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Role of water quality and groundwater fluctuations as precursors in sustainable development and management of groundwater resources

P. RAJENDRA PRASAD, C. SUBBA RAO &
N. V. B. S. S. PRASAD
Department of Geophysics, Andhra University, Visakhapatnam, India
ahivisakha@hotmail.com

Abstract Water quality and hydrogeological studies conducted in the Tammileru and Vamsadhara River basins and in the coastal and urban aquifers of Visakhapatnam, India, have provided critical information on the anomalous behaviour of ionic concentrations and their ratios, which are specific to different hydrogeological conditions. The ionic ratios of the groundwater in the Tammileru basin have proved to be an effective tool for identifying the geological formations, while their transient behaviour has provided major clues for evaluating the point and non-point sources of contamination, which otherwise were not evident from field observations. The field and model studies in the urban and coastal aquifers of Visakhapatnam have clearly brought out contradicting relationships between the rise and fall of the water table and the associated ionic concentrations, which can be explained only with specific hydrogeological models. Low permeability values suggest high contact time resulting in enrichment through adsorption of common ions. Contrasting behaviour of fluoride reflects the presence of F-bearing minerals and adsorption phenomena. A holistic approach will provide suitable monitoring and management strategies for sustainable development and management of groundwater resources.

Key words adsorption and ion exchange; groundwater quality; ionic ratios; water table fluctuations and electrical conductivity

INTRODUCTION

During the last decade, the considerable importance of groundwater quality has been realized in the rapidly developing nations. However, investigations are focused more on the urban areas and are only slowly spreading into the rural regions. In general, compliance with water standards is examined mostly in the domestic sector. However, the need to have suitable water quality in industrial and agricultural sectors has gained importance in recent years. There has been an acceleration in the use of groundwater in the developing nations, mostly those with arid and semiarid climates. Urbanization, modern agricultural practices, an upward trend in the socio-economic status of the population both in urban and rural areas, and the programmes and facilities offered by government and the financial institutions have accelerated the indiscriminate development and use of groundwater resources. In a country like India, monsoon failures and the rapid increase in use of water resources have virtually changed many perennial river systems into ephemeral streams. An integrated effect of all these developments has been over-exploitation and dependence on groundwater. In this context, several studies of the sustainable development of water resources have made use of methods based on the spatial and temporal distribution of water quality parameters for groundwater (e.g. Farnham *et al.*, 2002; Dano *et al.*, 2003; Thyne *et al.*, 2004).

GROUNDWATER QUALITY STUDIES

Studies of spatial and temporal variations of water quality in three different hydrogeological settings in India demonstrate the role of groundwater quality in sustainable development.

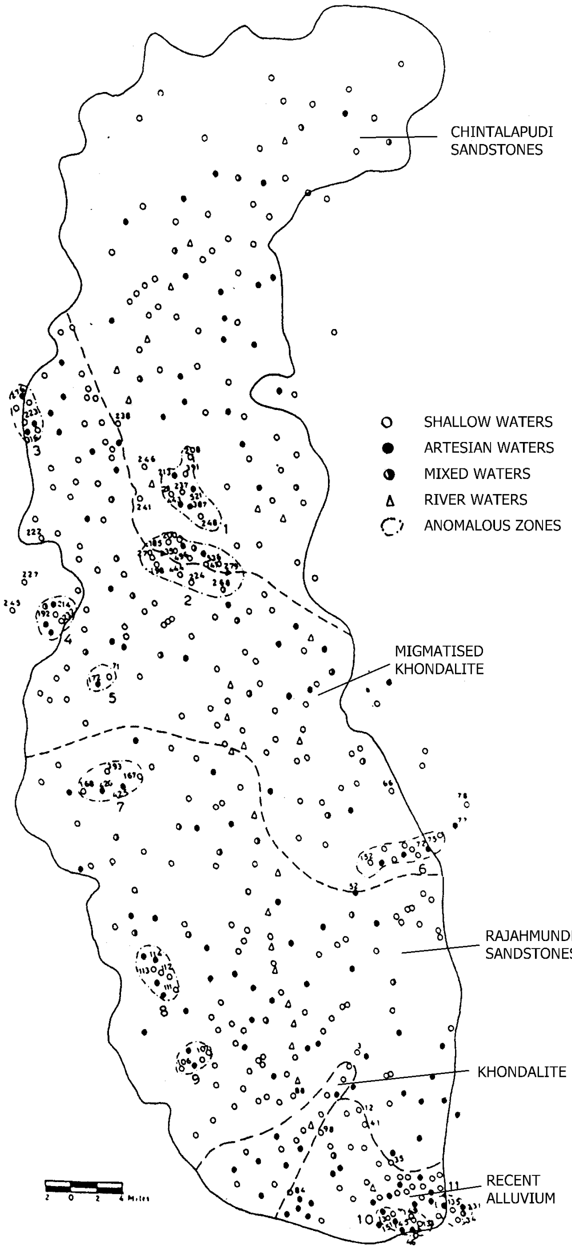

Fig. 1 Location of water sampling sites and the geological boundaries in the Tammileru River basin.

