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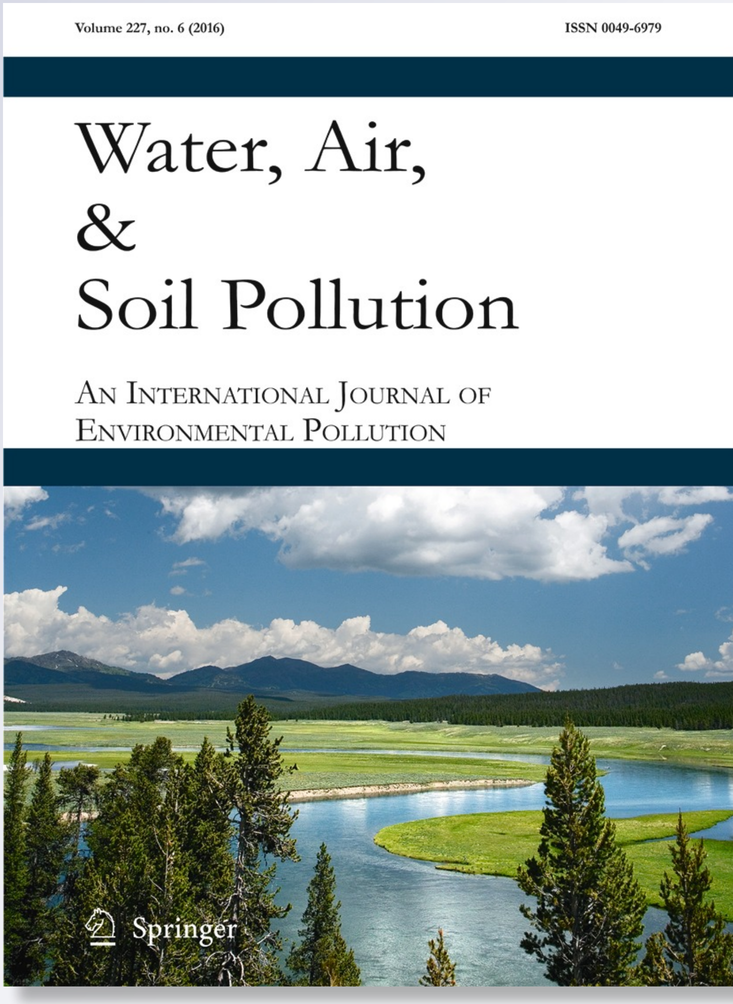

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Integrated Geophysical and Geochemical Assessment for the Comprehensive Study of the Groundwater

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Abstract Groundwater studies often involve using any one of geophysical, geological, geochemical, or chemical data in the assessment of its characteristics. An integrated method in using all the above had been carried out for more comprehensive and confirmative assessments along the Thandava River basin, India. The geophysical data included the recording of the vertical electrical soundings by Schlumberger array configuration in 50 stations along the basin. Thirty soil samples and rainfall data of 5 years included the geological data. Chemical characterizations for 117 groundwater water samples were carried for two seasons. This study proposes the advantages besides delineating the approach in carrying integrated rather than mere single parameter-based speculative study. This correlative and computer modeling aided study led to an in-depth along with confirmative assessments on various geological, geophysical, and chemical characteristics of the groundwater along with the pollution status. Comprehensive details of groundwater like geomorphology, potential water zones, flow pattern, soil types, geochemical evolution of ions, chemical status, and suitability can be accessed by applying this type of integrated study.

Keywords Groundwater · Chemical · Geological · Geophysical · Integrated assessment

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1 Introduction

Human civilization prospered in the vicinity of water sources and especially along river banks. We often heard tales pertaining to their quality and quantity for years, either for potable or agricultural use. However, settlements in due course and indiscriminate exploitations made groundwater suffer in maintaining its basic characteristics. Reasons might not be limited but vigilance in time might restore or reduce the onslaught and thus safeguard futuristic needs. Often, assessments of groundwater involve multiple approaches base on the type of interpretation and thus status leading to management strategies. It seems wise that an understanding of the quantitative and qualitative changes in groundwater system because of existing and proposed hydrologic stresses is a pre-requisite for their proper management.

The idea of weathered, fractured, and freshwater basements along with local environment would enhance these chances in any given area. The demand for groundwater use will continue to increase, and further problems are likely to become evident because of land use and climate changes. This will involve ongoing evaluation of groundwater's sustainable yields and management regimes including the use of entitlements in the light of changing knowledge about climate, hydrogeology, and other factors influencing water scarcity, as well as continuing policy adjustment in the light of improving knowledge and an increase in experience (Andrew et al. 2005).

In general, groundwater assessments often involve geophysical, geological, or chemical data in the assessment of it's various characteristics. Respective data interpretation reveals either geomorphology or geology or geo-hydrochemistry of those areas. Now-a-days, modeling, remote sensing, and computed assessments are being widely used with the above conventional methods of assessments. River and reservoir basin studies follow a close trend in their assessments using the above approaches. According to Lewis Brent (2001), it is possible to take an image of the subsurface quickly and inexpensively through application of various nonintrusive surface geophysical methods. Electrical resistivity studies have extensively been used in groundwater geophysical investigations because of the correlation that often exist between electrical properties, geologic formations, and their fluid content (Zohdy and Jackson 1969; Fitterman and Stewart 1986). Schwartz and McClymont (1977) and Stoller and Roux (1975) had reported that the variations in the apparent resistivity in the given area can often be related qualitatively to geological features, and for delineation of aquifers, these are the pre-requisites for the assessment of regional/local groundwater potential.

Delineation of aquifers and subsequently their groundwater potential assessment were carried out in different parts of India, using different geophysical, geological, geochemical, remote sensing, and geographic information system (GIS) methods depending on the local hydro-geological conditions (Rai 2009), while isotope and GIS integration studies have been reported by Elias and Ierotheos (2006). A new hydro-chemical technique based on electrical conductivity logs was developed for the delineation of water-bearing fractures in hard rock areas and tested in the Maheshwaram watershed (Saxena et al. 2005). An integrated study was carried out in Bairasagara watershed in Karnataka, India to investigate the subsurface conditions in hard rock environment with the aim of identifying zones with groundwater potential (Chandra et al. 2006). The geochemical studies on the Dankar, Thinam, and Gete lakes in the Spiti valley of higher Himalaya have been carried out to understand the nature of lithology and the type of weathering at the source (Das and Dhiman 2003). However, the geochemistry and quality assessment of Dhanbad, India has been reported by Singh et al. (2007) and hydro-geological and hydrochemical study on Kali-Ganga, India was also reported by Umar et al. (2001). In an integrated approach of weathering, chemisorptions and trace metal fluxes to the oceans have been reported by Dowling et al. (2003) along the Bengal basin's groundwater. The quality assessment and determination of pollution sources of interactive study in southern Europe has been reported on Axios-Varda River by Milovanovic (2007), while integration of thematic maps and GIS for the identification of groundwater zones has been reported by Murthy et al. (2003).

The studies on the groundwater involving integrated approach that have been reported are mainly based on the geophysical dominance assessments relating to areas in and around the present study, including mathematical modeling based on resistivity (Vinoda Rao and Gurunadha Rao 2006) and integration of geo-electrical and pumping data (Rao 2003). The electrical resistivity survey was applied by Kshirasagar and Rao (1989) in Varaha River basin, India while Sarma and Swamy (1981) applied this on Visakhapatnam basin, India to study the pollution status. In assessment, development, and management of surface/groundwater resources to meet the demands of water supply from available water resources, a novel approach of integrated assessment was carried out by us and is reported in the present paper. In this present investigation, the resistivity survey was carried out in 50 locations along the Thandava Reservoir during June 2012 along with soil sample collection and their analysis for the comprehensive assessment of the groundwater's characteristics. It was aimed that the integrated approach of the various parameters would reveal realistic conclusions rather than speculative assumptions based on single parameter assessments.

