JOURNAL OF
ENVIRONMENTAL HYDROLOGY
The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com
VOLUME 9 2001

MULTIVARIATE ANALYSIS FOR IDENTIFYING THE GOVERNING FACTORS OF GROUNDWATER QUALITY

N. Subba Rao
J. Prakasa Rao
D. John Devadas
K. Srinivasa Rao
C. Krishna

Hydrogeology Laboratory
Department of Geology
Andhra University, India

The R-mode factor analysis technique has been successfully applied to understand the processes responsible for the decline of groundwater quality in Guntur urban area, Andhra Pradesh, India. Factor I is dominated by TDS, Na, Cl, SO_4 and K, factor II by pH and CO_3, and factor III by NO_3 variables. They measure salinity, hardness, alkalinity and pollution, and are interpreted as representing the role of climate, water-rock interaction, land use and anthropogenic sources.

INTRODUCTION

Significance of groundwater quality assessment in the land feasibility programs has not hitherto been given due importance in our system of planning. As a consequence, people are subjected to the waterborne diseases (Niranjan Babu et al., 1997). Decline of groundwater quality can be due to several natural and artificial processes. Identification of these processes has to be thoroughly understood before attempting to halt the deterioration of water quality. To elucidate the interrelationship among the observed chemical variables and the processes involved, multivariate techniques have been widely used (Lawrence and Upchurch, 1982; Usunoff and Gyzman, 1989; Razack and Dazy, 1990; Melloul and Collin, 1992; Briz-kishore and Murali, 1992; Ballukraya and Ravi, 1999).

Few reports related to geological and hydrogeological aspects of Guntur district, Andhra Pradesh, India (Figure 1) are available since the 1970s and they are scant and lack a holistic approach. Mallikharjuna Rao (1974) has described the charnockites and other associated rocks. Ramamohana Rao et al. (1984) have stated the geochemistry of the Precambrian mafic dikes of the district. Similarly, Ramamohana Rao and Prasad (1991) have reported the Archaean granites of Guntur district. The Central Ground Water Board (1987) have carried out some investigations, the major emphasis of which was on groundwater as a resource, while groundwater quality was not given due consideration. However, Subba Rao and Vachaspati (1978) and Subba Rao (1998) have reported the quality of groundwater of the district, but they have not considered the influence of land use types, and as such, the impacts of the urbanization of the area on the groundwater quality have still remained major unknowns. The aim of the present paper is, therefore, to use multivariate analysis to determine the chemical processes responsible for the poor quality of groundwater in the Guntur urban area, which covers an area of 123 sq km (Lat. $16^o15'$-$16^o20'$ N and Long. $80^o22'30''$-$80^o30'$E) (Figure 1).

DESCRIPTION OF THE STUDY AREA

Guntur is one of the developing urban areas of Andhra Pradesh (Figure 1). The area experiences a semiarid climate with the temperature ranging from 16.6^o to 40.8^o C, and has an average annual rainfall of 920 mm. The potential-evapotranspiration is 1778 mm (Prakasa Rao, 1997). It has a gentle gradient (2^o to 4^o), sloping towards the southeast from the northwest. Black-cotton-soil and sandy clay loam are the dominant soil types, with a thickness of 0.50 to 8.50 m from the ground surface. The drainage of the area shows a sub-dendritic pattern.

Geological formations belong to the Archaeans and Quaternaries. The former group comprises mainly charnockites, which constitute albite, anorthite, diopside, hypersthene, orthoclase and quartz as major minerals and magnetite, ilmenite, apatite and olivine as accessory minerals (Prakasa Rao, 1997). Pegmatite, granite and quartz veins and basic dikes traverse them. The thickness of the weathered zone ranges from 3 to 20 m, and the fractured zone varies from 10 to 45 m, which follows the massive rock zone. Distribution of the fractures appears to be very limited, because of minor occurrence of lineaments. The latter group is composed of sedimentaries, which have various proportions of clay, silt, sand and gravel with intercalations of kankar. The various combinations of these sediments have a thickness of about 2 to 48 m, which occurs as alternative zones at different depths.