Tammileru River Basin

The Tammileru River basin, which is located in the eastern Ghats of India, is underlain by a variety of geological formations ranging in age from the Archaean basement to Recent alluvium. Hydrochemical studies were carried out to assess groundwater quality, to elicit possible relationships between quality of groundwater and the geological formations, and to detect anomalous zones of groundwater quality and their possible origin.

A total of 887 groundwater samples were collected from existing open wells and boreholes during both post- and pre-monsoon periods, and were analysed for major anions and cations (viz. Cl, HCO_3, SO_4 and Ca, Mg, Na, K) and were subjected to *in situ* measurements of pH, temperature and electrical conductivity. The guidelines prescribed by Taylor (1958), Hem (1970) and IHD–WHO Working Group (1978) were strictly adhered to during the collection and analysis of the water samples. The location of the sample sites and the boundaries of the geological formations are presented in Fig. 1.

Table 1 Statistical representation of ionic concentrations (after application of least squares).

Constituent ion	Nature of water sample	General range (ppm)	Mean value (ppm)	Standard deviation (ppm)	General range (ppm)	Mean value (ppm)	Standard deviation (ppm)
		Chintalapudi sandstones			Migmatized Khondalites		
Chloride	S W	60–140	87.5	37.2	80–180	120.2	38.2
	A W	60–120	78.6	33.1	80–160	98.3	27.6
Bicarbonate	S W	250–575	410.6	5.4	400–575	467.3	58.0
	A W	300–500	398.4	60.0	350–700	476.7	62.2
Sulphate	S W	10–45	28.6	14.3	10–37	19.8	5.3
	A W	10–45	26.5	8.6	25–70	56.3	9.6
Calcium	S W	50–80	68.0	19.6	30–80	63.4	18.6
	A W	30–50	38.6	14.7	40–80	65.4	9.7
Magnesium	S W	7–27	19.2	5.1	30–50	46.7	15.3
	A W	7–25	17.8	4.8	60–75	68.7	18.7
Sodium	S W	25–80	60.6	28.7	60–90	73.2	12.7
	A W	50–90	62.0	14.2	50–80	62.0	8.2
Potassium	S W	5–12	7.9	1.8	10–50	32.1	5.1
	A W	5–12	8.7	2.3	7–18	12.3	2.2
		Rajahmundry sandstones			Alluvium		
Chloride	S W	100–180	159.3	30.6	180–360	260.0	54.3
	A W	100–180	152.4	26.5	150–250	195.0	31.8
Bicarbonate	S W	350–475	400.3	59.8	250–450	380.7	55.3
	A W	300–565	408.6	60.3	350–650	421.6	75.3
Sulphate	S W	20–50	37.6	5.3	100–250	120.3	28.6
	A W	10–40	20.2	5.6	20–80	37.8	13.2
Calcium	S W	100–185	129.5	27.0	50–55	70.7	13.5
	A W	40–130	76.4	18.1	30–65	41.3	12.6
Magnesium	S W	30–70	53.0	17.5	15–40	26.9	8.6
	A W	25–50	36.4	10.7	50–70	53.2	14.7
Sodium	S W	90–140	108.3	16.4	60–250	178.6	29.3
	A W	70–100	86.1	12.3	70–250	183.7	31.6
Potassium	S W	10–15	13.0	2.1	13–40	27.0	6.8
	A W	2–11	8.2	2.2	8–20	16.0	2.1

S W = Shallow water; A W = Artesian water.

The hydrochemical data were subjected to a regional residual separation technique (Agocs, 1951; Skeels, 1967; Rao *et al.*, 1975) in order to isolate zones of anomalous behaviour. The data, after separating the local anomalous values, were subjected to statistical analysis in order to determine values of arithmetic mean, range and standard deviation (Table 1 and Fig. 2). The local geological formations are characterized using the ionic concentrations and their ratios (Sarma *et al.*, 1987). Out of many ratios tested, Cl/SO_4, Cl/Mg, HCO_3/Cl, Na/K were found to be the most effective discriminators in identifying the geological formations of the region (Table 2).