2 Study Area

The Thandava River basin extends over an area of 909.48 km^2. The river basin length from North to South is 49.88 km between latitude 17° 50′ and 17° 15′ North, and the maximum width from East to West is 21° 5′ between longitude 82° 17′ and 82° 45′ East. This basin covers water of Visakhapatnam and East Godavari districts of Andhra Pradesh state in India. The basin is surrounded by Sabari sub-basin of Godavari in the North and Varaha River basin in the East, Bay of Bengal in the South, and Pampa and Yeleru in the West. The upper reaches and most of the eastern portion lie in Visakhapatnam district, and the lower portion and Western side lie in East Godavari district. About 2/3 of the catchment lie in the former district, and the remaining lies in the later district. The Thandava River originates at an altitude of 129.5 m and flows over the Chintapalli, Narsipatnam, Tuni, and Yelamanchili taluks for a length of 99.7 km. The Thandava River rapidly falls to 304.8 m in its first 9.5 km reach.

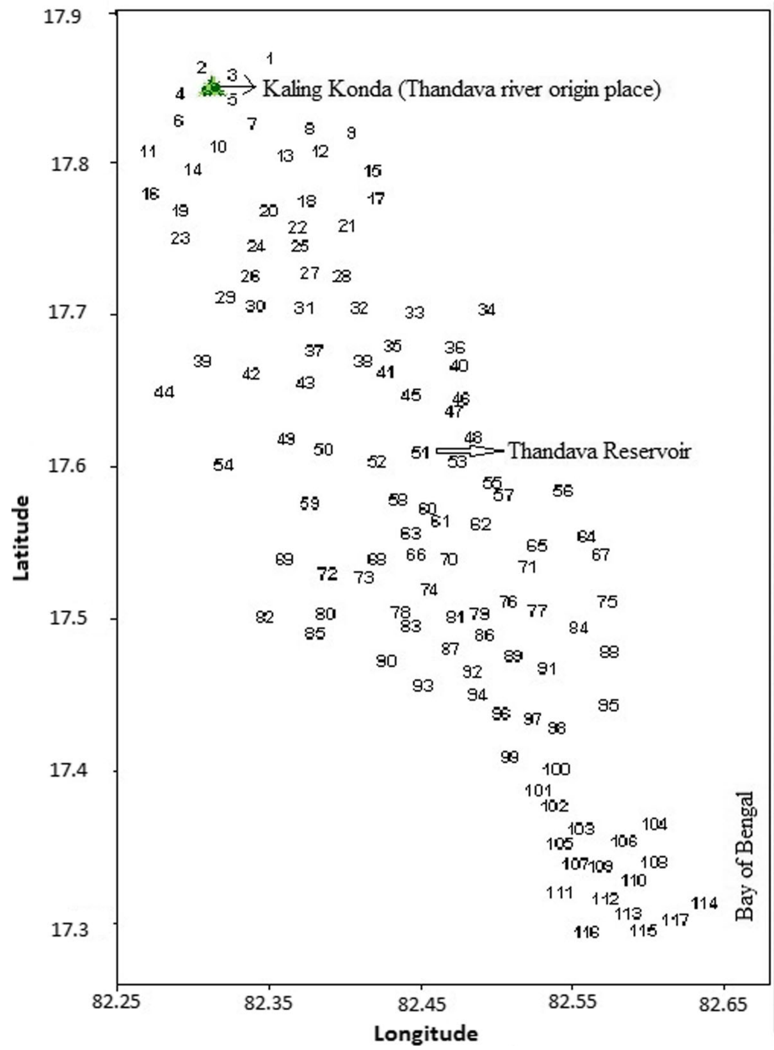
After traveling about 14.4 km, it receives a tributary Sapegedda kalva, lower down Peddagadda lanka, another tributary flowing in West-ward direction falls in to the Thandava, after the later, traversing a distance of 19.3 km from its origin. The level at this confluence is 198.2 m. After traveling another 10.4 km, a small tributary from the West comes and joins the Thandava River, and the bed falling in this reach works out to about 80.46 m. At about 40.2 km of its traverse, a minor tributary formed by the small streams viz, Dhara gedda and Chittampadu gedda and Gorri gedda, joins the Thandava flowing in South-ward direction. After 4.8 km confluence, another tributary Addakala gedda joins the main river from the West. Lowering down after 11.2 km, another tributary from West Sarugudu gedda, taking its origin in Sarugudu forests falls in Thandava River. After this, there are no streams worth monitoring that join the Thandava River. This reach is flat, and the average bed slope is mild until the river enters into the Bay of Bengal at Pentakota in Visakhapatnam district.

Topographically, the Thandava River rises in Eastern Ghats hill then ranges and merges in the Bay of Bengal. The basin is surrounded by hills almost all around except in the southern part which is plain. The entire catchment consists of undulating country, with a series of ridges and villages interspersed with low hill ranges. Large flat areas are not available in this basin. The Northern and Western sides of the basin are hilly with dense forests. Particularly, the Northern hilly range is the area of heavy rainfall. The slopes of these hills are covered with thick jungles and in some places mixed with bamboo. The Eastern portion of the Thandava basin is generally flat and of low elevation. The coastal belt is sandy. The sampling stations of groundwater samples, resistivity stations, soil samples, and rain gauge stations are shown in Fig. 1.

3 Materials and Methods

The planning made prior to collection of the samples makes any study to be conducted with ease and accuracy. The plan includes the location of sampling sites and parameters to be analyzed, methods of data collection, and also the handling procedures. Sampling points should be such that they represent the existing environment (APHA et al. 1995). The discussions with the Groundwater Board, Andhra Pradesh prior to the sample collections and before the finalizing of the number, parameters to be analyzed, divisions/sub-divisions to be covered, district topographical marking of the stations, etc., had made meaningful effects at various stages of the work in the study area. A trail run before the execution made things sorted out, and realities at the ground level had shown significant deviations from the hypothetical assessments and allowed the work to be carried without any haphazard.

Problems occur during or after sampling which may drastically change the sample composition from its true form as natural waters are great matrixes of dynamic phases. These are due to a variety of causes, the principal among which are contamination and loss of substance due to precipitation, complex formation, adsorption, or ion exchange on the container wall. Compounding these difficulties is the main task in sampling. One has to consider such constraints existing in different geological settings before arriving at an average or compositions of rock formations and their contributions to groundwater quality. Electrical conductivity (EC) and pH provide an integrated characteristic of the ionic composition of water and its thermodynamic state (APHA et al. 1995). Keeping this in view, water samples collected from cluster of wells located in the same geological formation and similar hydrological setting were collected and analyzed in the field for EC and pH.