Hydrogeologically, the Archaeans and Quaternaries are considered as crystallines and unconsolidated (Figure 1). Groundwater occurs under water table to confined conditions. Depth to water table varies from 3 to 13 m below ground level (bgl). It appears that the general behavior

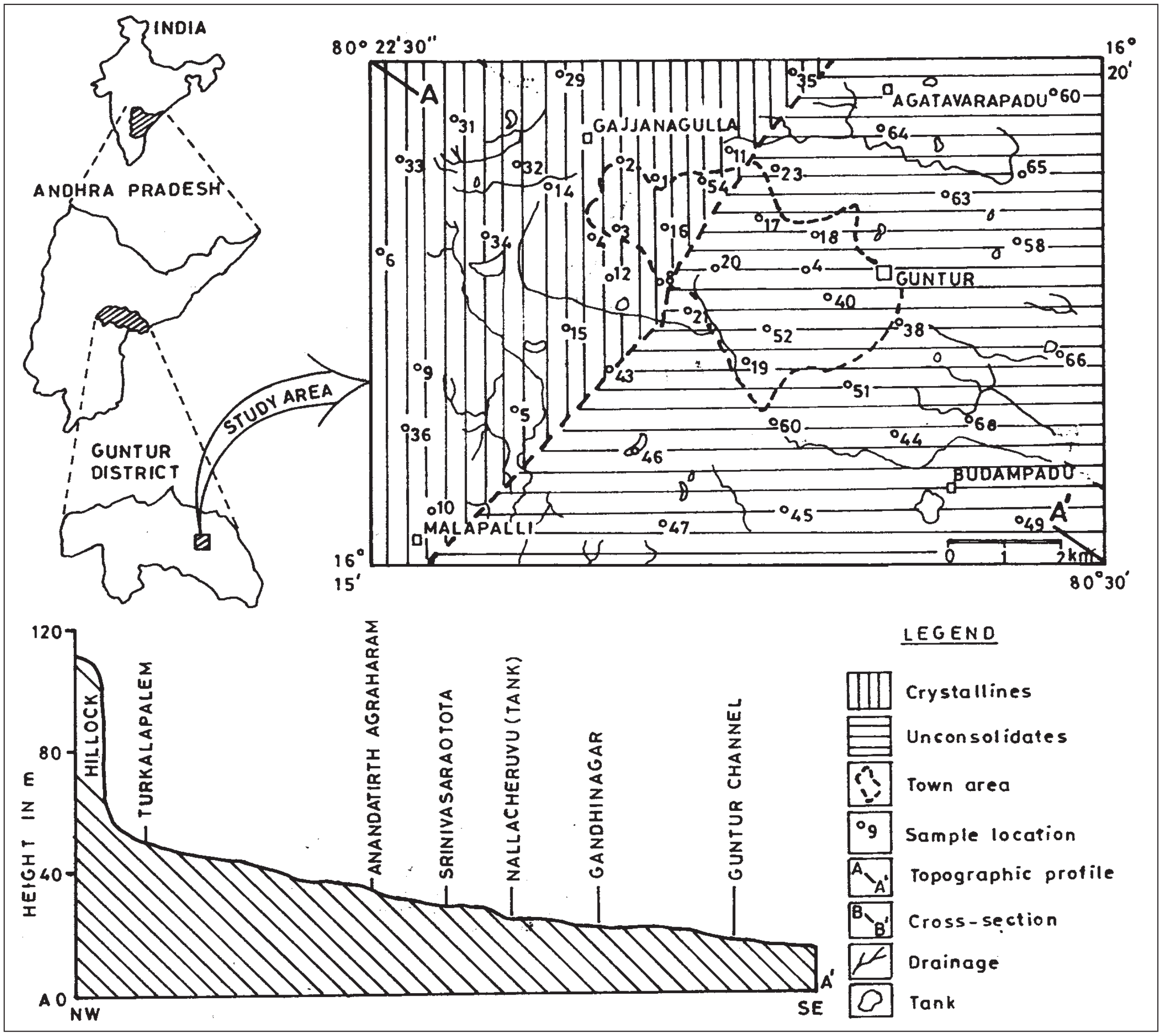

Figure 1.

of the groundwater flow follows the topography of the area. The movement of groundwater is very slow, because of gentle slope with clay horizons and limited fractures at depth.