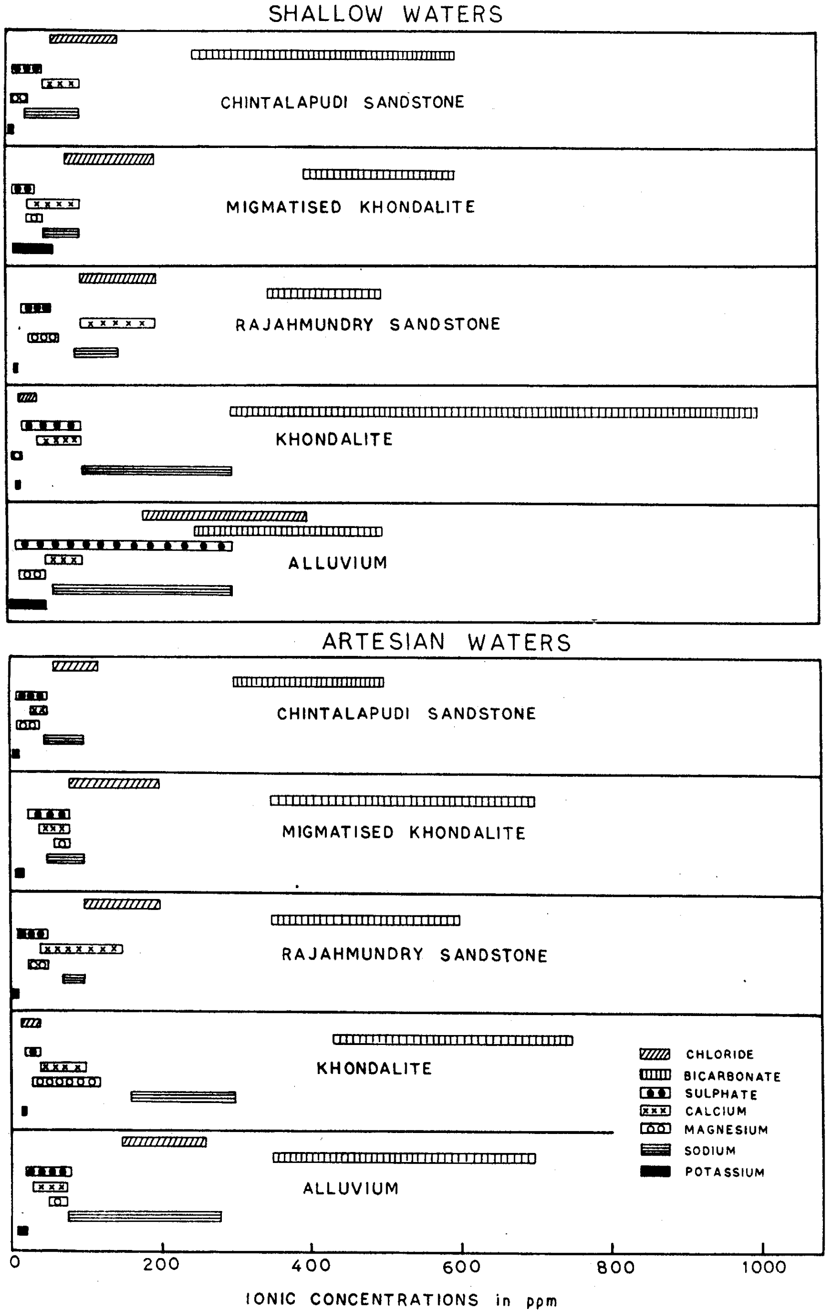

Fig. 2 Ranges of ionic concentrations in the groundwaters of the Tammileru basin (Pre-monsoon).

Table 2 Ionic ratios in groundwaters of Tammileru basin.

		Geological formation in which waters are present				
Ionic ratio	Nature of water sample	Chintalapudi sandstone	Migmatized chondalite	Rajahmundry sandstone	Khondalite	Alluvium
Cl/SO_4	S W	3.50	5.60	3.75	0.46	1.45
	A W	3.00	2.66	4.66	0.46	4.10
Cl/Mg	S W	5.70	3.50	3.00	2.00	8.90
	A W	3.60	2.00	4.00	0.42	3.25
HCO_3	S W	4.10	3.60	2.80	23.60	1.29
	A W	4.40	3.75	3.17	21.50	2.56
Na/K	S W	7.35	2.00	9.60	14.80	6.73
	A W	8.80	6.00	13.07	13.10	12.50

S W = Shallow water; A W = Artesian water.

Tables 1 and 2 and Fig. 2 reveal that the range in ionic concentrations is defined more precisely for water from the confined than from the unconfined aquifers, and there is less scatter about the arithmetic mean and lower standard deviation values for waters from confined aquifers. It can be seen from Fig. 1 that 11 zones exhibit quality abnormalities which can be attributed to geological characteristics, such as the occurrence of migmatization and kaolonization, and to the occurrence of contamination through industrial effluents. Khondalites are characterized by the low Cl concentrations, ranging from 15 to 40 ppm and higher Na concentrations up to a maximum of 300 ppm. The migmatized khondalites are associated with higher K concentrations, possibly reflecting the presence of illite in these formations. The HCO_3 content is found to be less in sandstones compared with the Khondalites and migmatized Khondalites, while the ranges of ionic concentrations in the Chintalapudi and Rajahmundry sandstones are comparable. Slightly higher solute levels associated with the Rajahmundry, compared to the Chintalapudi sandstones, could be explained by a larger grain size and the presence of more cementing material in the former formation. Except for Ca and Mg, all other anions and cations, and especially Cl, are present in higher concentrations in alluvium.