S.No.	Sampling Stations
1	Thandava Reservoir
2	Thandava Colony
3	Nathavaram Right Canal – 1
4	Nathavaram Right Canal – 2
5	G.Gudem
6	Chammachintta
7	Thandava Right Canal
8	Vennelapalem
9	Rangulakotturu
10	Valasampeta
11	Mallampeta
12	Agraharam – 1
13	Nathavaram
14	Rajanagaram
15	Gandhinagaram
16	Edurupalli Right Canal
17	Nathavaram Left Canal – 1
18	Nathavaram Left Canal – 2
19	Venkayyapalem
20	Gandhi Nagar
21	Thandava Left Canal – 1
22	Thandava Left Canal – 2
23	Srungavaram
24	Vedurupalli – 1
25	Vedurupalli – 2
26	Golugonda Peta
27	Peda Golugonda – 1
28	Peda Golugonda – 2
29	Gunupudi Nathavaram
30	Gunupudi Poru
31	Gunupudi Town
32	Gunupudi Minor
33	S.B.Patanam
34	Allipudi Major Canal
35	Allipudi
36	Kotnanduru – 1
37	Kotnanduru – 2
38	Agraharam – 2
39	D.Polavaram
40	Kolimeru
41	Maruvada
42	Kummarilova
43	Tuni
44	Payakarao Peta – 1
45	Payakarao Peta – 2
46	Satyavaram
47	M.S.Peta – 1
48	M.S.Peta – 2
49	M.S.Peta – 3
50	Pentakota

Fig. 1 Sampling stations along Thandava River basin

Likewise, 117 water samples were collected in the pre- and post-monsoon seasons. Subsequently, based on the average values and their relative variations and the geological, geomorphological, and geo-hydrological characteristics (even though resistivity values might alter even for small differences in geological areas), the well which possesses EC and pH hydro-geological values close to that of a general average trend of the cluster, has been identified as a sampling location. Wherever significant anomalies were present in a local scale, an attempt was made to identify the reasons for such anomalies before they are eliminated from sampling. However, locations of specific geological, hydrogeological significance, and stations in the vicinity of industrial units were given importance in sample collection. Therefore, during the entire study, care was taken in identifying the nearest possible source to the river path of a particular area and which was a potable source of the local people. A minimum of 1 km distance and a maximum (depending on potable source in the area) of 3 km distance was maintained between different sampling stations. In all the cases, the sample source selected is a public open or bore well or that which is privately owned but used by the locals as potable sources are only considered. The groundwater samples were collected in 3-L capacity polythene bottles having double stoppers. Prior to the collection, the well-cleaned sample bottles were rinsed thoroughly with the sample water having been collected and filled to the neck, avoiding bubbling and closed air tight.

In case of bore well water collection, water samples that were collected only after considerable quantity (around 2–3 L) were discarded after pumping. This allows the collection of sample of water beyond the top layer and also to reduce the stagnant water in the pipes. In open wells, water samples from a depth of about 1 m from the upper surface of water were collected as these represent the inner layers and also to avoid the accumulated dust layers on top. The station's latitude and longitude were obtained using GPS at the site. The values of coordinates were cross checked using topo sheets of the respective District's Ground Water Board office. The collected water samples were brought to the laboratory and stored in the dark to avoid major chemical alterations (Golterman et al. 1978) and analyzed on the next day. The collected water samples were analyzed for both physical and chemical properties. The samples were analyzed for their physical characteristics like pH and EC. The analysis includes the estimation of the total dissolved solids (TDS), and the anionic species include bi-carbonates (HCO_3^-), chlorides (Cl^-), fluorides (F^-), phosphates (PO_4^{3-}), and sulphates (SO_4^{2-}). The cationic analysis is carried for the estimation of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+). The rainfall data of the area for 5 years had been collected from the Groundwater Department assessments at two of their rain gauge stations. All the parameters in the present study were analyzed by following standard methods prescribed by the American Public Health Association (APHA et al. 1995) for the water analysis.

The electrical resistivity meter (ERM) method has been very popular with groundwater studies due to simplicity of the technique (Muhammed et al. 2007) and was used in the present study whereby consecutive readings are taken automatically and the results are averaged continuously. The "Schlumberger" and "Wenner" array configurations are two electrode layouts which are widely employed in the resistivity surveys (Emenike 2001). The different arrays (Wenner, Schlumberger, and double-dipole) were compared using the absolute value of the sensitivity and its spatial distribution. On a per-measurement basis, there was almost no difference between the Wenner and the Schlumberger surveys. However in this study, the Schlumberger array layout was used. By putting two electrodes into the ground and inducing an electric current through the ground, a potential field is created. Two additional electrodes are used to measure the potential at some location. Increasingly deeper measurements are achieved by using a bigger separation between the current electrodes. Moving the current electrode and having the potential electrode fixed is named the "Schlumberger" method (Frohlich and Urish 2002). The Schlumberger soundings were carried out with maximum current electrode spacing (AB) at 400 m (AB/2 = 200 m). The field data acquisition was generally carried out by moving two or four of the electrodes used, between each measurement.

4 Results and Discussion

The groundwaters had the pH in the range of 7.12 to 8.52 in pre-monsoon and 7.12 and 8.70 in the post-monsoon seasons. The above values indicate the dominance of the alkaline waters in these areas and thus signify the use for all purposes either for drinking, agricultural, or industrial purposes according to the standard values (I.S.I. Indian Standards Institution 1983). The electrical conductivity values of the water samples ranged from 178 to 4828 μSiemens/cm in pre-monsoon and 562 to 4280 μSiemens/cm in post-monsoon. The concentrations of TDS range from 110 to 3093 in pre-monsoon and 294 to 3428 mg/L in post-monsoon in the area. The higher values in some cases of EC and TDS can be attributed to the presence of high concentrations of sodium, chlorides, and carbonates in those sampling areas (Atekwana et al. 2004). The high concentrations of TDS show implications on color, odor, and aesthetic nature besides many industrial concerns.

The concentration of the cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) in the investigated area ranged from 08 to 272, 04 to 272, 06 to 680, and 01 to 175 mg/L, respectively, in the pre-monsoon season. The range when observed in the post-monsoon season for the samples collected from same locations was, 20 to 226, 14 to 154, 24 to 560, and 01 to 110 mg/L. The anion (HCO_3^-, Cl^-, SO_4^{2-}, F^-, and PO_4^{3-}) concentrations in the groundwater samples of the area ranged from 40 to 722, 09 to 1018, 01 to 284, 0.12 to 1.64, and 0.001 to 1.206 mg/L in the pre-monsoon season and 80 to 702, 42 to 872, 02 to, 415, 0.10 to 2.12, and 0.001 to 1.66 mg/L, respectively. The highest temperature recorded in this basin is 117 °F in June and lowest is 58 °F in December of that year. During May, as generally considered for the summer season month, the temperature ranges from 81.7 to 99.2 °F and for monsoon and winter months would range from 75.9 to 87.9 °F and 66.4 to 80.5 °F, respectively. The rainfall average at Kotananduru and Tuni rain gauge station for the previous 5 years was 3.5 and 4.8 m, respectively. A statistical summary of the chemical analysis data in the pre- and post-monsoon seasons is shown in Table 1.

4.1 Geophysical Assessment

Water is an important agent in the formation of landforms and thus geophysical assessment of an area invariably signifies the potentiality of groundwater (Scheidegger 1973). The electrical resistivity of rock is a property which depends on lithology and fluid content and depends on many factors like the mineral content, texture, moisture content, salinity, fissures, and fractures of geological formations. The resistivity values of rocks vary depending upon the presence of secondary porosity such as weathered, fractured, and joints (Parkhomenko 1967). The ultimate objective of vertical electrical soundings (VES) used in resistivity study at any locality is to obtain a true resistivity log similar to, for example, the induction log of a well at the locality, without actually drilling the well (Sabet Mohamed 1975). In general, traditional methods for characterizing protective layers include test hole drilling and analyses of log, with the objective being to characterize thickness and/or lateral extent of the protective layer. The disadvantage of such investigations is being labor intensive and expensive. The 50 resistivity values (μm) at various thicknesses (m1, m2, and m3) are shown in Table 2.

