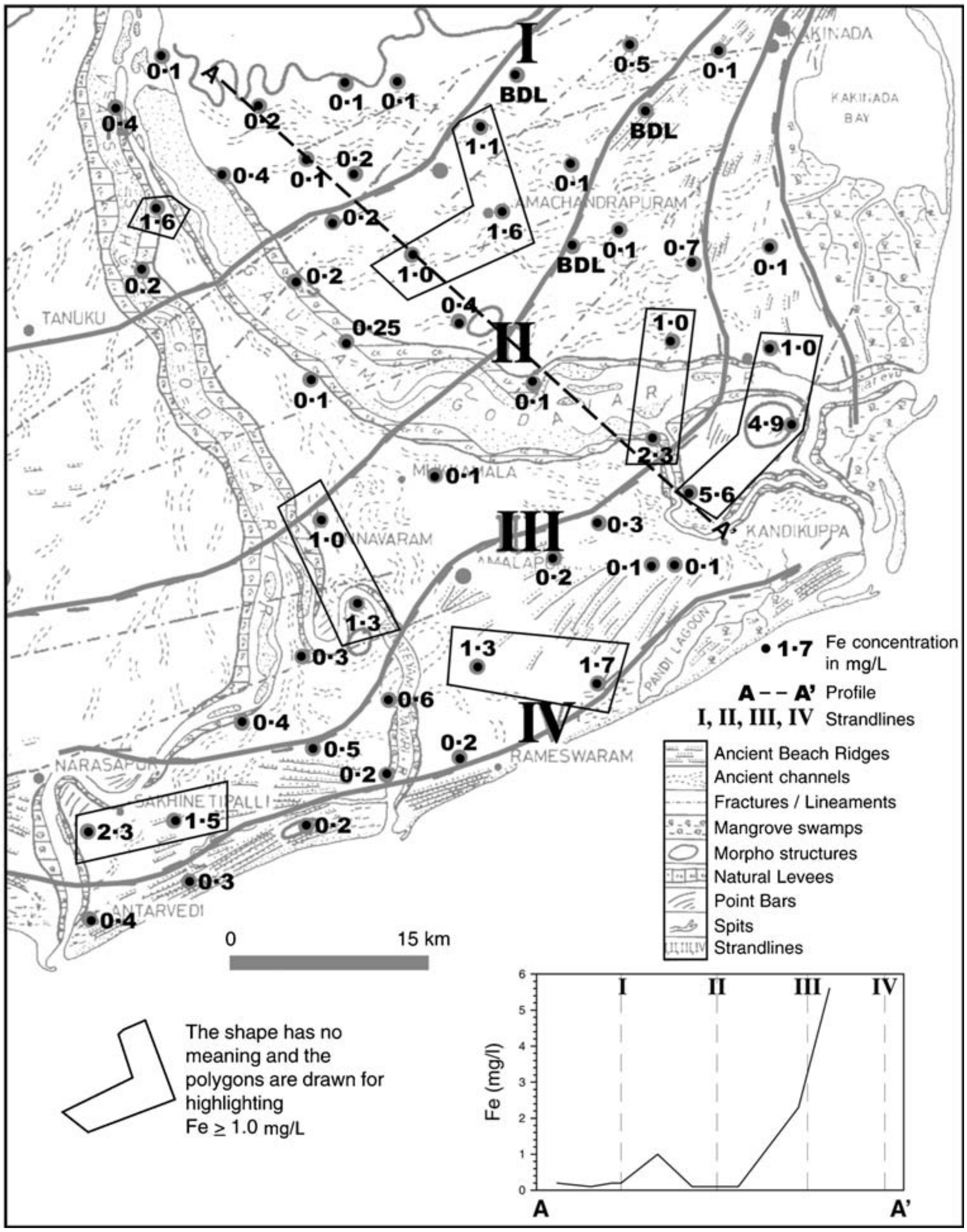

Fig. 6 Fe concentrations (mg/l) in the groundwater of Godavari delta

Koram (1992) reported that if NO_3 is introduced into a manganese/iron or sulphate-reducing zone, even in the absence of OC, it is thermodynamically unstable. If appropriate bacteria are present, they may denitrify using reduced manganese, reduced iron and sulfides as electron donors. The autotrophic denitrification indicates that the increase of Mn, Fe and SO_4 levels in the groundwater. Though inverse relation between Fe–Mn and NO_3 is clearly observed at some places, high concentrations of NO_3 are also associated with high Fe and Mn at other places (Fig. 8). The results presented in Fig. 8 are contrary to the observations made by Lind (1983), Bottcher et al. (1985) and Mariotti et al. (1988) that the groundwater having Fe has little or no NO_3. Nitrate in water may be accompanied by low concentrations of dissolved iron (typically <0.2 mg/l) (Korom S, Personal communication). He also informed that the association of high nitrate concentrations with high iron concentrations was noticed in the groundwater near a copper mine in USA. Though this is impossible based on thermodynamic considerations, but it may be possible with kinetic limitations (personal communication).