The existing land use consists of 48 percent of the land utilized for agricultural purposes, 33 percent for residential needs, 10 percent for industrial requirements, and the rest for public utilities (vacant sites, commercial and transport and communication meets). Nearly 85 percent of the fertile agricultural lands around the area are now being converted for urban purposes (residential and industrial).

Urban wastes consisting of domestic wastes, human organic wastes and to some extent, small-scale industrial waters in the area are transmitted through covered and uncovered conduits and are finally let into streams, tanks, topographic-lows and also directly onto the ground, especially during the monsoon season. The urban wastewaters contain (mg/l) the pH, TDS, Ca, Mg, Na, K, HCO_3, Cl, SO_4 and NO_3 in the range of 6.7 to 6.9, 1630 to 1860, 55 to 65, 77 to 88, 360 to 540, 40 to 59, 220 to 300, 500 to 640, 65 to 80 and 50 to 65, respectively (Prakasa Rao, 1997).

METHODOLOGY

Water samples were collected from forty-nine wells during May 1997 and were analyzed for major ion chemistry (pH, TDS, Ca, Mg, Na, K, CO_3, HCO_3, Cl, SO_4, and NO_3), following the standard methods (Brown et al., 1974). All chemical parameters are expressed in mg/l. The ion-balance-error is found within the stipulated limit of 5 percent (Mandel and Shiftan, 1981). The statistical analyses of these chemical parameters are shown in Table 1.

Table 1. Summary of Chemical Composition of Groundwater

Parameters	Range (mg/l)		Mean	Standard Deviation	Standard Error	Confidence Level, 95%
	Min	Max				
pH	7.20	8.60	8.13	0.44	0.06	8.13, 0.14
TDS	278	6568	2697.96	1603.40	229.06	2697.96, 552.03
Ca	4	75	34.47	16.19	2.31	34.47, 5.57
Mg	10	160	80.04	34.14	4.88	80.84, 11.76
Na	37	1948	739.31	499.65	71.38	739.31, 72.03
K	1	18	7.14	4.77	0.68	7.14, 1.64
CO_3	20	30	25.38	6.24	1.22	25.38, 3.04
HCO_3	120	650	434.49	103.12	14.73	434.49, 35.50
Cl	20	2910	1015.90	741.17	106.74	1015.90, 257.24
SO_4	10	512	184.04	124.45	17.78	184.04, 42.85
NO_3	14	39	28.96	8.41	1.20	28.96, 2.89

Among multivariate techniques, R-mode factor analysis has been widely employed for understanding hydrogeochemical association and processes controlling them (Drever, 1988; Razack and Dazy, 1990; Melloul and Collin, 1992; Briz-kishore and Murali, 1992; Ballukraya and Ravi, 1999). As a first step, correlation analysis that reveals the relationship between two variables is calculated for the major ion chemical data from the study area. The TDS shows good positive coefficient of correlation with Na, Cl, SO_4 and K, moderate correlation with Mg, Ca and HCO_3 and low correlation with HCO_3 and CO_3 (Table 2). Since correlation analysis reveals similarities or differences in the behavior of pairs of ions, and does not conveniently identify groups of ions that behave similarly, factor analysis is carried out for the chemical data from the study area to help in hydrogeochemical interpretation of the data. For factor analysis, first principal components are calculated, which have the eigenvalue and the percentage of the variance explained by each factor. Principal component analysis gives communality of unity for each component (Table 3). Only those factors having eigenvalues greater than unity (Kaiser, 1958) are considered for final analysis. Three factors having eigenvalues greater than unity have been extracted from the chemical data from the study area (Table 3).

Though factor analysis reduces the dimensionality of the problem, the meaning of these factors may sometimes be difficult to deduce (Davis, 1986). The interpretation can be simplified using certain rotational procedures. For the present study, Kaiser's varimax rotation has been applied in