A recent repeat survey in the region has shown a general increase in the ionic concentrations which can be attributed to over-exploitation of groundwater relative to its replenishment. This is also reinforced by a predominant change in land use and irrigation patterns. Furthermore, the increase in spatial extent of contamination, both in lateral and vertical extents, in the lower reaches of the Tammileru basin reflects recharge of the confined aquifers through open wells by effluents from the tanning and dyeing industries. Water quality criteria have helped not only the identification of the contaminated zones but also facilitated determination of the optimum level for pumping in this region.

Urban and coastal aquifers of Visakhapatnam

A regular monthly inventory of water levels and water quality made at 97 well locations from the urban and coastal aquifers of Viakhapatnam has shown contradictory behaviour between electrical conductivity and water level fluctuations (Fig. 3).

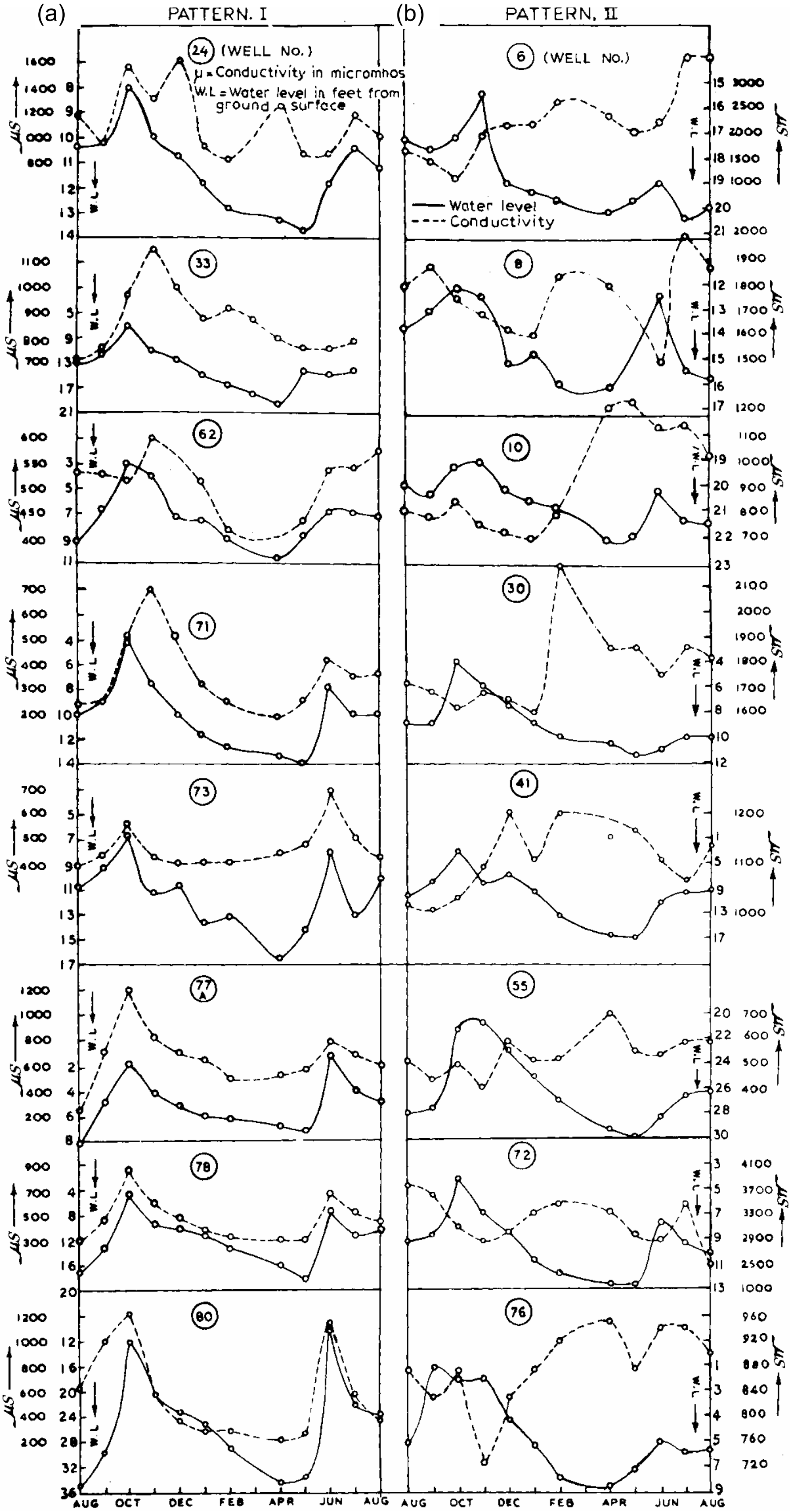

Fig. 3 Water table and electrical conductivity fluctuations.

