Evaluation of Total Dissolved Solids and Quality Zones of Groundwater Using Vertical Electrical Soundings and GIS Method

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1 Introduction

Groundwater is a major source of fresh water which is generally used for domestic, agricultural and industrial purpose in many countries of the world. Total dissolved solids (TDS) are important to measure because it is combined content of all organic and inorganic substances present in groundwater as molecular/ionized/micro granular (10–6 m, size particles solution) forms. Generally, major sources of TDS in groundwater are geochemical (groundwater and underground rock chemical process) and leaching process from agricultural contamination, and anthropogenic sources (discharge from sewage and industrial plants). Generally, TDS can be considered a primary water quality measurement because it is showing combined effect of different pollutants and it may be used as a basic characteristic of drinking water. Collection of groundwater from boreholes for groundwater quality analysis generally or may not be readily available mainly because water of those boreholes is without geochemical analyses. In such case, geoelectric sounding may provide a useful way to estimate TDS concentration [1]. Vertical electrical sounding (VES) method is subtle and can be utilized precisely to determine groundwater quality [2–4].

For present states of groundwater quality on the basis of TDS during VES survey without hydrogeochemical analysis of groundwater, resolving this problem to calculate the TDS (without hydrogeochemical analysis) of groundwater, We developed a mathematical empirical model in this work that can capture the in-situ aquifer

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groundwater TDS. We are unaware with the fact that the VES technique has the capability to determinate the TDS with the help of ρ of groundwater at the aquifer. With this idea, we attempted to develop an empirical relationship between TDS and ρ of groundwater, in order to use ρ of groundwater to predict the TDS of groundwater.

There is limited literature work exists which revealed a relationship to predict the TDS based on ρ of groundwater. However, Mehrdadi et al. [5] and Maedeh et al. [6] try to predict TDS on the basis of ρ, using Artificial Neural Network (ANN, a black box model) to predict TDS in groundwater. But they used less number of samples (one hundred only) date for training of network process in ANN while ANN requires voluminous data for good prediction. While work is available for prediction of TDS on the basis of other hydrogeochemical component (like EC, Ca, pH, SO_4, [7]) of groundwater. Therefore, we outlined an objective to estimate TDS on the basis of ρ of groundwater during VES survey.

2 Material and Method

2.1 Study Area

The study area has a geographical area of 87.25 km^2 (Fig. 1). The two rivers Koovam (or Cooum) river in North, Adyar river in South, Bay of Bengal coast in East bound the study area and in the city boundary in West. The elevation ranges from 5 to 15 m above mean sea level. The Survey of India (SOI) Topographic sheet 66C/1 and
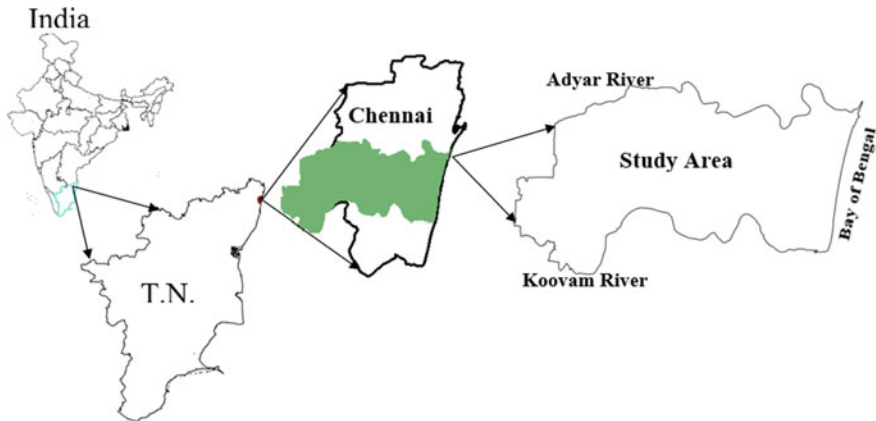
Fig. 1 Location map of the study area

66C/4 covers the whole study area. The rivers have deposited substantial amount of alluvium—mixture of sand sit and clay-that forms an important aquifer in Chennai city.

Geologically, the alluvial deposits rest on hard rock in the eastern and southern parts. The hard rock is mainly charnockites of Archaean age. In the northern and western part, the alluvium rests over tertiary and gondwana group of rocks. The average thickness of alluvium varies from 10 m along the southern boundary to a maximum of 30 m in the central and eastern part of the study area. Shallow open dug wells of depth varying from 8 to 10 m and borewells in the depth range of 30 m to 75 m are the common groundwater extraction structures in the area [8]. The study area has a tropical climate with mean annual temperature is 24.3 (min) to 32.9 °C (max) and humidity ranges from 58 to 84%. Chennai receives the major part of the rainfall during the north-east monsoon period and south-west monsoon is generally erratic [9]. The normal annual rainfall recorded in the Meenambakkam observatory is 1323.7 mm and in the Nungambakkam observatory is 1285.6 mm.