Table 2: Correlation Coefficient Matrix

Parameter	pH	TDS	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3
pH	.00										
TDS	0.39	1.00									
Ca	0.06	0.63	1.00								
Mg	0.09	0.68	0.50	1.00							
Na	0.38	0.99	0.64	0.69	1.00						
K	0.46	0.84	0.44	0.51	0.82	1.00					
CO_3	0.78	0.37	0.11	0.04	0.36	0.41	1.00				
HCO_3	-0.09	0.57	0.55	0.50	0.58	0.43	-0.05	1.00			
Cl	0.41	0.98	0.59	0.63	0.95	0.85	0.39	0.45	1.00		
SO_4	0.42	0.92	0.50	0.62	0.92	0.77	0.37	0.64	0.85	1.00	
NO_3	-0.44	0.18	0.22	0.05	0.15	0.17	0.06	0.24	0.17	0.14	1.00

order to obtain a simple structure. A set has been taken to rotate the factors (varimax rotated) in such a way that all their components are closer to +1, 0 and –1, representing the contributions of corresponding variables to the total variance as a positive-contribution, a no-contribution and a negative-contribution, respectively. The factor loadings depict the influence of a factor on a variable and *vice-versa.* Thus, the factor I gives the largest eigenvalue and explains the greatest amount of variance in the data set (Table 3). The factor II represents low eigenvalue and explains the greatest of the remaining variance and so forth. The final step of the factor analysis is to project the data on the rotated significant factors. The scores obtained by this projection are called factor scores, which are used to understand the nature of variables. Dalton and Upchurch (1978) have stated that the factor scores are related to the intensity of the chemical process described by each factor. Negative numbers reflect areas unaffected by the process, positive numbers indicate areas most affected and near-zero numbers affect to an average degree (Lawrence and Upchurch, 1982).

GOVERNING FACTORS OF GROUNDWATER QUALITY

The final rotated factor matrix obtained for the present data is given in Table 3. Final statistics show that the three factors extracted explain 77.20 percent of total variance. The communalities of the variables and proportion of their variance explained by the extracted common factors vary from 0.827 to 0.982, suggesting the factor analysis model be represented adequately the overall variance of the data set.

Figure 2 illustrates the spatial distribution of the scores for the factors I, II and III. The factor I shown in Table 3 has an eigenvalue of 7.412 and explains 52.94 percent of the total variance. It shows high loadings on TDS, Na, Cl, SO_4 and K, moderate loadings on TH, Mg, HCO_3 and pH, and

Table 3: Rotated Factor Matrix

Variables	Factor I	Factor II	Factor III	Communality
pH	0.281	0.849	-0.090	0.868
TDS	0.864	0.207	0.087	0.982
Ca	0.294	0.155	0.248	0.827
Mg	0.436	-0.085	-0.023	0.947
Na	0.850	0.198	0.057	0.970
K	0.840	0.251	0.072	0.825
CO_3	0.261	0.884	0.058	0.858
HCO_3	0.454	-0.229	0.208	0.884
Cl	0.870	0.234	0.079	0.951
SO_4	0.833	0.187	0.045	0.913
NO_3	0.111	0.018	0.978	0.969
Eigen Values	7.412	2.295	1.101	
% of variance	52.94	16.39	7.87	
Cumulative % of variance	52.94	69.33	77.20	

low loadings on Ca and CO_3. It suggests the quality of groundwater be mainly controlled by the high loading parameters. The combination of TDS with Na and Cl measures high salinity, TH (Ca and Mg) with SO_4 represents permanent hardness, pH with HCO_3 characterizes alkaline nature, and SO_4 and K indicates pollution. Gentle slope and sluggish-drainage conditions supporting longer-residence time of groundwater, more water-rock interaction and higher solubility of minerals mark mostly saline water and enrichment of Na and Cl (UNESCO, 1984; Subba Rao et al., 1997). Enrichment of TDS, Na and Cl is also possible, because of the effect of urban wastewaters (Subba Rao and Krishna Rao, 1990; Somasundaram et al., 1993) and high rate of evapotranspiration (Drever, 1988; Karanth, 1991). The high K suggests pollution from application of potash fertilizers to agricultural lands (Cain et al., 1989). The high SO_4 is related to the long-history of evaporation process (Datta and Tyagi, 1996) and also the effect of industrial pollution (Subba Rao and Krishna Rao, 1990; Ballukraya and Ravi, 1999). The Ca, Mg, Na and K reflect the weathering of country rocks (Mohan et al., 2000).

