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Hydrogeochemistry and Groundwater Quality Assessment of Lower Part of the Ponnaiyar River Basin, Cuddalore District, South India

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Abstract The Lower Ponnaiyar River Basin forms an important groundwater province in South India constituted by Tertiary formations dominated by sandstones and overlain by alluvium. The region enjoyed artesian conditions 50 years back but at present frequent failure of monsoon and over exploitation is threatening the aquifer. Further, extensive agricultural and industrial activities and urbanization has resulted in the increase in demand and contamination of the aquifer. To identify the sources and quality of groundwater, water samples from 47 bore wells were collected in an area of 154 km^2 and were analysed for major ions and trace metals. The results reveal that the groundwater in many places is contaminated by higher concentrations of NO_3, Cl, PO_4 and Fe. Four major hydrochemical facies Ca–Mg–Cl, Na–Cl, Ca–HCO_3 and Na–HCO_3 were identified using Piper trilinear diagram. Salinity, sodium adsorption ratio, and sodium percentage indicate that most of the groundwater samples are not suitable for irrigation as well as for domestic purposes and far from drinking water standards. The most serious pollution threat to groundwater is from nitrate ions, which are associated with sewage and fertilizers application. The present state of the quality of the lower part of Ponnaiyar River Basin is of great concern and the higher concentration of toxic metals (Fe and Ni) may entail various health hazards.

Keywords Chemical processes · Factor analysis · Groundwater quality assessment · Hydrochemical facies · Hydrogeochemistry

1 Introduction

The quality of groundwater at any point below the surface reflects the combined effects of many processes along the groundwater flow path. Chemical reactions such as weathering, dissolution, precipitation, ion exchange and various biological processes commonly take place below the surface. Hydrogeochemical study is a useful tool to identify these processes that are responsible for groundwater chemistry. Several authors have reported about the presence of contaminants in soils (Muir & Baker, 1978; Wu, 1980) and waters (Kolpin, Barbash, & Gillion, 1998) in various part of the globe and also in India (Elango, Kannan, & Senthil Kumar, 2003; Srinivasa

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Rao, Reddy, & Nayudu, 1997; Subba Rao, Gurunadha Rao, & Gupta, 1998). Contamination of the groundwater by domestic, industrial effluents and agricultural activity is a serious problem faced by developing countries.

The Tertiary sandstone aquifer of Lower Ponnaiyar River Basin in Cuddalore district is well known for its groundwater potential. This sandstone is separated from the upper alluvial formation by impervious clay layer and hence, the groundwater occurs under confined condition in the sandstones and in phreatic condition in the shallow alluvial aquifer. Artesian wells were present in the area during the early 1950s but the dewatering for mining lignite in Neyveli, over exploitation for agriculture activities and frequent failure of monsoon has resulted in reduction of confining pressure. This potential aquifer is also facing threat from anthropogenic activities and its quality is deteriorating at an alarming rate.

Under these circumstances a comprehensive hydrogeochemical study is necessary to identify the chemical processes that affect the groundwater quality of this area. Hence, hydrogeochemical investigations were carried out in the lower part of Ponnaiyar River basin, Tamilnadu, India, to evaluate the chemistry of groundwater, hydrogeochemical facies and assess the quality of groundwater.

2 Study Area

The study area forms the lower Ponnaiyar River basin, about 154 km^2 in area and lies between 11°42′33″N and 11°51′45″N latitudes and 79°33′21″E and 79°47′34″E longitudes (Figure 1). The northern and southern boundaries of the basin are defined by the Ponnaiyar and Gadilam Rivers (a distributary of Ponniyar River) which confluence into Bay of Bengal. A tropical climate prevails in the study and the average annual rainfall is 1,160 mm. Major part of the study area is devoted to agricultural activities, which include paddy, sugarcane, groundnut and gingili cultivation.

2.1 Geological and hydrogeological setting

The study area consists of sedimentary formations, which include sandstone, clay, alluvium, and small patches of laterite soils of Tertiary and Quaternary age. The upper reaches of the Ponnaiyar River basin to the west of the study area consist of charnockites and gneisses of Archean age. In the lower part of the basin, Ponnaiyar River has built up extensive alluvium consisting of mixtures of sand, silt and clay in the delta portions in and around Cuddalore and the thickness varies from 10 to 15 m. At some locations sandstones with intervening clay lenses underlie the

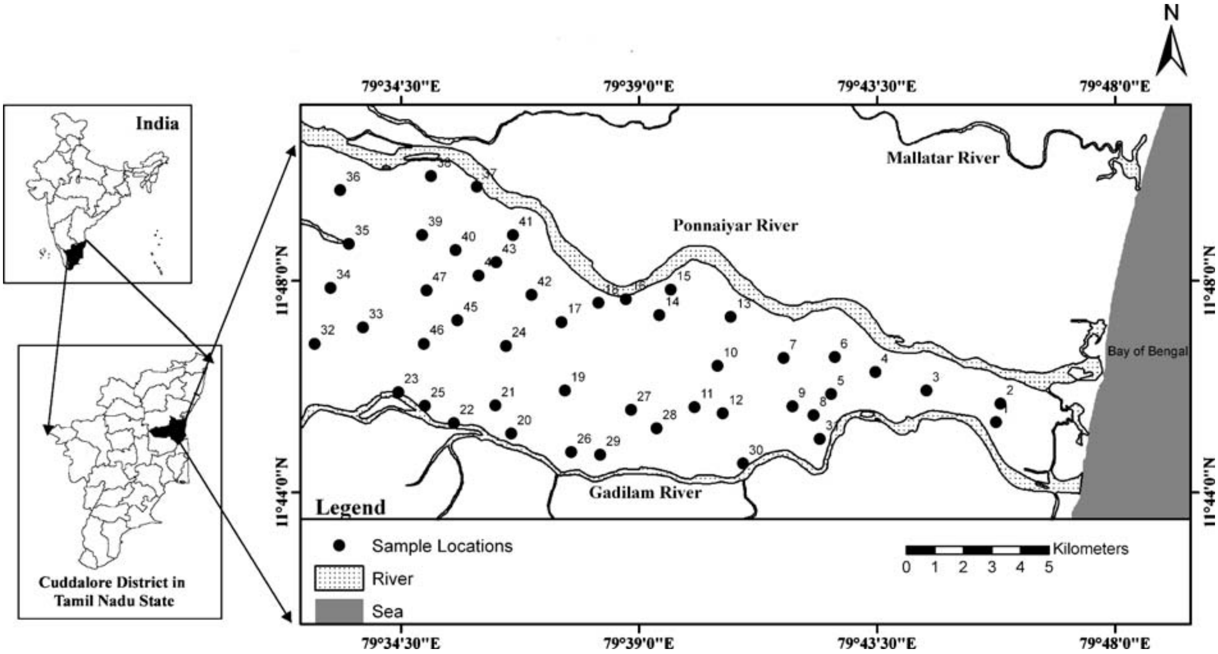


Figure 1 Study area and well location map.