The river water at R1 has 0.86 mg Fe/l and it decreased to 0.54 and 0.14 mg/l at R3 and R4 respectively (Fig. 4). At R4, the river water was mixing with

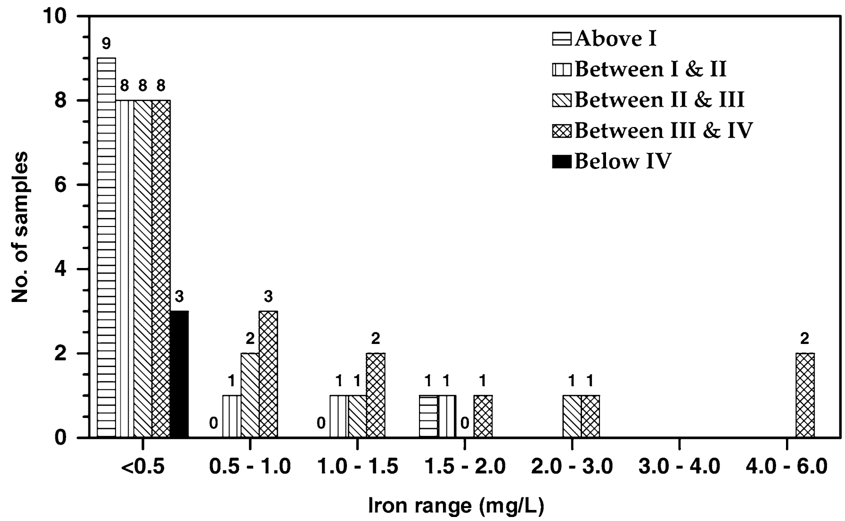

Fig. 7 Frequency distribution of Fe with reference to strandlines

Table 4 Fe concentrations (mg/l) in the groundwater located between Strandlines I and IV

Strandlines	*N*	Mean	SE	Median	Min	Max	SD
Above I	10	0.33	0.14	0.19	BDL	1.6	0.45
Between I and II	11	0.45	0.14	0.26	BDL	1.6	0.47
Between II and III	12	0.55	0.19	0.24	BDL	2.3	0.67
Between III and IV	17	1.21	0.40	0.52	0.1	5.6	1.65
Below IV	3	0.29	0.06	0.28	0.2	0.4	0.10

Table 5 Fe in the groundwater at different EC and pH levels

Sample no.	Low EC (µS/cm)	pH	Fe (mg/l)	Sample no.	High EC (µS/cm)	pH	Fe (mg/l)
301	240	5.76	55	154	9,800	7.39	0.1
306	148	6.26	61	25	9,200	7.30	1.3
305	200	6.15	69	138	5,600	6.79	BDL
310	200	5.50	8.1	128	8,400	7.29	0.1
319	173	5.57	6.7	35	5,000	7.22	5.6
308	710	6.15	3.7	38	5,750	7.56	BDL
327	1,170	6.47	3.7	44	7,300	7.48	BDL
320	300	5.97	3.3	34	4,400	6.97	4.9
				17	6,300	7.05	0.2
				3	6,700	7.70	0.4
				28	23,000	7.53	1.7

seawater. The EC at this place (R4) was 21,000 µS/cm against an EC of 260 µS/cm at R1. The EC at R4 is about half of the seawater EC (i.e. about 50,000 µS/cm; Hem 1986). The Fe content in sea water (0.0034 mg/kg) reflects the element's relatively low mobility (Matthess 1982). Though the EC of river water at R4 indicates dilution of seawater by river water, the decrease of Fe in the river water at R4 may not be due to the dilution. In estuarine media, the distribution of dissolved iron is complicated by the strong gradients of several physico-chemical properties like salinity, turbidity, temperature, dissolved oxygen concentration, pH, Eh and the character and the concentration change of particles which result from the mixing of fresh and saline waters (Millward and Tuner 1995). The decrease in iron from fresh river waters to the sea water indicates its removal. The removal of iron is apparently the repetitious process in estuaries (Ouddane et al. 1999). This behaviour is similar to that reported in a majority of other estuaries. Ouddane et al. (1999) have well documented the works of various investigators on the subject. The non-conservative behaviour was explained by the aggregation of colloidal iron during estuarine mixing or by an association between dissolved iron and dissolved organic matter (Ouddane et al. 1999). Contrary to the above observation on river and sea water mixing on the surface, similar mixing in the underground i.e. the mixing of groundwater with seawater at