The factor II contains an eigenvalue of 2.295 and accounts for 16.39 percent of the variance of the data set (Table 3). It has high loadings on pH and CO_3 and low loadings on K, Cl and TDS. The rest of the variables show very low or negative loadings. The high loadings on pH and CO_3 indicate alkaline nature and represent the role of dissolved CO_2 in the groundwater system. Waters of semiarid regions (because of the high evaporation rates) and waters of clay horizons (because of their poor-drainage conditions) exhibit high amounts of salts and may cause significant rise in pH (Hem, 1991). Hem (1991) has stated that the water lost alkaline earth elements (Ca and Mg) through the exchange process may later participate in chemical reactions, which raise the pH. In soils, leaching of $CaCO_3$ from the kankar formations increases the pH values. In fact, HCO_3 can

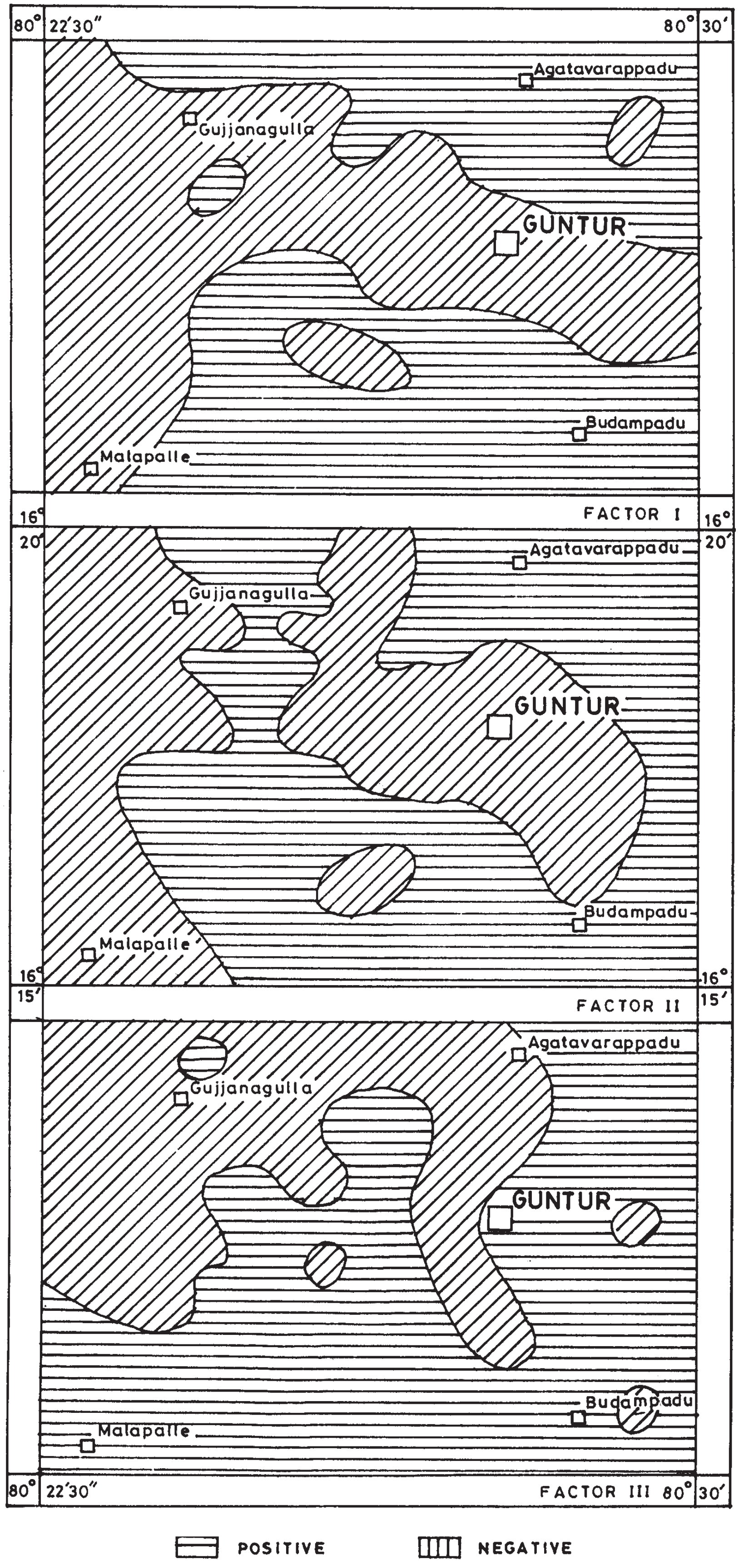

Figure 2. Distribution of factor scores

be attributed to the presence of CO_2 in the soil zone. Oxidation of organic matter generates CO_2, which then combines with water to form H_2CO_3, which further dissociates to H and HCO_3 ions. Therefore, all these conditions increase the concentration of pH value, leading to conversions of HCO_3 to CO_3. The loadings on K, Cl and TDS are interpreted as representing the role of weathering of country rocks, climate and anthropogenic sources, as mentioned above.

From the Table 3, it is seen that the factor III shows an eigenvalue of 1.101 and explains 7.87 percent of the total variance. The rest of the variables do not have significant loadings. This factor consists of high loading on NO_3 and low loadings on Ca and HCO_3. The NO_3 has no known lithologic source and hence it reveals pollution, which is attributed to the urban wastewaters and agricultural practices involving chemical (nitrogenous) fertilizer applications (Penky *et al*., 1989; Subba Rao and Krishna Rao, 1990; Somasundaram *et al*., 1993; Uma, 1993; Ballukraya and Ravi, 1999). The Ca and HCO_3 are expected owing to the reasons explained in factor I and factor II.

CONCLUSIONS AND SUGGESTIONS