Table I Aquifer parameters

S. no.	Formation	Specific yield	Transmissivity	Hydraulic conductivity
1	Alluvium	7.2	98	19.7
2	Tertiary formation (Cuddalore sandstone)	1.4–3.5	46–134	16–33

alluvial sand up to a depth of 50 m below ground level. The Quaternary formations consist of sediments of fluvial, fluvio-marine and marine facies, which include various types of soils, fine to coarse grained sands, silts, clays, laterite and lateritic gravels. In the coastal tract, except at the confluence point of river, wind-blown sands of 1.5 to 3 km width occur commonly in the form of low and flat-topped sand dunes, excepting at the confluence of the river with sea. However, irregular mounds of 10 to 15 m altitude are a prominent feature due to wind action in the study area. The groundwater occurs in both unconfined and confined conditions in alluvial and sandstone formations, respectively. The depth of bore wells ranges 50 to 180 m below ground level, and deeper bore wells extending up to 300 to 400 m are also seen at some locations. The water level occurs at 1 to 7 m and 10 to 35 m below the ground level in the unconfined and confined aquifers, respectively (Table I).

3 Methodology

Groundwater samples were collected after well inventory survey from 47 representative wells during July 2004 (Figure 1). The samples were collected after 10 min of pumping and stored in Poly Ethylene bottles at 10°C. Immediately after sampling, pH and electrical conductivity were measured in the field. Total dissolved solids (TDS) were calculated from EC multiplied by 0.64 (Brown, Skougstand, & Fishman, 1970). Nitrate (NO_3), *ortho*-phosphate (PO_4), and sulphate (SO_4) analyses of the water samples were carried out using spectrophotometer, and carbonate (CO_3), bicarbonate (HCO_3), calcium (Ca), and magnesium (Mg) were determined by volumetric methods. Sodium (Na) and potassium (K) were determined using flame photometer. Nitrate was analysed using cadmium column by reduction method. Trace metal concentration were determined using Varian SpectrAA200 model flame Atomic Absorption Spectrophotometer. High purity analytical reagents were used throughout the study, and chemical standards (Merck, Germany) for each elements were prepared separately.

4 Results and Discussion

4.1 Major ion chemistry

The pH of the groundwater in the study area ranges from 6.7 to 7.9 (Figure 2) with an average value of 7.28. Only few samples have pH value less than 7. All other samples have values more than 7, indicating alkaline nature of the samples. The EC (Figure 3) and TDS values range from 625 to 2,969 mS/cm and 400 to 1,900 mg/l with an average value of 1,256.66 mS/cm and mg/l 804.26, respectively. Based on this value, the water samples of the study area are classified as fresh to brackish in nature (Freeze &

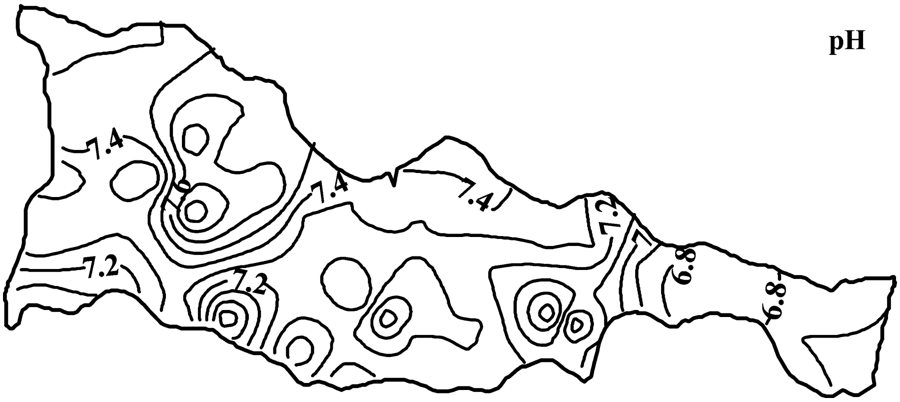


Figure 2 Spatial distribution of pH of the groundwater from the study area.

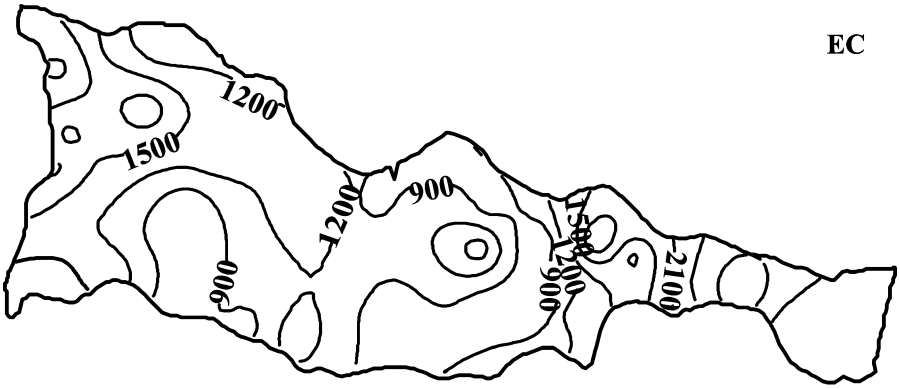


Figure 3 Spatial distribution of electrical conductivity in the study area.

Cherry, 1979; Table II). The large variation in TDS is mainly attributed to anthropogenic activities and to geochemical processes prevailing in this region.