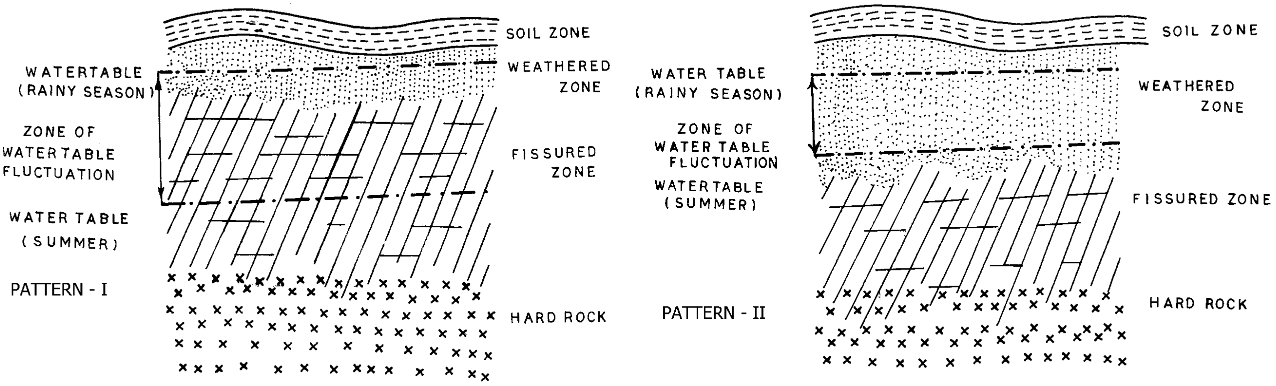

Fig. 4 Generalized hydrogeological cross-section.

The general hydrogeological cross-section of the area (Fig. 4) exhibits a sandy loam top soil underlain by weathered kaolinised Khondalite, which in turn is underlain by the fractured and fissured rock zone that gradually merges into hard and relatively less fractured rock below (Sarma, 1967). The water table is usually within the kaolinized zone but is found in the fractured zone during the pre-monsoon period. Field observations indicate that some of the wells penetrate a very thin weathered zone, whereas others penetrate a thick weathered zone.

Detailed investigations of the groundwater levels and the associated electrical conductivity values indicate two different patterns. In the first pattern, the water level fluctuations exhibit a positive relationship with changes in electrical conductivity, while in the second pattern an inverse relationship is observed. However, some wells show a mixed trend. An increase in conductivity with the lowering of the water table is observed in situations where the water table fluctuations are within the weathered zone, while the decrease in conductivity is observed in a situation where the water table drops from the weathered zone down into the fractured zone. Sarma & Venkateswarulu (1967) reported groundwater pockets with high electrical conductivity in the khondalitic region of the eastern Ghats, while Swaine & Schneider (1971) referred to changing chemical composition of groundwater due to ion exchange. Schoeller (1959) noted that argillaceous minerals are liable to adsorb elements from, or exchange ions with, groundwater, and the existence of groundwater pockets with high conductivity is explained by base exchange processes in areas where a higher grade of weathering occurs (Sarma & Krishnaiah, 1976).

Industrial pollution

Only 42% of the wells in an industrial township of Visakhapatnam had waters with conductivity less than 1500 μS cm^{-1} which contrasted with very high conductivity of wells affected by effluents. High levels of chloride and sulphate or magnesium and bicarbonate were also characteristic of contaminated wells.

Some of the industries discharge their effluents into the porous surface soil from where they spread and infiltrate into the sub-surface and mainly contaminate shallow aquifers in the vicinity of existing open wells. The areas far from the effluent discharge