From the foregoing analysis, it is concluded that three factors such as factor I (high loadings on TDS, Na, Cl, SO_4 and K, moderate loadings on TH, Mg, HCO_3 and pH, and low loadings on Ca and CO_3), factor II (high loadings on pH and CO_3 and low loadings on K, Cl and TDS) and factor III (high loading on NO_3 and low loadings on Ca and HCO_3) are retained to understand the processes including climate, water-rock interaction, land use and anthropogenic sources responsible for the inferior chemical quality of groundwater. Thus, the present study stresses the need for implementation of ameliorative measures to minimize the impacts of poor groundwater quality and overcome adverse groundwater quality conditions in the Guntur urban area.

REFERENCES

Ballukraya, P.N. and R. Ravi; Characterization of groundwater in the unconfined aquifers of Chennai City, India. J. Geol. Soc. India, Vol. 54, pp. 13-22; 1999.

Briz-kishore, B.H. and G. Murali; Factor analysis for revealing hydrogeochemical characteristics of a watershed. Environ. Geol., Vol. 19, pp. 3-9; 1992.

Brown, W, Skougstad, N.W. and M.J. Fishman; Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases. U.S. Dept. of Interior Book 5, 160 p; 1974.

Cain, D., Helsel, D.R. and S.E. Ragone; Preliminary evaluation of regional groundwater quality in relation to landuse. Ground Water, Vol. 27, pp. 230-244; 1989.

Central Ground Water Board; Groundwater Resources and Developmental Potential of Guntur District, Andhra Pradesh State, 36 p; 1987.

Dalton, M.G. and S.B. Upchurch; Interpretations of hydrogeochemical facies by factor analysis. Ground Water, Vol. 10, pp. 228-233; 1978.

Datta, P.S. and S.K. Tyagi; Major ion chemistry of groundwater in Delhi area: Chemical weathering process and groundwater flow regime. J. Geol. Soc. India, Vol. 47, pp. 179-188; 1996.

Davis, J.C.; Statistics and Data Analysis in Geology. John Wiley and Sons, 646 p; 1986.

Drever, J.I.; The Geochemistry of Natural Waters. Prentice-Hill, Inc., New York, 462 p; 1988.

Hem, J.D; Study and Interpretation of the Chemical Characteristics of Natural Waters. 2254, 3rd ed. Scientific Publ., Jodhpur, India, 263 p; 1991.

Kaiser, H.F.; The varimax criteria for analytical rotation in factor analysis. Psycometria, v. 23, pp. 187-200; 1958.

Karanth, K.R.; Impact of human activities on hydrogeological environment. J. Geol. Soc. India, Vol. 38, pp. 195-206; 1991.