It was expected that based on the resistivity values, the lithology, weathered, fractured pattern, depth to basement, and resistivity variations can be evaluated. The soil and alluvium layer was underlain by weathered shale, and the weathered shale was underlain by fractured shale. It was observed that the resistivity soundings falling under high-density lineament zones provide favorable results when compared with soundings that fall under other zones. Moderate-to-good groundwater yields were tapping from weathered zones, where no fracture zones were present. In the high-resistivity stations, the thickness of alluvium followed by weathered shale's was greater, and the percolation of the groundwater in the unconsolidated material led to the formation of the moderate-to-good yields without presence of fractured zones.

In cases of constant thickness values at various depths though the fracture zone was not present, yields were high, maybe due to the presence of high alluvium thickness and the weathered zone, and also recharge from the adjacent canal sources of the river. Some areas were devoid of fractures and alluvium zones with low yields during rainy season and dried up during summer season. Whereas areas covered with high alluvium and more fractured zones were abundant with rich

Table 1 Statistical summary of chemical analysis data—pre- and post-monsoons

Parameter[a]	Minimum		Maximum		Mean		Standard deviation	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
pH	7.1	7.1	8.5	8.7	7.7	7.6	0.37	0.34
EC	178	562	4828	4280	1237.7	1513.6	770.7	723.0
TDS	110	294	3093	3428	855.1	1034.7	542.2	532.1
Ca^{2+}	08	20	272	226	59.9	68.6	35.5	39.5
Mg^{2+}	04	14	126	154	37.5	43.4	23.	23.6
Na^{+}	06	24	680	560	139.6	177.1	112	100.2
K^{+}	01	01	175	110	18.1	17.2	27.5	22.3
$HC0^{-}_{3}$	40	80	722	702	216.4	275	121	104.7
Cl^{-}	09	42	1018	872	167.3	215.6	177	163.6
SO_4^{2-}	01	02	284	415	51.6	74	38.6	81.1
F^{-}	0.1	0.1	1.6	2.12	0.81	0.8	0.4	0.3
PO_4^{2-}	0.001	0.001	1.2	1.66	0.18	0.3	0.3	0.3

TDS total dissolved solids, *EC* electrical conductivity (μSiemens/cm)

[a] All parameters are expressed in milligrams per liter, except pH and EC

Table 2 Vertical electrical soundings at various depths along Thandava River basin

S. no.	Sampling stations	Resistivity (μm)			Thickness (m)		
		μ1	μ2	μ3	m1	m2	m3
1	Thandava Reservoir	25.61	29.54	141.2	1.42	17.9	55.26
2	Thandava Colony	142	4029.7	407.7	1.35	7.99	–
3	Nathavaram Right Canal 1	37.02	13.16	19.02	1.12	1.91	9.42
4	Nathavaram Right Canal 2	39.59	7.28	599.8	1.58	10.9	10.83
5	G. Gudem	23.61	176.2	62.5	4.84	12.5	41.82
6	Chammachintta	177	25.81	81.61	2.84	14.9	36.4
7	Thandava Right Canal	10.69	183.4	45.15	0.96	2.18	15.47
8	Vennelapalem	38.63	137.5	514.4	9.04	12.2	52.89
9	Rangulakotturu	203.8	150.2	161.9	2.33	3.72	42.1
10	Valasampeta	137.7	25.85	192	1.36	12.3	5.74
11	Mallampeta	59.12	92.63	20.85	1.09	6.88	45.62
12	Agraharam 1	331.8	6332.6	1252.5	0.69	8.24	–
13	Nathavaram	14.28	22.9	2267.8	1.41	48.8	–
14	Rajanagaram	33.52	5.27	522.2	3.47	16.8	–
15	Gandhinagaram	45.95	66.17	508.4	2.22	7.73	19.89
16	Edurupalli Right Canal	19.42	6.08	602.5	4.64	11.9	6.09
17	Nathavaram Left Canal 1	154.4	17.61	48.35	3.64	41.6	–
18	Nathavaram Left Canal 2	125.1	236.6	534.2	1.52	7.39	–
19	Venkayyapalem	287	61.17	2892	3.73	39	–
20	Gandhi Nagar	51.01	24.87	50.44	1.94	16.6	42.6
21	Thandava Left Canal 1	126.8	186.9	42.32	0.71	2.12	7.62
22	Thandava Left Canal 2	15.37	9.53	79.31	1.71	18.1	29.49
23	Srungavaram	30.75	37.3	3693.4	1.3	60.9	–
24	Vedurupalli 1	50.91	179.1	338.3	1.57	6.15	61.81
25	Vedurupalli 2	72.87	7214.5	72.87	0.65	0.15	7.95
26	Golugonda Peta	130.7	54.57	59.25	2.4	1.46	71.5
27	Peda Golugonda 1	99.53	237.8	21.29	1.37	3.65	26.39
28	Peda Golugonda 2	161.8	79.59	702.9	5.12	25.4	46.93
29	Gunupudi Nathavaram	180.3	603.2	22.25	1.08	3.41	8.7
30	Gunupudi Poru	103.1	438.8	304.1	1.41	2.21	16.62
31	Gunupudi Town	27.96	10.26	22.77	1.78	9.11	13.3
32	Gunupudi Minor	12.49	10.73	166.47	1.08	11.6	26.25
33	S.B.Patanam	109.3	66.5	55.27	1.55	16.5	50.31
34	Allipudi Major Canal	10.52	3.44	260.9	1.28	7.3	–
35	Allipudi	29.77	25.96	56.36	0.66	258	4.75
36	Kotnanduru 1	40.81	13.08	83.34	1	14.7	32.04
37	Kotnanduru 2	55.51	10.35	875.8	2.2	12	–
38	Agraharam 2	26	120.7	11953	2.59	43.8	–
39	D.Polavaram	8.2	50.22	30.22	1.99	9.94	53.46
40	Kolimeru	28.46	4.68	199.1	1.08	20.3	12.27
41	Maruvada	19.54	245	2.47	0.9	1.68	3.27
42	Kummarilova	160.1	41.27	4086.1	4.66	50.3	–
43	Tuni	10.01	25.58	35.52	1.49	10.9	5.1

Table 2 (continued)

S. no.	Sampling stations	Resistivity (μm)			Thickness (m)		
		μ1	μ2	μ3	m1	m2	m3
44	Payakarao Peta 1	349.7	46.27	3.96	1.33	6.23	43.08
45	Payakarao Peta 2	14.31	4.58	217.7	1.55	9.59	–
46	Satyavaram	5.34	2.3	13.11	1.47	6.27	21.63
47	M.S.Peta 1	47.29	168.1	5.43	1.75	9.82	36.38
48	M.S.Peta 2	13.67	6.82	10.48	2.28	4.61	29.26
49	M.S.Peta 3	69.1	124	6.48	1.34	6.84	31.14
50	Pentakota	0.017	0.019	–	1.35	–	–

groundwater resources. These areas show much lower resistivity values compared with rocky regions. It was apparent that the primary porosity is clear within the geology, but groundwater occurrence was mainly due to the secondary porosity, i.e., weathering, joints, fissures, and fracture/lineaments. Most of the wells (68 %) located in this zone yield a good prospect of groundwater, as these wells do not dry up even in summer. The high resistivities were located over topographic high at the Southern and North-eastern portions of the study area as these areas are mountainous rocky segregations. The wells located in high resistivity zones gave relatively poor yields. The major part of the basin constitutes the values relating to pediplain with moderate and plain weathering. The thickness of piedmont zones increased from Northern area to Southern areas of the present river basin, where the apparent resistivity values were found to decrease in the same direction. The alluvium consists of pebbles, gravel, sand, silt, and clay, ranging in thickness from 2 to 26 m occurring from a Northern direction of the study area and presence of coastal plain to deep.