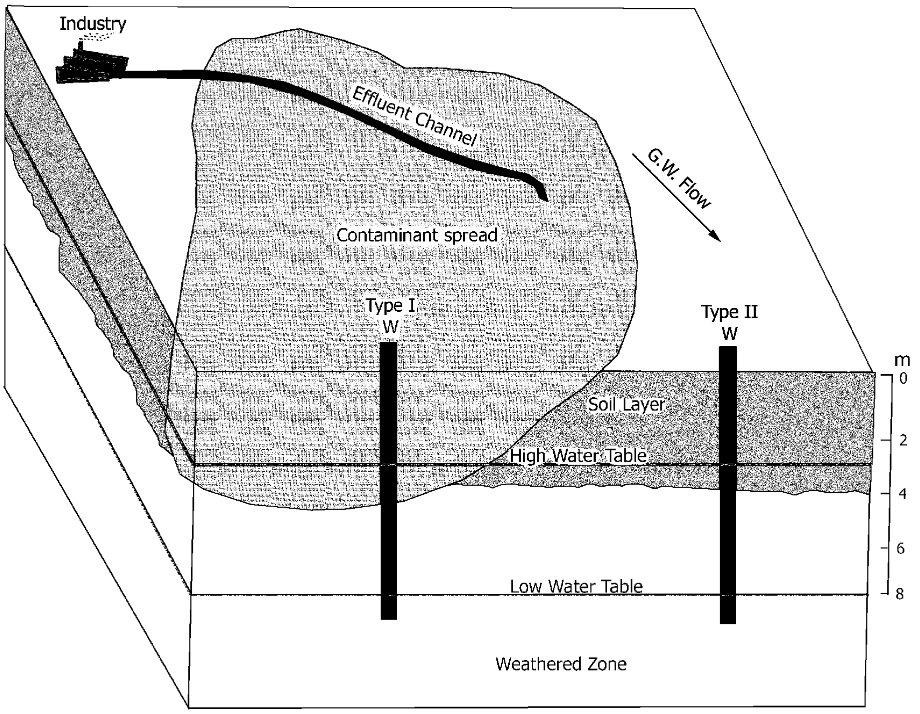

Fig. 5 Sketch of water level fluctuations in the vicinity of the industrial area.

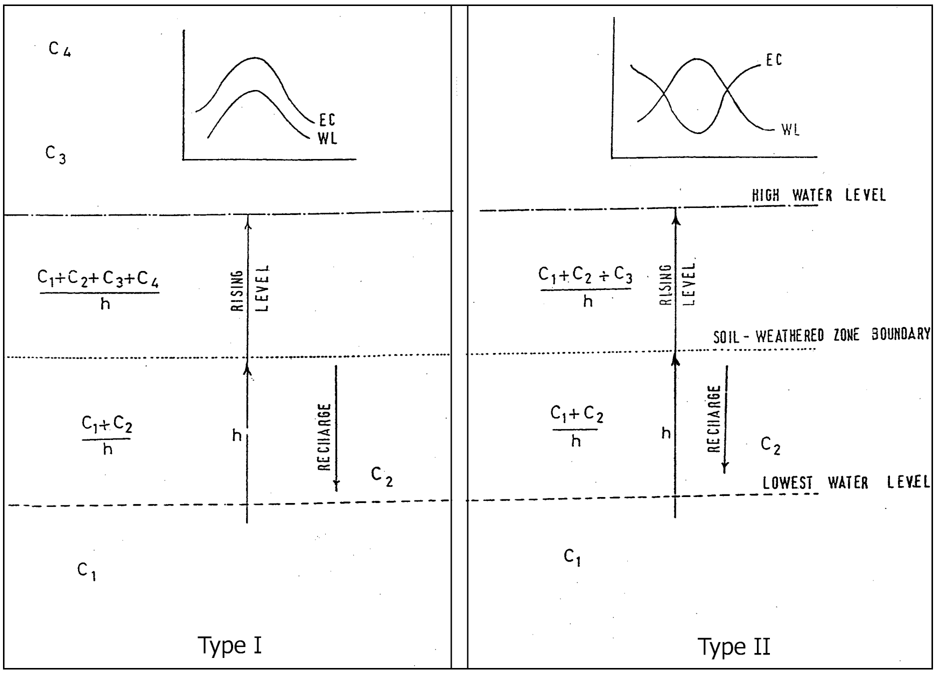

Fig. 6 Model of mixing of waters in an industrial township of Visakhapatnam.

sites are not contaminated unless they are affected by the drawdown zone associated with heavy pumping. A schematic view of the water level fluctuations in this region is presented in Fig. 5.

Studies in the vicinity of a zinc smelter plant and a polymer unit (Handa, 1975; Hoeks, 1977; Subba Rao *et al*., 2003) have developed a water quality model based on the mixing of various waters (Fig. 6). The model takes into account the conductivity of water in the weathered clay zone when the water level is at its lowest (C1), the conductivity of recharging rainwater (C2), the conductivity of water in the soil zone (C3), the conductivity of the effluent (C4) and changing water table level (h). The model accounts for both dilution by low conductivity recharge waters and also for rises in conductivity due to the influence of effluents and water in the soil zone. Furthermore, it can replicate the different behaviour of conductivity and water table fluctuations exhibited by Type I and II wells (Figs 5 and 6). Petty John (1982) reported that the intermittent flushing of contaminants into the ground during recharge periods may cause cyclic fluctuations in groundwater chemistry. Groundwaters are diluted due to rapid recharge although surface contaminants may act to increase the salinity (Scanlon, 1989). Modelling in the present suggests that both the process of dilution and contamination are simultaneously occurring due to the shallow nature of the water table and also its rapid fluctuation.

Lower Vamsadhara River basin

The hydrochemical studies of the groundwater of the Lower Vamsadara River basin have revealed a complex spatial and temporal behaviour. Increasing ionic concentrations are associated with rising groundwater tables, even following recharge from rainfall, while decreasing concentrations are associated with a lowering of the water table. The use of ionic ratios for the identification of hydrogeological formations also appears to be quite effective in this region. In addition, a leachate analysis was conducted in order to quantify the maximum possible ionic contribution to the groundwater from the geological formations through processes of adsorption and ion exchange. This has facilitated identification of point and non-point sources more precisely and resolved the contributions of geological formations. The zones of anomalous ionic concentration occupy almost 15% of the total study area (Fig. 7) and indicate possible point sources of pollution.