Lawrence, F.W. and S.B. Upchurch; Identification of recharge areas using geochemical factor analysis. Ground

Water, Vol. 20, pp. 680-687; 1982.

Mallikharjuna Rao, J.; Studies on the charnockites and associated rock types around Lam, Guntur district, A.P. Unpubl. Ph.D. thesis submitted to Osmania University, Hyderabad, India, 1974.

Mandel, S. and Z.L. Shiftan; Groundwater Resources Investigation and Development. Academic Press Inc., New York, 269 p; 1981.

Melloul, A. and M. Collin; The principal component statistical method as a complementary approach to geochemical methods in water quality factor identification: application to coastal plain aquifer of Israel. J. Hydrol., Vol. 140, pp. 49-73; 1992.

Mohan, R., Singh, A.K., Tripathi, J.K. and G.C. Chowdhary; Hydrochemistry and quality assessment of groundwater in Naini Industrial Area, Allahabad district, Uttar Pradesh. J. Geol. Soc. India, Vol. 55, pp. 77-89; 2000.

Niranjan Babu, P., Subba Rao, N., Chandra Rao, P. and J. Prakasa Rao; Groundwater quality and its importance in the land developmental programmes. Indian J. Geol., Vol. 69, pp. 305-312, 1997.

Pekny, V., Skorepa, J. and J. Vrba; Impact of nitrogen fertilizers on groundwater quality-some example of Czechoslovakia. Jour. Contam. Hydrol, Vol. 4, pp. 51-67; 1989.

Prakasa Rao, J.; Environmental Evaluation of Groundwater Quality of a Developing Urban Area of Andhra Pradesh, India. Unpubl. Ph.D. thesis submitted to Andhra University, Visakhapatnam, India, 1997.

Ramamohana Rao, T. and G.J.S. Prasad; Fe-epidote from Archaean granites of Guntur district, Andhra Pradesh. Jour. Ind. Acad. Geosci., Vol. 34, pp. 21-29; 1991.

Ramamohana Rao, T., Satyanarayana Raju, B.V. and G.S. Madhusudhana Rao; Geochemistry of the Precambrian mafic dykes of Guntur district, A.P., Jour. Ind. Acad. Geosci., Vol. 29, pp. 2-30; 1984.

Razack, M. and J. Dazy; Hydrogeochemical characterization of groundwater mixing in sedimentary and metamorphic reservoirs with combined use of Piper's principle and factor analysis. J. Hydrol., Vol. 114, pp. 371-393; 1990

Somasundaram, M.V., Ravindran, G. and J.H. Tellam; Groundwater pollution of the Madras urban aquifer, India. Ground Water, Vol. 31, pp. 4-11; 1993.

Subba Rao, C. and A.V.P.S. Vachaspati; Chemical quality of groundwater in Guntur district, Andhra Pradesh. Geophy. Resear. Bull., Vol. 17, pp. 73-83; 1978.

Subba Rao, N.; Groundwater quality in crystalline terrain of Guntur district, Andhra Pradesh. Visakha Sci. Jour., Vol. 2, pp. 51-54; 1998.

Subba Rao, N. and G. Krishna Rao; Intensity of pollution of groundwater in Visakhapatnam area, Andhra Pradesh. J. Geol. Soc. India, Vol. 36, pp. 670-673; 1990.

Subba Rao, N., Prakasa Rao, J., Chandra Rao, P., Niranjan Babu, P. and G. Krishna Rao; Hydrogeochemical zoning in crystalline terrain and its significance to water quality. J. Geol. Soc. India, Vol. 49, pp. 715-719; 1997.

Uma, K.O.; Nitrates in shallow (regolith) aquifers around Sokoto town, Nigeria. Environ. Geol., Vol. 21, 70-76; 1993.

UNESCO; Groundwater in Hardrock, Studies and Reports in Hydrology, 32, Paris, 228 p; 1984.

Usunoff, E.J. and A.G. Guzman; Multivariate analysis in hydrochemistry: an example of use of factor and correspondence analysis. Ground Water, Vol. 27, pp. 27-34; 1989.

ADDRESS FOR CORRESPONDENCE

N. Subba Rao
Hydrogeology Laboratory
Department of Geology
Andhra University
Visakhapatnam 530 003
India

Email:subbarao@usa.net