Table 6 Correlation of Fe with NO_3, Mn and PO_4

Variables	Geological formation	*N*	Correlation coefficient
Present work			
Fe and Mn	Coastal alluvium	12	0.65
Fe and Mn	Fluvial alluvium	19	0.89
Fe and PO_4	Fluvial alluvium	20	0.55
Fe and NO_3	Coastal alluvium	20	–0.33
Other work			
Fe and Mn (Ayotte et al. 2000)		32	0.30
Fe and Mn (Woo et al. 2000)		19	0.23
Fe and (NO_3–N) (Woo et al. 2000)		17	0.08

S. Yanam village (No. 28, Fig. 1) has shown a relatively higher concentration of 1.7 mg Fe/l. This well was intruded by sea water. The higher Fe at this well may be due to its location in the ferruginous sand formations. The EC of seawater and fresh water mixing on the surface (at R4, Fig. 4) and below the ground surface (at well no. 28, Fig. 1) were 21,000 and 23,000 µS/cm, respectively.

Conclusion

The Fe concentrations in the groundwater of lower Godavari river basin varied from below detection limit to 69 mg/l while the concentration varied from 0.14 to 0.86 mg/l in the river and 0.17–0.32 mg/l in spring waters. Very high concentrations (> 10 mg/l) were observed in the upper reaches of the area. The iron concentrations decreased from 0.86 mg/l in the river water at the upstream point to 0.54 mg/l, which further decreased to 0.14 mg/l at the point where the seawater mixes with the river water. Though, the mixing of sea water and fresh water at the surface (in the river) and below the ground surface (in the groundwater) show an EC of approximately half of the seawater conductivity, the distribution of Fe in the surface water is complicated by several physico-chemical properties which resulted in Fe removal in the mixing water. The Fe concentration observed due to surface and sea water mixing was 0.14 mg/l while the mixing of the same seawater with groundwater contained 1.7 mg Fe/l. In the study area, iron is contributed to the groundwater from existing geological formations and not by any external sources. High concentrations of iron were observed in both open and bore well waters. The groundwater in khondalite, fluvial and coastal alluvium formations have higher Fe as compared to other formations. Higher Fe was observed in the groundwater of sandy formations and at some locations along the river courses. The iron concentrations were observed to increase with the progradation of delta. The wells located between the strandlines (palaeo coastlines) have relatively higher Fe and are suspected to fall in the palaeo channels. Generally, high Fe in the study area is associated with low EC and low pH. It is negatively related with nitrate. No better correlations were observed between Fe and other constituents except positive correlation with Mn in Fluvial and Coastal alluvium. The negative association of Fe and Mn with nitrate and positive association between Fe and Mn can be explained by the autotrophic denitrification that might have taken place in the subsurface.