Out of many possible ionic ratios, K/Ca, Cl/Ca, Mg/Cl, HCO_3/Cl, Na/HCO_3 and F/Ca are effective for identifying hydrogeological units. As in the other study areas, ionic concentrations become diluted during recharge from rainwater. The typical hydrogeological situation of fluctuations in the water table and in ionic concentrations is shown in Fig. 8. It is observed that the concentration of K, Cl, SO_4, NO_3 and Na are very high in clayey compared with sandy soils. The adsorption of K onto clay minerals is responsible for its relative abundance in clays (Matthess, 1982) and may affect the behaviour of K in the study area (Fig. 8). Similarly, the retention of Cl in clays is responsible for higher concentrations of this ion in the clayey formations of the Lower Vamsadhara River basin. In spite of the negative charge associated with clay surface, Bernstein & Bernstein (1989) and Hem (1986) have attributed the retention of chloride by clayey soils to the large size of the ion.

At Buravalli (Fig. 8), a point source involving animal waste from a cattle barn was identified as a possible cause of the high NO_3 concentrations. NO_3 has a larger ionic size compared to chloride and is more likely to be retained in clayey soils (Rao, 1986).

Furthermore, the negatively charged clay particles attract positively charged ions, such as Mg^{2+}, Ca^{2+}, Na^+, K^+ and NH_4^+, which adhere to the negatively charged surface of clay minerals and cause a residual positive charge that further helps in the retention of anions. In addition, denitrification process will be slower in clayey soils (Klimas & Paukstys, 1993) than in sandy formations resulting in further accumulation of nitrates in the clay. When the water levels are within this layer, the retained ions in clay are released into the water as explained by Freundlich's isothermal equation (Matthess, 1982).

$$C_t = K\,C_w^n$$

where C_t = quantity of adsorbed substance; C_w = concentration of substance in solution; K and n = coefficients.

Similar observations were reported by Woodward (1988). All of the ionic concentrations were observed to be higher in clayey than in sandy formations with the exception of F which suggests the presence of F-bearing minerals in the sands.

The general level of concentrations of Ca, Mg, Na, K, Cl, SO_4, HCO_3, F, PO_4, NO_3 and Fe in groundwater are consistent with the local geological formations which contain biotite, feldspar, flourapatite, fluorite, garnet, hornblende, magnetite, pyroxens, quartz, sillimanite and ion ores. The leachate analysis experiment supported the conclusion that the hydrochemical properties of the groundwater reflect a significant contribution from the geological formations relative to that from fertilizers. In particular, the high concentrations of PO_4 and F in groundwaters are related to the local geology.

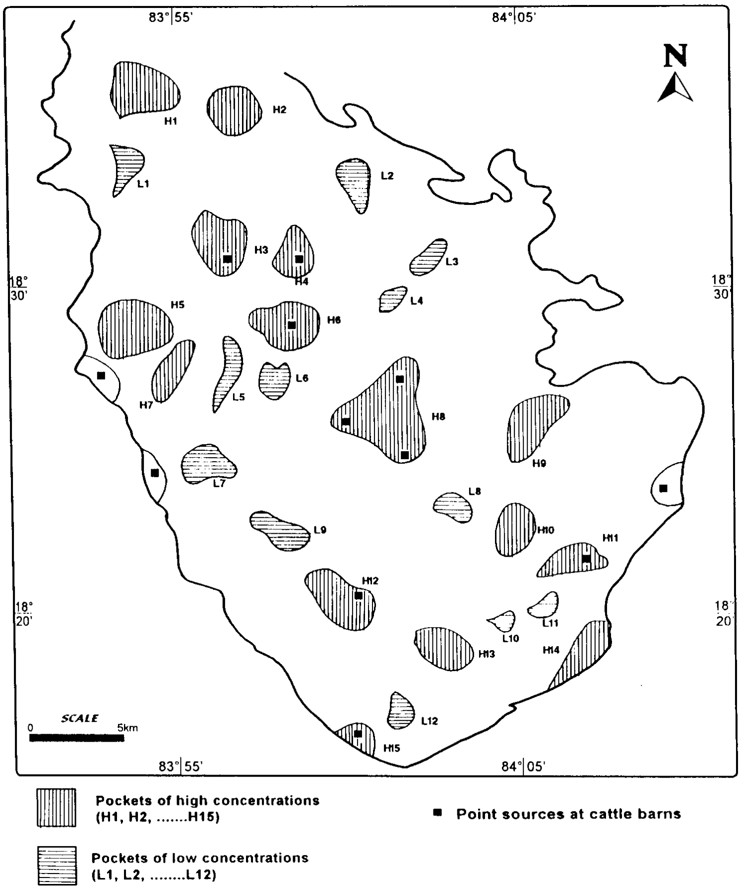

Fig. 7 Zones of anomalous ionic concentrations.