The average sounding curves confirmed that the curve began to descent, after the last measured data point and shows the presence of fractured bedrock at a depth of about 4 m and subsequent depths showed that the bedrock was in fact fractured sandstone (Fig. 2). Basing on the above observations, being the hardest part of the aquifer, the prospects of the groundwater seems to have poor yields. The plots flat shape for the minimum, which apparently narrows down the possible range for the value of the true resistivity of the conductive layer, above bedrock, to about 35 m. These preferred orientations of deep-seated fractures are responsible for the groundwater potential zones in the study area, and this is ably assisted from the torrential rainfall in these parts in comparison with others. However, in areas where such information is not available or is rather scanty, it is difficult to infer either the thickness of the alluvial column or the presence of granular zones in the subsurface formations, particularly in the marginal areas where marked irregularity of the basement topography and a wide variation in the nature of the sediments are usually observed (Raju and Reddy 1998; Bose et al. 1973).

Basing on the above observations, it was a segregation of three zones in the study area as a Pleistocene coastal belt, the Central zone and Northern part of the basin formed by Archean type rock and khondalites, and the remaining portion is unclassified crystalline which also belongs to Archean group. The Northern part of the area was topographically narrow longitudinal valleys formed by the discontinuous recent hill ranges of Archean complex as basement for the younger sediment formations, which are occupying the Southern part of the area. The younger sediments were fringing at North, with the hard, compact crystalline rocks whereas, towards South these were concealed mostly by thick veneer of alluvial and Gondwana sedimentary formations. The high resistivities were located over topographic high at the Southern and North-easten portions of the study area. The wells located in high resistivity zones give relatively poor yields. The geomorphology of basin is shown in Fig. 3, and the groundwater potential zones are shown in Fig. 4.

4.2 Geochemical Evolution of Groundwater

To identify the geochemical evolution and sources of dissolved salts in groundwaters, Piper's trilinear

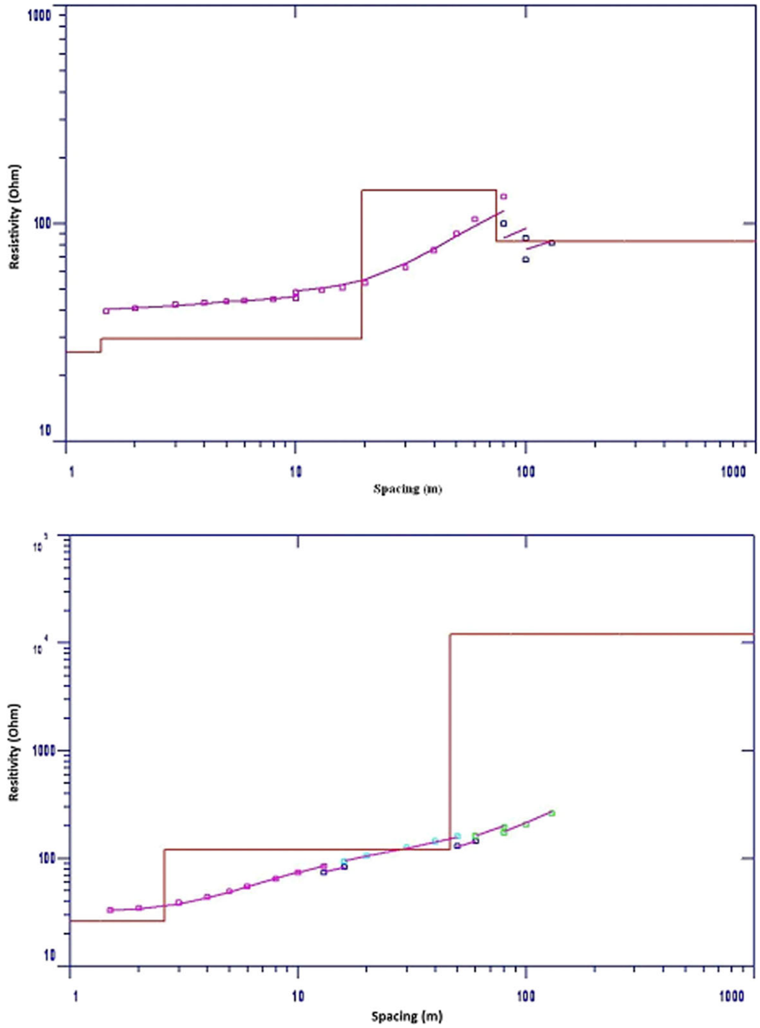
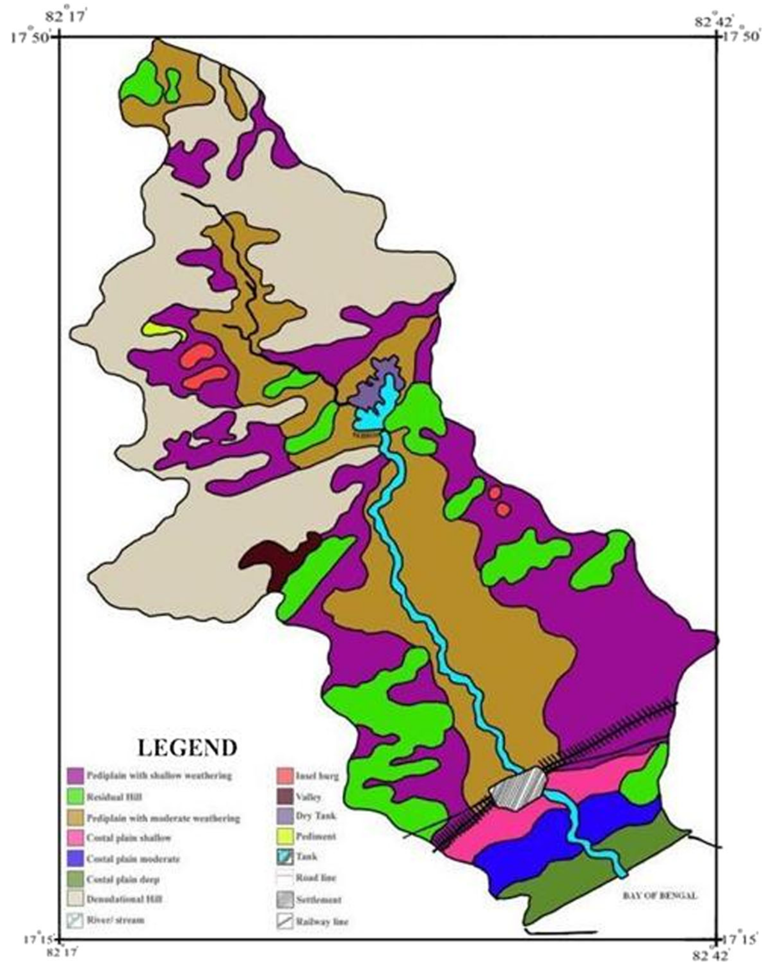


Fig. 2 Resistivity vs thickness plots

diagram (Piper 1994) was used. Polluted zones can also be predicted by using Piper diagrams (Jeong 2001; Chen et al. 2007). The diagram is the combination of the percentages of the total milliequivalents per liter of cations and anions. The chemical data of the pre-monsoon season in the percentage mode of all the groundwater samples in the study area falling in zone 5 are 23.93 % which include the stations 1–14, 20, 27–31, 41, 47, 89, 92, 94, 97, 107, and 112. The samples falling in zone 7 constitute 31.62 %, and these are 21, 25, 33–35, 37, 38, 40, 46, 53, 63–65, 67–73, 76–80, 82, 84, 86, 100, 101, 104–106, 110, and 115–117. The samples observed in zone 9 had a percentage of 44.44 % of the whole samples, and the stations which come under this are as follows 15–19, 22–24, 26, 32, 36, 39, 42–45, 48–52, 54–62, 66, 74, 75, 81, 83, 85, 87–91, 93, 95, 96, 98, 99, 102, 103, 108, 109, 111, 113, and 114.