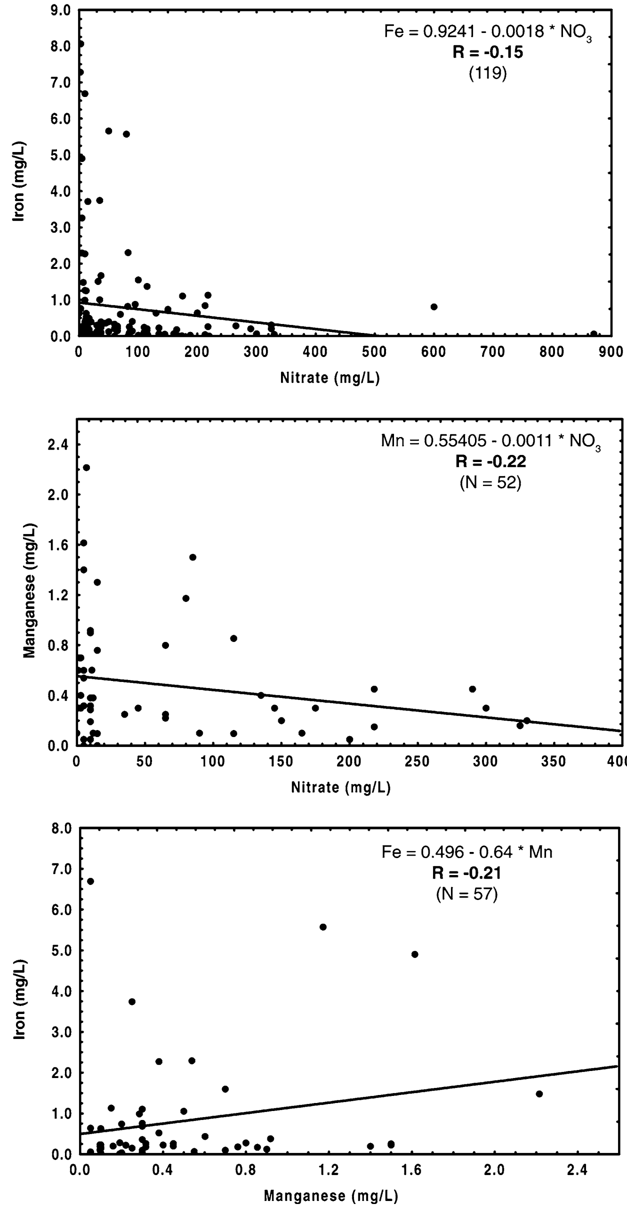

Fig. 8 Relationships between nitrate, iron and manganese

Acknowledgments The author is awarded Research Associateship by Council of Scientific and Industrial Research, New Delhi (Award No. 3(31)042-2 K1/1). The financial support from CSIR for carrying out this study is gratefully acknowledged. The author is grateful to Dr. B. K. Handa (formerly of Central Ground Water Board, Chandigarh) for his guidance and valuable suggestions. He is also grateful to the reviewer for his valuable suggestions to improve the paper.

References

APHA (American Public Health Association) (1976) Standard methods for the examination of water and waste water, 14th edn. APHA, American Water Works Association and Water Pollution Control Federation, Washington DC

APHA (American Public Health Association) (1989) Standard methods for the examination of water and waste water, 17th edn. APHA, American Water Works Association and Water Pollution Control Federation, Washington DC

Ayotte JD, Nielsen MG, Robinson GR Jr, Moore RB (2000) Relation of Arsenic, Iron and manganese in groundwater to aquifer type, bedrock lithogeochemistry and landuse in the New England Coastal Basins. USGS Water-Resources Investigations Report 99-4162:1-63

Bottcher J, Strebel O, Durynesveld WHM (1985) Vertikale Stoffkonzentrationsprofile im Grundwasser eines Lockergesteins-Aquifers und deren Interpretation (Beispiel Fuhrberger Field). Z Dtsch Geol Ges 136:543–552

HACH (2002) Water analysis hand book. HACH company, Calorado

Hem JD (1986) Study and interpretation of the chemical characteristics of natural water, 3rd edn. US Geol Surv Water Supply Pap 2254:1–264

Korom SF (1992) Natural denitrification in the saturated zone: a review. Water Resour Res 28:1657–1668

Lind AM (1983) Nitrate reduction in the subsoil. In: Golterman HL (ed) Denitrification in the nitrogen cycle. Plenum, New York

Mariotti A, Landreau A, Simon B (1988) ^{15}N isotope biogeochemistry and natural denitrification process in groundwater: application to the Chalk aquifer of northern France. Geochim Cosmochim Acta 52:1869–1878

Matthess G (1982) The Properties of groundwater. Wiley, New York

Millward GE, Tuner A (1995) Trace metals in estuaries. In: Salbu B, Steinnes E (eds) Trace elements in natural waters. CRC Press, Boca Raton

Naidu AS (1968) Some aspects of texture, mineralogy and geochemistry of modern deltaic sediments of the Godavari River. PhD, Andhra University, India

NRSA (National Remote Sensing Agency) (1994) Landuse planning atlas, east Godavari district. AP, Govt. of India, India

Ouddane B, Skiker M, Fischer JC, Wartel M (1999) Distribution of iron and manganese in the Seine river estuary: approach with experimental laboratory mixing. J Environ Monit 1:489–496

Rao NS (1997) The occurrence and behaviour of fluoride in the groundwater of the lower Vamsadhara River basin, India. Hydrol Sci J 42:877–892

Rao GD, Setty BK, Raminaidu Ch (1989) Heavy mineral content and textural characteristics of coastal sands in the Krishna–Godavari, Gosthani–Champavathi, and Penna River deltas of Andhra Pradesh, India: a comparative study. In: Exploration and research for atomic minerals (vol 2), Department of Atomic Energy, Govt. of India, India

Sagar TVSRK, Sarma BBG (1956) Occurrence of lignitic material in the Godavari Delta. Curr Sci 2:54–55

Sambasivarao M (1979) Geomorphology and evolution of the modern Godavari delta. PhD, Andhra University, India

Sambasivarao M, Vaidyanadhan R (1979) Morphology and evolution of Godavari Delta, India. Z Geomorph NF 23:243–255

WHO (World Health Organization) (1984) Drinking water quality control in small community supplies. In: Guidelines for Drinking Water Quality (vol 3), Geneva

Woo NC, Moon J, Won JS, Hahn JS, Lin XY, Zhao YS (2000) Water Quality and pollution in the Hunchun Basin, China. Environ Geochem and Health 22:1–18