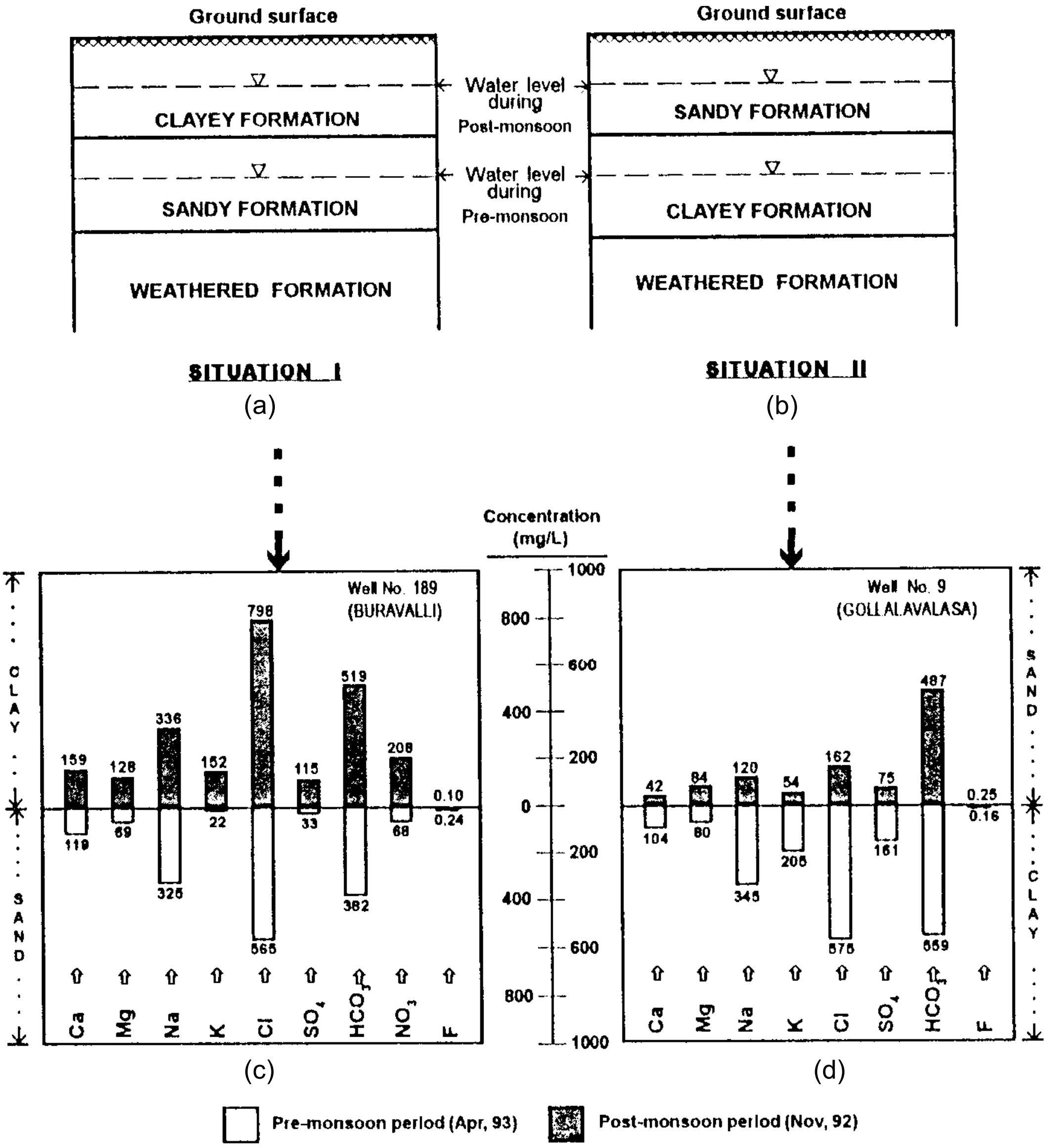

Fig. 8 The hydrogeological settings and associated hydrochemical properties in the Vamsadhara River basin.

CONCLUSIONS

The hydrochemical investigations carried out in time and space domains in different river basins have provided information on characteristic ionic concentrations and ratios which can be used to identify geological formations. The ionic ratios are observed to be better indicators for this purpose. The water level fluctuations and the associated changes in ionic concentrations are observed to be controlled by the local hydrogeological conditions, and especially the clay and sand content of the water-bearing formations. The hydrochemical behaviour of the groundwaters in time and space are observed to be the result of adsorption and ionic exchange phenomena. Information on changes in quality parameters through time and space may be valuable in constraining the development and management of water resources in the study region.

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