Cation chemistry indicates that 36% of the samples are Ca≥Na>Mg>K, while the remaining 64% belong mostly to the Na>Ca>Mg>K; these cations generally show an increasing trend towards downstream. The sodium concentration in the study area ranges from 56 to 301 mg/l with an average concentration of 111 mg/l (Table II) and shows good correlation with Cl (*r*= 0.75), indicating that these ions have been derived from same source. If halite dissolution is responsible for sodium, Na/Cl ratio should be approximately equal to 1, whereas ratio greater than 1 is typically interpreted as Na released from silicate weathering reaction (Meyback, 1987). In the present study, Na/Cl

Table II Drinking water specification given by ISI (1983) and WHO (1993) and minimum, maximum and average ion concentration

S. no.	Water quality parameters	WHO (1993)		Indian Standard Institution (1983)		Results of chemical analysis of groundwater samples			
		Maximum accept limit (mg/l)	Maximum allowable limit (mg/l)	Highest desired limit (mg/l)	Maximum permissible limit (mg/l)	Parameters	Min	Max	Average
1	EC	–	–	–	–	EC (mS/cm)	625	2,969	1,256.66
2	TDS	500	1,500	500	–	TDS (mg/l)	400	1,900	804.26
3	pH	6.5	8.5	6.5–8.5	6.5–9.5	pH	6.7	7.9	7.28
4	Calcium	75	200	75	200	Ca (mg/l)	42	212	89.62
5	Magnesium	50	150	30	100	Mg (mg/l)	18	89	39.58
6	Potassium		12	–	–	K (mg/l)	1	124	6.98
7	Sodium	–	200	–	–	Na (mg/l)	56	301	111.57
8	Bicarbonate	–	–	–	–	HCO_3 (mg/l)	98	512	244.02
9	Chloride	200	600	250	1,000	Cl (mg/l)	89	900	220.98
10	Sulphate	200	400	–	–	SO_4 (mg/l)	1	45	9.68
11	Nitrate	45	–	–	–	NO_3 (mg/l)	1	612	143.66
12	Lead	–	0.1	0.1	No relaxation	PO_4 (mg/l)	0	94	11.26
13	Zinc	–	15	5	15	Na%	24	67	39.49
14	Iron	0.3	1.00	0.3	1	SAR	1.9	8.8	3.51
15	Manganese	–	0.3	0.1	0.3	Fe (mg/l)	0	6.65	1.02
						Mn (mg/l)	0.002	1.526	0.07
						Zn (mg/l)	0.006	7.9	0.71
						Pb (mg/l)	0.01	0.19	0.07
						Ni (mg/l)	0.016	0.144	0.08

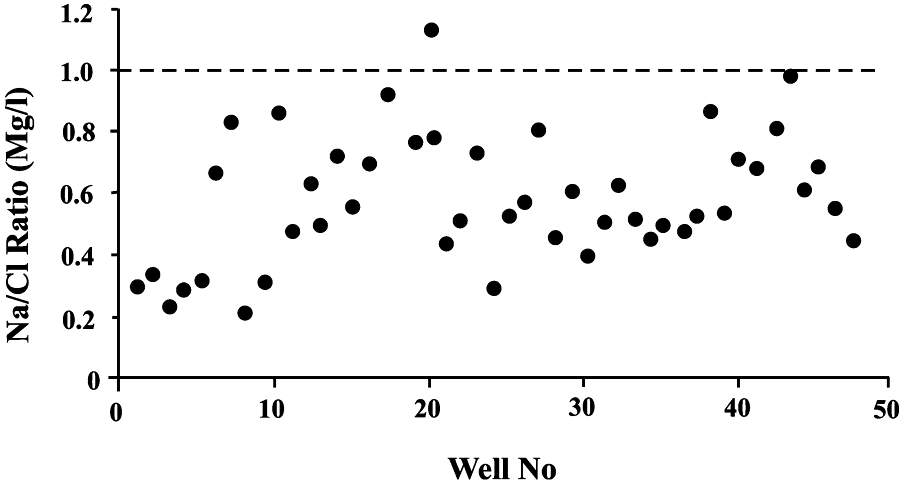


Figure 4 Na/Cl ratio suggests seawater intrusion and irrigation return flow.

ratio of groundwater samples generally varying from 0.35 to 1.13 (Figure 4). Samples having Na/Cl ratio greater than 1 in the study area are rare and hence sodium might have come from irrigation return flow and anthropogenic activity. If silicate weathering were the probable source of sodium, the water samples would have HCO_3 as the most abundant anion than sodium, and it is well supported by high values of HCO_3 than Na. The Na/Cl ratio of the groundwater from the coastal area (0.359 to 0.515) indicating salinization is mainly the result of mixing with sea water, whereas in the inland area, the sodium is derived from irrigation return flow and concentrated due to evaporation.

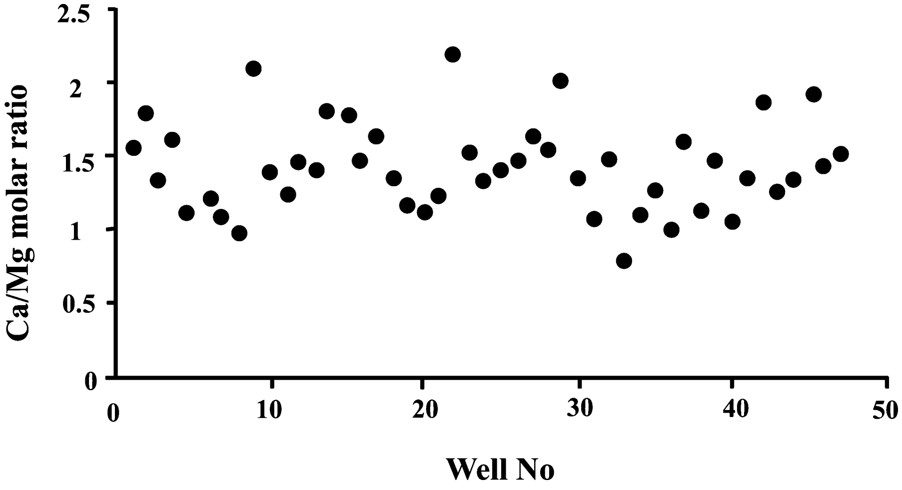
Calcium and magnesium concentrations in groundwater vary from 42 to 212 and 18 to 69 mg/l with average concentrations of 90 and 40 mg/l, respectively (Table II). They have the highest correlation coefficient (0.84) among the major ions indicating the presence of a ubiquitous source of Ca and Mg, probably from the dissolution of low magnesium carbonate or dolomite precipitates. Further, Ca/Mg ratios of the most of the groundwater samples range from 1.5 to 2.2 indicating that dolomite contributes solutes to the groundwater (Figure 5) (Eq. 1).

$$(\mathrm{Ca,Mg})\mathrm{CO}_3 + \mathrm{CO}_2 + \mathrm{H}_2\mathrm{O} = 2\mathrm{HCO}_3^- + 0.5\mathrm{Ca}^{2+} + 0.5\mathrm{Mg}^{2+} \qquad (1)$$

Potassium concentration in groundwater varies from 1 to 124 mg/l with an average of 7 mg/l (Table II). Potassium ions present in the groundwater might have come from irrigation return flow.