The sampling stations of the post-monsoon season that come under the above zones of the same are as follows in their respective percentages zone 5 is 10.25 % with stations 1, 2, 11, 43, 90, 92, and 94–99; zone 7 is 32.47 % of 8, 9, 17, 20, 22, 23, 25, 32, 35, 37, 38, 48, 52, 53, 56, 65, 66, 70, 71, 74–78, 85, 87, 100, 105–108, 110–113, and 115–117 stations; and that of zone 9 is 57.26 % of stations 3–7, 10, 12–16, 18, 19, 21, 24, 26–31, 33, 34, 36, 39, 40–42, 44–51, 54, 55, 57–64, 67–69, 72, 73, 79–84, 86, 88, 89, 91, 93, 101–104, 109, and 114. The above observations indicate that the samples in these zones are carbonate dominant supplemented by the alkali (Na, Mg) ions and thus can be referred as slightly hard water type (Table 3) and were also earlier

Fig. 3 Geomorphology of Thandava River basin



observed by Kumar et al. (2013) in Visakhapatnam area. In the present case, it is evident that the carbonate hardness results from the dominance of alkaline earths (Ca^{2+} and Mg^{2+}) and that of the weak acids (HCO_3^-) indicating the influence of local geology on the genesis of the ions in the groundwater. This water type (zone 5) represents the fresh water environment as these waters are close to the standards of fresh water, in general having less salinity and TDS. The movements of the drainage (sub-dendritic) in the rainy season from the elevated to the plains along the stretch of the Southern part highly donate this kind of activity in the sub-surface topography. The noncarbonate hardness is attributed to the abundance of alkalies (Na^+, K^+) and strong acids (Cl^- and SO_4^{2-}), which are the effect of marine environment and/or clay horizons and topographic lows.

The waters occurring in zone 7 belong to brackish/saline type, and these represent the polluted zones in the study area. The mixed type (zone 9) represents the cations and anions that are not excessive of 50 % in their total concentration due to various combinations of ions observed from the results. Deviations from the general to an extent were observed in the geochemical evolution of the groundwater classification. These include the stations where the TDS value is greater than 1000 mg/L but fall in the mixed type in the pre-monsoon season are 49, 51, 52, 58, 59, 61, 91, 95, 111, and 113 and that of the fresh water are stations 25 and 112. In case of the post-monsoon season, the deviations include stations 5, 6, 10, 13, 14, 19, 21, 31, 33, 36, 44, 47, 49, 50, 58, 62, 68, 72, 73, 82, 84, and 89 which should be a marine environment, according to the criteria but were falling in the mixed type of water in the diagrams. In post-monsoon season, there were no deviations of station

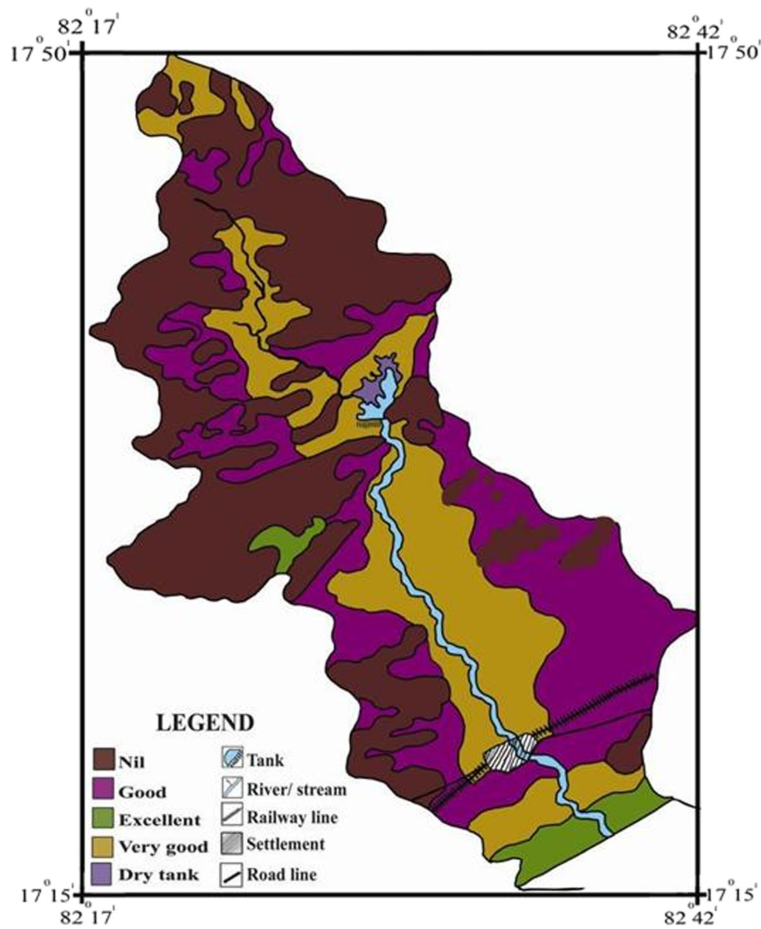


Fig. 4 Groundwater potential zones along Thandava River basin

having the TDS value more than 1000 mg/L and falling in the fresh water environment of the classification.

The probable reason for these sample deviation from the normal trend would be their under saturation environment towards the new environment and sooner or later they would shift to maintain the new environment leaving the characteristics of the old environmental conditions. The index values confirm the above as $CA_1 = Cl^- - (Na^+ + K^+)/Cl^-$ and $CA_2 = Cl^- - (Na^+ + K^+)/(SO_4^{2-} + HCO_3^- + CO_3^- + NO_3^-)$, where CA_1 and CA_2 are cation and anion ratios (Schoeller 1965) and had yielded the CA_1/CA_2 ratio represent the under saturation with environment. When there is an exchange of Na^+ and K^+ in the groundwaters with Mg^{2+} or Ca^{2+} in the rock/weathered products (clays), both the indices will be positive. If there is a reverse exchange, then both the indexes will be negative. Another reason that would explain this deviation would be the recent changes in those areas like extension or compression between the fractures in the rocks to allow a different type of water into the former environment and thus exhibiting variation. In cases of marine characteristics, observation in the fresh water zones might be resulting from the forced intrusion of seawater due to over exploitation of groundwater, where the upward pressure would force the surrounding waters to pave their way out by widening the linear fractures in the rocks. This is generally not observed in the natural circumstances, where the groundwater remain static. These observations clearly

Table 3 Water hardness index

Degree of hardness	ppm (or mg/L)
Soft	<17.0
Slightly hard	17.1–60
Moderately hard	60–120
Hard	120–180
Very hard	>180

point out the sources of pollutants due to the anthropogenic activities in and around these and thus these stations are being polluted. The geochemical evolution of the groundwater in the pre- and post-monsoon seasons were shown in Fig. 5a, b.

Stations showing the marine environment observed in most cases of the post-monsoon season, even in the absence of their TDS values less than 1000 mg/L or in cases of existence of the environment, which is suitable for fresh or mixed type of water, might be the effects of the upland characteristics carried through different facies of different places after the rainfall, where these were observed. This dominance neither observed far away from the coast line nor the middle of fresh water environment nor would be temporary till the flow is settled and there by the origin of the local geology would be evolved with time log. During the flow of water from the elevated to the downstream, results of the restless chemical equilibria among various solute and solvents showcase these types of invariable environments and that to especially surrounding the flowing water bodies and often groundwater gets polluted (Das and Kaur 2007; Datta and Tyagi 1996).

The flow pattern of the groundwater can be correlated with the hydro-geochemical facies as stated by Ophori and Toth (1989) where, low TDS, Mg^{2+}/Ca^{2+} ratio and SO_4^{2-}, and high HCO_3^- occur in the recharge areas. They further stated that the opposite conditions, such as high TDS, Mg^{2+}/Ca^{2+} ratio, and SO_4^{2-} and low HCO_3^-, are associated with the discharge areas. They further reported that the groundwater with Ca^{2+}–Mg^{2+}–HCO_3^- and Na^+–HCO_3^- types are dominant in the recharge areas, while Ca^{2+}–Mg^{2+}–SO_4^{2-}–HCO_3^- and Na^+–HCO_3^- types occur in the discharge areas. It was evident from the above observations that indiscriminate deforestation of the mangroves along these coastal stations where earlier they were the natural bearers of pollution, now making the topographic groundwater to suffer the pollution from the elevated. In some areas, the flattening of the land for huge constructions has been paving the path for the pollutants to migrate from one area to the other. Ophri and Toth also reported that there are very high chances of the groundwater being polluted in cases where the flow rates are high at recharge zones due to the high dissolution rates of the ions.

According to the correlation of hydro-geochemical facies with the flow pattern of groundwater system, the average values which were observed in the pre-monsoon season, the low TDS (<1000 mg/L), low Mg^{2+}/Ca^{2+} ratio (0.67) and SO_4^{2-} (<100 mg/L), and high HCO_3^-/Cl^- ratio, (2.15) and of the same when observed in the post-monsoon season are as follows, 0.75 and 1.81 along with Na^+–HCO_3^- type hydrogeochemical facies observed in the parameters suggest that these areas lie in the predominated recharge zones (Table 4). However, Mg^{2+}/Ca^{2+} ratio >1 in the pre-monsoon for stations 17, 18, 22, 43, 45, 47, 49, 57, 68, 73, 75, 83, 84, 90, 107, 111, and 112 stations and in the post-monsoon for stations 4, 14, 15, 22, 25, 28, 29, 37, 46, 59, 67, 70, 77, 79, 80–82, 84, 86–88, 94, 104, and 112, indicate the association of these areas with discharge source. The above variations in the local

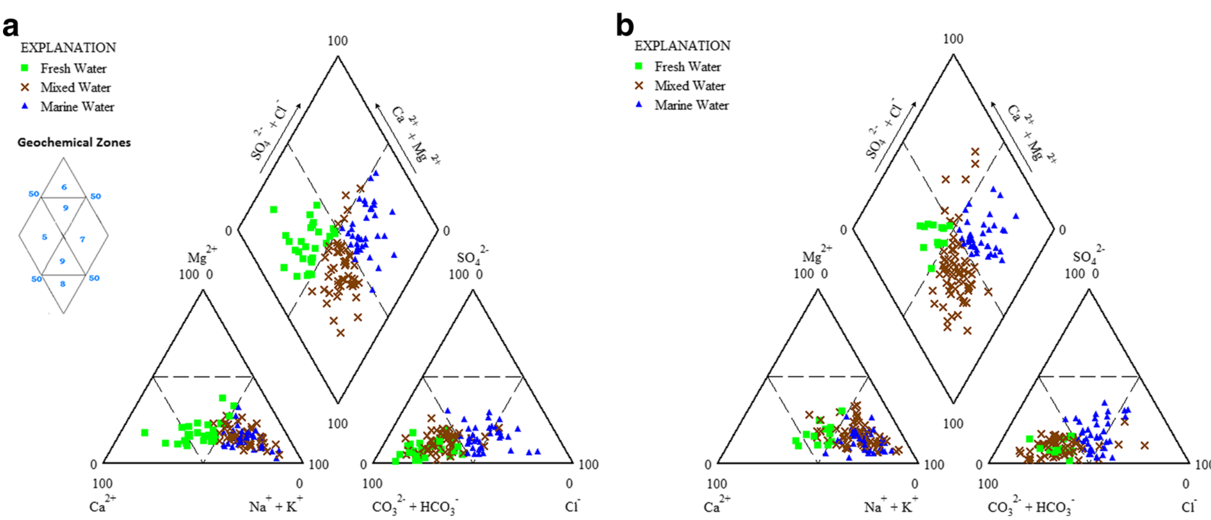


Fig. 5 **a** Geochemical evolution of groundwater—pre-monsoon. **b** Geochemical evolution of groundwater—post-monsoon

Table 4 Hydro-geochemical ratios of groundwater samples along Thandava River basin

Hydro-geochemical ratio	Mean	
	Pre-monsoon	Post-monsoon
Mg^{2+}/Ca^{2+}	0.67	0.75
Ca^{2+}/Mg^{2+}/total cations	0.01	0.07
Na^{+}/K^{+}/total cations	0.11	0.12
Cl^{-}/Na^{+}	1.26	1.33
HCO_3^{-}/Cl^{-}	2.15	1.81
Na^{+}/Cl^{-}	1.07	1.04
$CA_1 = Cl^{-}\ (Na^{+} + K^{+})/Cl^{-}$	157.63	306.40
$CA_2 = Cl^{-}\ (Na^{+} + K^{+})/(SO_4^{2-} + HCO_3^{-})$	167.341	210.000

CA cation and anion index

geology are being dominant in places of very high agricultural activities (Karlen et al. 1997) and also due to other factors like the crust weathering (Chebotarev 1955) taking place in those stations. In the present study, it can be concluded that the above variations by either the low concentrations of Ca^{2+} due to ion exchange between Ca^{2+} and Na^{+} and/or by the preferential removal of Ca^{2+} by precipitation as carbonates (kankar and/or calcrete) (Kumar 2011). These waters seldom deviate from the local geology and thus are potable and reliable for agriculture with normal fertilizer additions. Earlier, Sarma and Swamy (1986) reported the similar context with respect to the Visakhapatnam basin and delineated the chemically polluted zones.

4.3 Geological Assessment

The soil/aquifer samples collected at some of the points were thoroughly analyzed for the differentiation and origin basis in and around the river basin. Table 5 shows the summarized results of the analysis and its outcome in assessing the local geology and the possible sources and their types in the study area. Soils differ in their capacity for crop production and suitability for irrigated agriculture. Their physiochemical properties which determine the crop production suitability and capacity are governed by several factors operating singly and/or collectively, i.e., topography, geology, climate, agronomy, etc. The behavior of sub-soil waters also plays an important part in the final outcome and under natural conditions; there shall be a soil-water crop relationship peculiar to each area. Jury et al. (1987) observed that chemical reactions between soil and pesticides do enhance groundwater pollution and Arias-Estévez et al. (2008) reported groundwater pollution based on the soil types.