Anion chemistry shows that the samples analysed belong to: $Cl>HCO_3>SO_4>NO_3$, $HCO_3>Cl>NO_3>$

Figure 5 Ca/Mg ratio suggests carbonate dissolution.



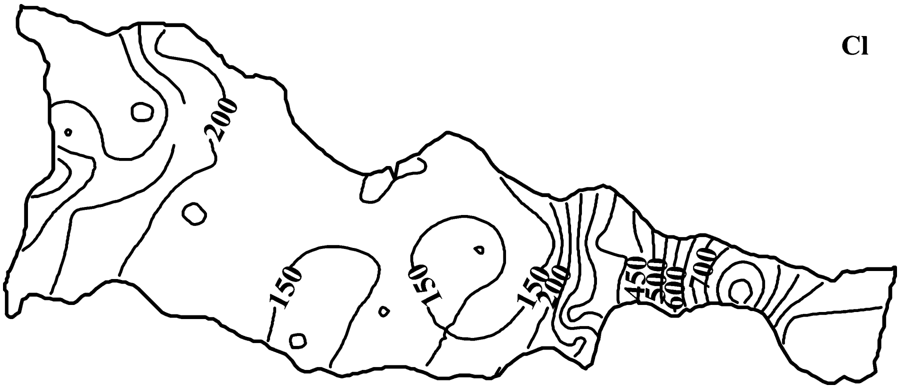


Figure 6 Spatial distribution of chloride ion concentration.

SO_4 and $NO_3 > HCO_3 > Cl > SO_4$. Chloride and bicarbonate are the dominant ions in the study area ranging from 89 to 900 mg/l and 98 to 512 mg/l with average concentrations of 221 and 244 mg/l, respectively (Table II; Figures 6 and 7). The concentration of chloride indicates that saltwater intrusion and irrigation return flow might be responsible (Lusczynski & Swarzenski, 1996); this is also supported by the Cl/HCO_3 ratio. Generally a ratio of more than 2.8 indicates severe contamination with seawater (Ragunath, 1982). Groundwater samples collected from five bore wells at an average depth of 40 m and located 6 km from the coast reveal Cl/HCO_3 ratios of 2.5 to 11.87 indicating severe contamination by saline water intrusion (Figure 8). However, well no. 1 has very low Cl/HCO_3 even though it is located near the sea because it is a shallow well. Along with the large-scale urban development, the large quantity of groundwater drawn by industries in the study area has resulted in the reversal of hydraulic gradient along the coast, and consequently seawater has intruded affecting deep aquifers along the coastal areas.

The source of bicarbonate is attributed to natural processes such as dissolution of carbonate minerals in presence of soil CO_2 (Eq. 2).

$$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^- \text{ and} \quad CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \tag{2}$$

Sulphate concentration of groundwater vary from 1 to 45 mg/l with an average concentration of 10 mg/l (Table II), possibly derived from gypsum dissolution. The pockets of higher nitrate concentration (Figure 9) in the groundwater of the study area are related to the use of fertilizers in agricultural land and sewage effluents. The significant correlation coefficients of Ca vs. NO_3 and Mg vs. NO_3 in groundwater indicate that an increase in hardness is associated with increasing NO_3 concentration. The nitrate concentration of groundwater ranges from 1 to 612 mg/l with an average of 144 mg/l (Table II). Similarly, pockets of higher concentration of phosphate are distributed in the range of from 0 to 94 mg/l (Table II; Figure 10). The higher concentration of PO_4 also indicates the

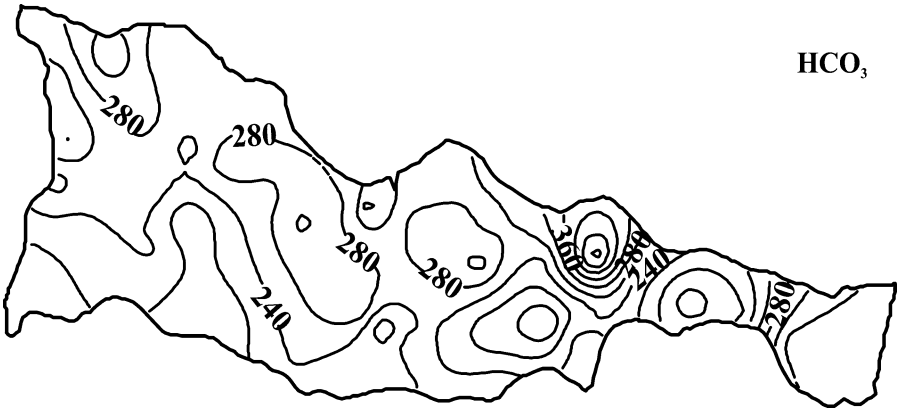


Figure 7 Spatial distribution of bicarbonate ion concentration.

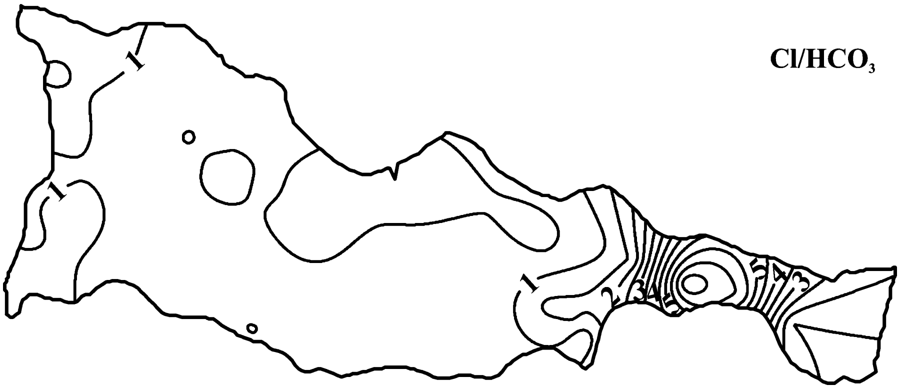


Figure 8 Cl/HCO$_3$ ratio suggests seawater intrusion near the coastal area.

contribution of fertilizers used for agriculture. Piper trilinear diagram (Piper, 1953; Figure 11) shows that Ca–Mg–Cl and Na–Cl are the dominant hydrochemical facies. It also suggests that carbonate, silicate weathering and seawater intrusion are the primary factors increasing the major ion chemistry of the study area. The Na–HCO$_3$ and Ca–Mg–HCO$_3$ combination present to a certain extent in the study area is due to irrigation return flow and anthropogenic activities.

4.2 Trace metals in groundwater

Selected trace metals Fe, Mn, Zn, Pb and Ni were studied in groundwater samples of the study area. The concentration of iron in most of the groundwater samples is higher than the standard of 0.3 mg/l (Table II; Figure 12). The high values are attributed to the corrosion effect of borehole materials in water, the redox environment in groundwater, and laterite soil. The manganese concentration in 23% of groundwater samples is higher than the prescribed values of 0.3 mg/l (WHO, 1993) and the excess Mn is due to the organic circulation by plants and leaves (Offiong & Edet, 1998).

Lead concentration in natural water is mainly attributed to anthropogenic activities as it is extensively used in some pesticides such as lead arsenate. In the study area, except for the sample nos.10, 36, 46, 47, the concentration of lead is well below the WHO (1993) standard. The concentration of nickel in drinking water is normally less than 0.02 mg/l, but high concentration of nickel compounds is considered to be carcinogenic when related to pulmonary exposure (WHO, 1993). The concentration of nickel in the groundwater of the study area ranges from below detection level to as high as 0.144 mg/l (Table II), which may create problems to the human health.

4.3 Correlation matrix and factor analysis

The chemical composition of groundwater characterised by the major inorganic compounds Ca, Mg, Na, K, HCO$_3$, Cl, SO$_4$ PO$_4$ and NO$_3$ is the result of natural chemical weathering and due to atmospheric and anthropogenic inputs (Chan, 2001). The concentration of each compound is separated in two partial contributions, one related to weathering reactions, and

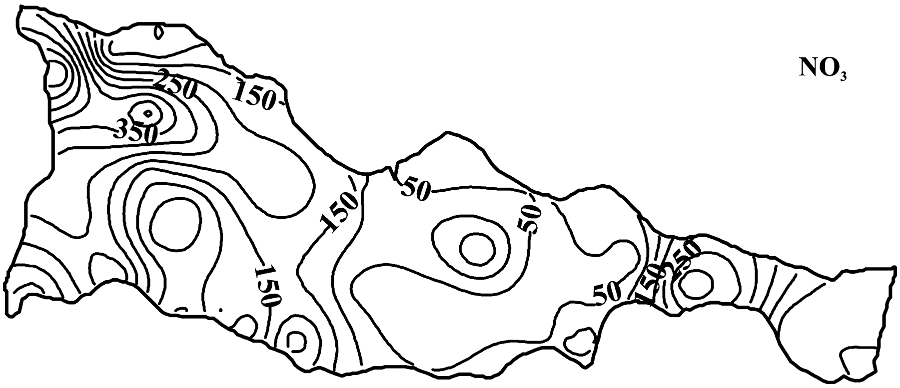


Figure 9 Spatial distribution of nitrate ion concentration.

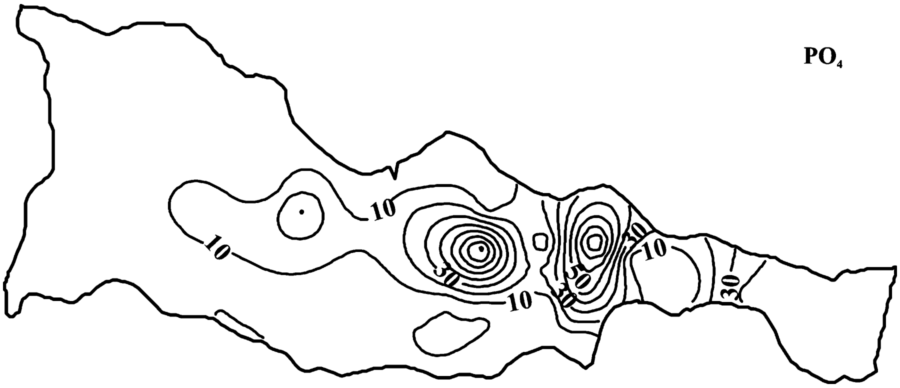


Figure 10 Spatial distribution of phosphate ion concentration.

the other related to pollution. Factor analysis was applied to distinguish the partial contributions.

The variables for factor analysis were EC, Ca, Mg, Na, K, HCO_3, Cl, SO_4, NO_3, PO_4, Zn, Pb, and Ni. The correlation matrix for 13 variables is shown in Table III. Three factors were extracted to statistically represent the contributions influencing chemical composition of groundwater. R-mode factor analysis was carried out with the help of SPSS software to extract the factors. Based on three most significant factors the results of factor analysis indicate that these factors explain about 74.5% of the variance in the dataset given below.