The three main types of soils in this river basin are (i) red loamy soils in the upper reaches of the basin, (ii) red sandy soils in the interior, and (iii) coastal sands and alluvial soils in the coastal belts. The extent of these soils in the basin with respect to the total area is 63.80 % (582.00 km^2) of red sandy, 29.2 % (265.89 km^2) of coastal sands and alluvial, and 7 % (63.89 km^2) of red loamy. Red sandy soils cover the largest area (interior) in the basin. The regions occupied by acid granite, genesis, quartzite, and felpathic, with only subordinate rock types rich in iron and magnesium-bearing minerals, gives particularly to red soil, but at places yellow to gray or even black-colored soils. Some red-colored soils are of different constitution having been derived from the surface cropping of laterized rocks or from lime stone formations. This type of soil, though frequently red in color not always necessarily so, and the color is not due to a high percentage of the iron content.

Texturally, red soils comprise course sandy loams, medium fine sandy loams, fine sandy loams, and loams. The deep red soils exhibit a sandy loamy texture at the surface, loamy composition in the deeper layers (Emenike 2001). The soils usually are friable and light textured, sufficiently permeable to be well drained, have water retainability, negligible, salt content seldom, exceeding 0.2 %, a low base status, and are almost free from lime and carbonate concentrations. Generally, these soils are deficient in exchangeable bases but are deficient in nitrogen and organic matters but have sufficient potash and lime (Sparks and Liebhardt 1981). The extent of available phosphate is generally low to sufficient. Because of this, they are being friable, well drained and easily manageable, and are capable of withstanding heavy moisture saturation without detriment to crop growth.

The sand stones present in the study area belong to the upper Jurassic age and that of the Tirupati stand stone (Goundwana group). The general character and distribution of these would be the intercalation of clay and sandstones, brown in color, and are generally suitable for light tube wells with a discharge of about 30,000 l/h, and these groundwaters are in general good. Coastal sands and alluvial soils occur in the coastal belt of Thandava basin. Based on the results, it can be concluded that alluvial soils are of sedimentary type

Table 5 Results of soil and aquifer samples of Thandava River basin

S. no.	Sampling station	Place	Cumulative weight percent retained in sieve size (mm)						Passed through	Geology
			5.60	2.00	1.00	0.50	0.25	0.075	0.075	
1	Tuni	Aquifer	–	00.91	12.87	61.28	88.69	97.94	99.25	FMS
2	Satyavaram-1	River bed	00.9	13.41	43.91	76.77	92.07	98.68	100.11	MS
3	Satyavaram-2	River bed	–	00.45	30.30	42.86	90.41	98.87	99.13	FMS
4	Srirampuram	River bank	–	40.56	80.48	12.71	26.07	93.59	99.20	STS
5	Peddirajupalem	Aquifer	00.32	10.22	40.28	27.52	79.08	99.78	99.80	FMS
6	Payakarao Peta	Aquifer	00.5	20.66	21.21	68.71	91.97	99.37	100.00	MS
7	Rekhavanipalem	Aquifer	50.46	14.86	27.67	59.92	88.22	99.87	99.98	MS
8	Kumamrilova	River bed	–	10.88	11.68	72.23	93.39	99.94	100.00	MS
9	Kummarilova	River bank	10.97	10.28	14.93	23.39	52.44	95.60	99.32	FS
10	Manivada	Field	10.56	11.91	21.94	45.44	70.07	96.95	99.30	FS
11	Nandivampu	Field	–	–	–	20.33	80.58	90.90	99.57	STC
12	D. Polavaram	River bed	50.92	20.82	41.25	72.67	90.58	99.38	99.79	CS
13	Sitarampuram	River bed	–	10.31	40.91	31.01	77.51	99.72	99.72	FMS
14	Guntapalli	River bank	–	00.45	10.15	40.70	45.00	95.60	99.70	STC
15	Kollimeraka	Field	40.02	10.44	17.81	39.62	74.14	98.02	99.33	STC
16	Kollimeraka	River bed	–	00.30	20.15	14.71	59.91	99.03	99.14	STC
17	Atikivanipalem	Field	70.53	17.20	25.42	44.38	72.91	99.59	99.29	MS
18	T. Jaganadhapuram	Field	90.90	31.16	39.22	53.08	69.20	97.85	99.97	MCS
19	Surapurajupeta	River bed	–	50.25	24.12	54.30	85.15	99.01	99.45	MCS
20	Agraharam	River bank	10.36	15.61	23.27	74.92	89.68	99.95	110.00	MCS
21	Kakarpalli	River bed	20.52	90.93	23.18	67.04	93.49	99.29	99.29	MCS
22	Kakarapalli	River bank	12.35	23.93	29.18	54.04	63.74	95.80	100.05	MCS
23	Kotanaduru-1	River bed	10.43	90.91	20.88	55.06	88.52	99.49	99.80	MS
24	Kotnanduru-2	River bed	26.25	61.18	76.93	88.64	94.80	99.45	99.95	VCS
25	K. Mallavaram	Aquifer	–	10.66	20.98	23.79	81.35	99.74	99.85	FMS
26	K. Agraharam	River bed	10.93	14.68	42.95	80.21	95.47	99.12	99.49	MS
27	K. Agraharam	River bank	–	30.90	60.99	14.22	38.52	94.57	99.23	FS
28	Rapaka	Paddy field	–	80.63	16.59	35.57	61.42	95.68	99.29	SC
30	Sarabhavaram	River bed	00.95	10.54	20.29	65.88	95.44	98.99	99.63	MCS

FMS fine to medium sands, *FS* fine sands, *MS* medium sands, *MCS* medium to coarse sands, *CS* coarse sands, *VCS* very coarse sands, *FS* fine sands, *SC* sandy clay, *STC* silty clay, *STS* silty sands

and are found in the deltaic areas and on the coastal belt, which belong to the recent type. They are formed by annual depositions of rich silts brought down by rivers. On the basis of textural characteristics, these soils can be silty loams, clay, and rarely sandy loams. They are generally well drained and being inherently fertile (Emenike 2001). They respond well to irrigation and generally give high crop yields, but at some cases, there have been reports of saline depths at various depths along the coast (Kumar 2011). Todd and Mays (1980) referred high saline type of soils do pollute the groundwater due to hydro-chemical exchange of ions between soil grains and groundwater which coincides with the above observations.

5 Conclusions

The geological structure can be summed up as the coastal belt is Pleistocene, the Central zone and Northern parts with Archean type rock, and Khondalites, with the remaining as unclassified crystalline correlates with the geological and chemical data. From the geochemical perspective, these are correlated to the presence of the red and mixed soils, which predominantly exist in this basin. Being permeable and with low water holding capacity, they are favorable for irrigation in the region. Moreover, they were friable, well drained, and easily managed for the groundwater flow. As such, their behavior is normal and good for crop yields and has been an index for the nonpolluted, but modernization of the canals is needed. The chemical assessment reveals that the groundwater includes the geochemical zones due to carbonate hardness, noncarbonate hardness, and mixed types of water, which again correlates with the geophysical and geological assessments. The carbonate hardness results from the dominance of alkaline earths (Ca^{2+} and Mg^{2+}) and that of the weak acids (HCO_3^-) indicating the influence of soil chemistry on the groundwater chemistry as observed in the geological assessment and represents the fresh water environment. The mixed and marine traces from noncarbonate hardness due to abundance of alkalies (Na^+, K^+) and strong acids (Cl^- and SO_4^{2-}) are curtsey of clay horizons and topographic lows as observed in the coastal belts and mixture of little polluted zones. The integration of the geophysical, geological, and chemical data signifies the respective interpretation to be in tune with the correlated results. The above cannot be achieved in normal studies associated with any one interpretation of the groundwater.

Compliance with Ethical Standards

Conflict of Interest The authors express that the paper does not carry any conflict of interest.

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