Factor 1: Ca, Mg, Na, Cl, and SO_4
Factor 2: Na, K and HCO_3
Factor 3: NO_3, Zn, Pb and Ni

The Table IV shows that the variables Ca, Mg, Na, Cl, and SO_4 have high positive loadings on factor 1, and that the variables Na, K and HCO_3 have high positive

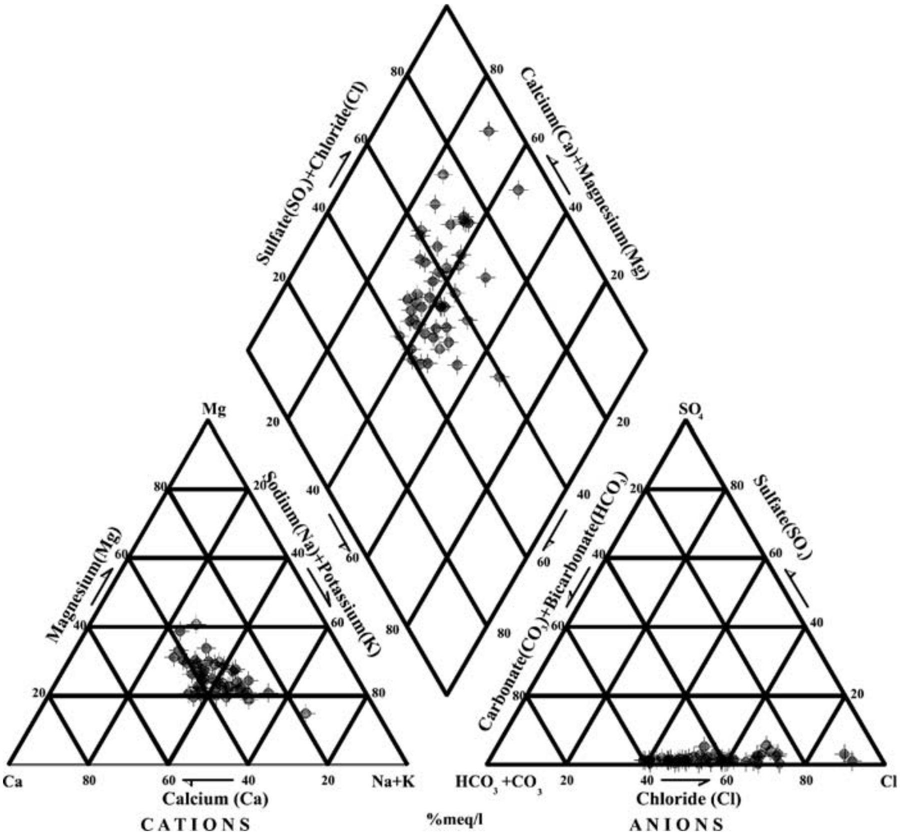


Figure 11 Piper diagram for hydrochemical facies of groundwater.

Figure 12 Spatial distribution of iron concentration.

loadings on factor 2. The factor loading of NO_3, Pb and Ni shows high positive value on factor 3. Three factors with different factor loadings indicate that three different contributions are involved in determining the chemical composition of groundwater. The presence of Na, Mg, and Cl indicates the saltwater signature, and gypsum dissolution is shown by Ca and SO_4. As mentioned in the previous section the HCO_3 can come from the dissolution of carbonate minerals. In this study, it is considered that the HCO_3 comes mainly from natural processes. Hence, factors 1 and 2 are assumed to be indicative of the natural processes. The NO_3, Zn, Pb and Ni of factor 3 are largely influenced by the contaminant source of the urban area rather than natural processes. Although electrical conductance of groundwater is largely influenced by factor 1, natural processes as well as anthropogenic inputs may determine its level. The relationship of factor loadings on the groundwater variables are shown in Figure 13.

5 Groundwater Quality and Assessment

Groundwater quality assessment of the study area was carried out to determine its suitability in terms of domestic and agricultural purposes based on the ISI (1983) and WHO (1993) standards (Table II). The quality of groundwater in the study area is highly influenced by agricultural activities, anthropogenic contamination and seawater intrusion. The sodium concentrations of groundwater at well nos. 2 and 6 are exceed the limits recommended by WHO (1993) and ISI (1983). Features that generally need to be considered for evaluation of the suitability of groundwater for irrigation use are salinity, sodium percentage

Table III Correlation matrix for groundwater samples in the study area

	EC	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^-	NO_3^-	PO_4^-	Fe	Mn	Zn	Pb	Ni
EC	1.00														
Ca	0.83	1.00													
Mg	0.75	0.84	1.00												
Na	0.90	0.63	0.50	1.00											
K	0.25	−0.07	−0.05	0.35	1.00										
HCO_3	0.35	0.02	0.05	0.47	0.42	1.00									
Cl	0.83	0.89	0.72	0.75	0.15	0.05	1.00								
SO_4	0.64	0.60	0.52	0.65	0.33	0.32	0.74	1.00							
NO_3	0.65	0.52	0.58	0.42	−0.13	−0.04	0.31	0.00	1.00						
PO_4	0.50	0.32	0.24	0.60	0.49	0.52	0.40	0.66	−0.03	1.00					
Fe	0.04	0.01	0.02	−0.03	−0.05	−0.02	−0.04	−0.11	0.14	−0.15	1.00				
Mn	−0.14	0.01	0.01	−0.17	−0.04	−0.22	0.06	0.13	−0.24	−0.06	0.02	1.00			
Zn	−0.02	−0.03	0.00	−0.09	0.02	−0.05	−0.03	0.01	0.07	−0.11	0.46	−0.02	1.00		
Pb	0.17	0.12	0.16	0.11	−0.09	0.05	−0.03	−0.05	0.37	0.06	0.06	0.01	0.23	1.00	
Ni	0.01	−0.07	0.01	−0.07	−0.13	0.15	−0.23	−0.23	0.32	−0.25	0.05	−0.15	0.17	0.70	1.00

Table IV Factor analysis of groundwater samples in the study area

Parameters	Factor 1	Factor 2	Factor 3
EC	0.91	0.33	0.16
Ca	0.96	−0.06	0.01
Mg	0.88	−0.09	0.11
Na	0.74	0.53	0.04
K	0.00	0.74	−0.16
HCO_3	0.04	0.83	0.14
Cl	0.92	0.10	−0.20
SO_4	0.67	0.44	−0.31
NO_3	0.59	−0.16	0.58
PO_4	0.37	0.74	−0.21
Fe	0.01	−0.14	0.31
Mn	0.03	−0.28	−0.33
Zn	−0.03	−0.05	0.40
Pb	0.11	0.06	0.77
Ni	−0.11	0.03	0.85

and sodium adsorption ratio (SAR). The salinity (with respect to total dissolved solids) of groundwater affects the growth of plants directly and also affects soil structure, permeability and aeration, which indirectly affect plant growth (Mohan, Singh, Tripathi, & Choudhry, 2000). As per the water quality classification based on SAR and EC values (USSL, 1954), 41 samples show medium to high salinity hazard and six samples indicate very high salinity hazard (Table V).

Table V Relationship between SAR and EC for the groundwater in the study area

SAR	EC	Water class	Sample nos.	Salinity hazard
<10	250	Excellent		Low
	251	Good	7, 9, 12, 16, 22, 27, 45	Medium
	751–2,250	Fair	4–5, 8, 10–11, 13–15, 17–21 23–26, 28–35, 37–38, 41–44, 46–47	High
	>2,250	Poor	1–3, 6, 36, 39	Very high

A perusal of Wilcox's (1955) diagram (Figure 14) shows that seven samples (S. nos. 7, 9, 12, 22, 27 and 45) are excellent to good, six samples (1–3, 6, 36 and 39) are doubtful to unsuitable, and all other 34 samples are good to permissible. Sodium concentration plays an important role in evaluating the groundwater quality for irrigation because sodium causes an increase in the hardness of the soil as well as a reduction in its permeability (Tijani, 1994). SAR

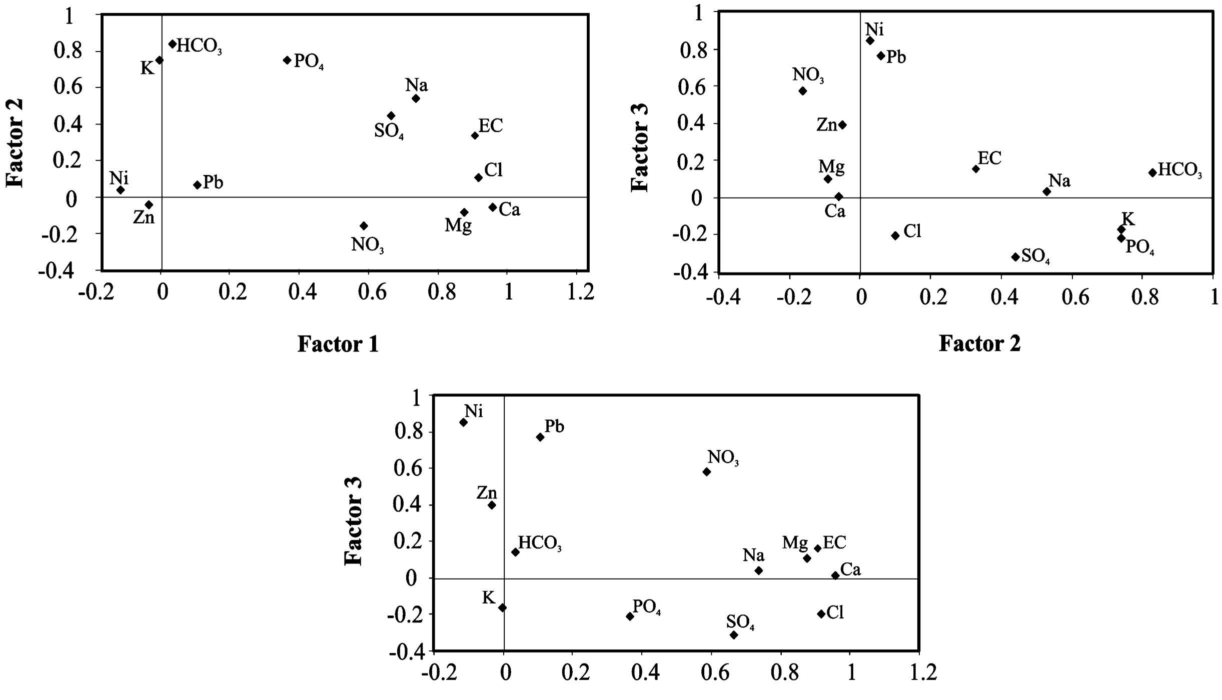


Figure 13 Distribution of variables among factors as given by factor analysis.

values are generally low whereas Na% in 21 groundwater samples is high and may not be suitable for irrigation (Table VI).

Leaching of nitrogenous fertilizers has led to increase of nitrate concentrations in the aquifer water. Most of the groundwater samples have high concentration of nitrate. The contour map (Figure 9) shows that groundwater in the western part of the study area is highly contaminated by NO_3. High nitrate concentrations in groundwater could pose potential hazard to infant health. The consumption of water with high nitrate concentration decreases the oxygen-carrying capacity of blood, causing blue babies or methemoglobinemia. Phosphorus is not commonly toxic to humans, animals and fish, but creates taste and odour problems and difficulties in water treatment. The Canadian Department of National Health and Welfare (1969) suggested a maximum limit of 0.2 mg/l for PO_4^- in water, while that of European Economic Community (Smeats & Amavis, 1981) is 0.54 mg/l. The *ortho*-phosphate concentration in the study area ranges from 0 to 94 mg/l; spatial distribution of phosphate (Figure 10) shows that isolated pockets of high phosphate are present in the central part of the study area. The iron concentration in nine wells exceeds the maximum permissible limit of 1 mg/l as per WHO (1993) and ISI (1983) standards. The contour map of iron (Figure 12) indicates that the southern part of the sampled area is highly contaminated by iron. Overall, comparative results indicate that the groundwater samples are not suitable for domestic purposes owing to high concentration of nitrate, phosphate and iron, while few of them are not suitable for irrigation purposes owing to high TDS and sodium concentration.

Table VI Irrigation quality based on sodium percentage

Na%	Water class	Sample nos.
20	Excellent	–
21–40	Good	1, 3–5, 8–9, 11, 13–16, 20–22, 24, 28–31, 33–36, 41, 44–45, 47
40–55	Poor	2, 7, 10, 12, 17–18, 23, 26–27, 32–33, 38–40, 42–43, 46
50–70	Very poor	6, 19, 25, 37

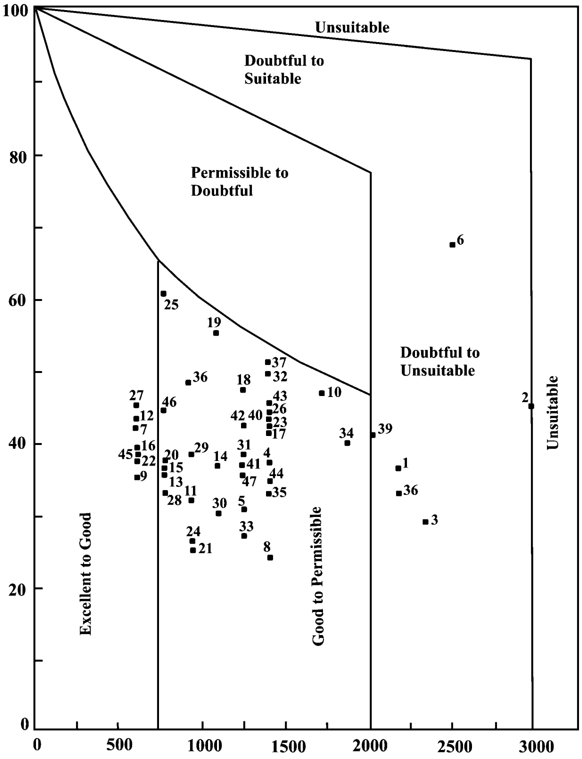


Figure 14 Sodium percentage vs. EC plot (Wilcox, 1955).

6 Conclusions

The lower part of Ponnaiyar River basin is a sedimentary terrain consisting of sandstone, clay, alluvium and lateritic soils. The chemical composition of the groundwater is controlled by mixing of seawater, ion-exchange reactions, dissolution processes and anthropogenic inputs. The results indicate that Na, K and Cl are mainly derived from irrigation return flow and anthropogenic activities in the inland area, and seawater intrusion in coastal areas. Calcium and magnesium are derived mainly from dissolution of carbonate precipitates along with ion exchange process in the groundwater. NO_3, Pb, and Ni are derived from irrigation return flow and anthropogenic activities in the study area. The groundwater is also polluted by open sewage systems and by various agricultural activities. The most serious pollution threat to groundwater is from nitrate ions, which are associated with sewage and fertilizer application. The present state of quality of the groundwater from lower part of Ponnaiyar River basin is far from drinking water standard and not suitable for domestic purposes. The higher concentration of toxic metals (Fe and Ni) may entail various health hazards and the use of such wells should be avoided. The technical measures that should be taken in order to preserve and improve water quality in the affected parts include (a) construction of sewer system extending throughout the area to collect waste water (b) treatment of collected waste water that is presently being discharged into adjoining rivers and irrigation channels (c) optimal amount of fertilizer application and (d) maintenance of optimal amount of pumping in the coastal area.

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References

Brown, E., Skougstand, M. W., & Fishman, M. J. (1970). Methods for collection and analyses of water samples for dissolved minerals and gases. Techniques of Water Resources Investigation of the US Geological Survey 5.

Chan, H. J. (2001). Effect of landuse and urbanization on hydrochemistry and contamination of groundwater from Taejon area, Korea. *Journal of Hydrology*, *253*, 194–210.

Department of National Health and Welfare (1969). *Canadian Drinking Water Standards and Objectives*, Canada.

Elango, L., Kannan, R., & Senthil Kumar, M. (2003). Major ion chemistry and identification of hydrogeochemical processes of groundwater in a part of Kancheepuram District, Tamil Nadu, India. *Environmental Geosciences*, *10*(4), 157–166.

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Englewood Cliffs, NJ: Prentice Hall (p. 604).

ISI (1983). *Drinking water standard-substances or characteristic affecting the acceptability of water for domestic use*. IS, 10500, pp. 1–22.

Kolpin, D. W., Barbash, J. E., & Gillion, R. J. (1998). Occurrence of pesticides in shallow groundwater of the United States; initial results from the National Water-quality Assessment Program. *Environmental Science and Technology, 32*, 558–566.

Lusczynski, N. J., & Swarzenski, W. V. (1996). *Saltwater encroachment in southern Nassu and SE Queen countries, Long Island, New York*. USGS Paper, pp. 1613–F.

Meyback, M. (1987). Global chemical weathering of surficial rocks estimated from river dissolved loads. *American Journal of Science*, *287*, 401–428.

Mohan, R., Singh, A. K., Tripathi, J. K., & Choudhry, G. C. (2000). Hydrochemistry and quality assessment of ground water in Naini industrial area Allahabad District, Uttar Pradesh. *Journal of the Geological Society of India*, *55*, 77–89.

Muir, D. C. G., & Baker, B. E. (1978). The disappearance and movement of three triazine herbicides and several of their degradation products in soil under field conditions. *Weed Research*, *18*, 111–120.

Offiong, O. E., & Edet, A. E. (1998). Water quality assessment in Akpabuyo, Cross River basin, South-eastern Nigeria. *Environmental Geology*, *34*(2/3), 167–174.

Piper, A. M. (1953). A graphic procedure in the chemical interpretation of water analysis. *USGS Groundwater Note*, *12*.

Ragunath, H. M. (1982). *Groundwater*. New Delhi: Wiley Eastern (pp. 285–286).

Smeats, J., & Amavis, P. (1981). European community directives relating to the quality of water intended for human consumption. *Water, Air, and Soil Pollution*, *150* (40), 483–502.

Srinivasa Rao, Y., Reddy, T. V. K., & Nayudu, P. T. (1997). Groundwater quality in the Niva River basin, Chitoor district, Andhra Pradesh, India. *Environmental Geology*, *32*(1), 56–63.

Subba Rao, N., Gurunadha Rao, V. V. S., & Gupta, C. P. (1998). Groundwater pollution due to discharge of industrial effluents in Venkatapuram area, Visakhapatnam, Andhra Pradesh, India. *Environmental Geology*, *33*(4), 289–294.

Tijani, M. N. (1994). Hydrochemical assessment of groundwater in Moro area, Kwara State, Nigeria. *Environmental Geology*, *24*, 194–202.

USSL (1954). *Diagnosis and improvement of salinity and alkaline soil*. USDA Hand Book no. 60.

WHO (1993). *Guidelines for drinking water quality, vol. 1. Recommendations* (2nd ed.). Geneva: WHO (p.130).

Wilcox, L. V. (1955). *Classification and use of irrigation water*. US Department of Agriculture, Circ 696. Washington, DC.

Wu, T. L. (1980). Dissipation of the herbicides atrazine and alachlor in a Maryland corn field. *Journal of Environmental Quality*, *9*(3), 459–465.