2.2 Method

Total twenty-three wells water samples have been collected ((Table 1) 7 for model generation and 16 for model validation) for laboratory-based (or gravimetric method) TDS measurement while 70 points were used for VES examination within study area. For VES survey we have used resistivity meter (SSR MP ATS). Statistical tests have been used to establish the relationship between the TDS and ρ of groundwater. The quadratic least square regression/non-linear/second order regression (QLSR/NLR/SOR) method was used to calculate regression coefficient (a, b and c) and the fitted value to establish relationship as Eq. (1) as

$$y = ax^2 + bx + c \tag{1}$$

Table 1 TDS and Resistivity of groundwater data sets at fixed location borewells

Sl. no.	Well ID	TDS (mg/l)	Resistivity (ρ)
1	4	500	59.219
2	47	1100	29.963
3	56	780	243.427
4	64	400	70.48
5	76	600	5.676
6	99	2040	356.85
7	108	1120	61.551

The residual sum of the square of differences for all n is given by:

$$S = \sum_{i=1}^{n} (ax^2 + bx + c)^2 \tag{2}$$

Values of a, b and c have to be determined so that S must be a minimum value:

$$\frac{\partial S}{\partial a} = 0, \frac{\partial S}{\partial b} = 0 \text{ and } \frac{\partial S}{\partial c} = 0 \tag{3}$$

Coefficients (a, b, c) values are given as:

$$a = \frac{\left(\left(S(x^2 y) \times S(xx) \right) - \left(S(xy) \times S(xx^2) \right) \right)}{\left(\left((S(xx) \times S(x^2 x^2) \right) - \left(S(xx^2) \right)^2 \right)} \tag{4}$$

$$b = \frac{\left(\left(S(xy) \times S(x^2 x^2) \right) - \left(S(x^2 y) \times S(xx^2) \right) \right)}{\left(\left(S(xx) \times S(x^2 x^2) \right) - \left(S(xx^2) \right)^2 \right)} \tag{5}$$

$$c = ((Sy_i)/n) - (b \times ((Sx_i)/n))) - (a \times (S(x_i^2)/n)) \tag{6}$$

where,

$$S(xx) = \left(Sx_i^2 \right) - ((Sx_i)^2/n) \tag{7}$$

$$S(xy) = (Sx_i y_i) - ((Sx_i) \times (Sy_i)/n) \tag{8}$$

$$S(xx^2) = \left(Sx_i^3 \right) - ((Sx_i) \times (Sx_i^2)/n) \tag{9}$$

$$S(x^2 y) = \left(Sx_i^2 y_i \right) - ((Sx_i^2) \times (Sy_i)/n) \tag{10}$$

$$S(x^2 x^2) = \left(Sx_i^4 \right) - ((Sx_i^2)^2/n) \tag{11}$$

2.3 Validation of Model

Statistical testing is a good tool to estimate the efficiency of any developed empirical model. Before testing the efficiency of a model based on observed and predicted data sets some statistical tools exist which can show that X (ρ of groundwater) and Y (TDS) are highly correlated (based on R^2 statistical tool) and a good model may be generated which have good power to express X in term of Y. Therefore we have used few statistical tests (Table 2) for estimating the efficiency of generated model based on observed data sets of TDS and ρ of groundwater.

Table 2 Mathematical expression of statistical tests

Coefficient of determination (R^2)	$R^2 = \left(\dfrac{\sum_{i=1}^{n}(V_M - \overline{V}_M) \times (V_O - \overline{V}_O)}{\sqrt{\sum_{i=1}^{n}(V_M - \overline{V}_M)^2 \sum_{i=1}^{n}(V_O - \overline{V}_O)^2}} \right)^2$
Standard error of estimate (SEE)	$\mathrm{SEE}_M = \left(\dfrac{\sum_{i=1}^{n}(V_O - V_M)^2}{n-1} \right)^{0.5}$
Root mean square error (RMSE)	$\mathrm{RMSE} = \sqrt{\left(n^{-1} \sum_{i=1}^{n}(V_M - V_O)^2 \right)}$
Relative-RMSE (R-RMSE)	$\mathrm{R-RMSE} = \sqrt{\left(n^{-1} \sum_{i=1}^{n} \left(\dfrac{V_M - V_O}{V_M} \right)^2 \right)}$
Percent RMSC (%RMSE)	$\mathrm{\%RMSE} = \left(\dfrac{RMSE}{\sum_{i=1}^{n}(V_O)} \times 100 \right)$
t-statistic test	$t = \sqrt{\left(\dfrac{(n-1)MBE^2}{RMSE^2 - MBE^2} \right)}$
Volume error (VE)	$\mathrm{VE} = n^{-1} \sum_{i=1}^{n} \left| \dfrac{V_O - V_M}{V_M} \right|$
Normalized RMSE (NRMSE)	$\mathrm{NRSME} = \dfrac{\sqrt{\left(n^{-1} \sum_{i=1}^{n}(V_M - V_O)^2 \right)}}{\overline{V}_O}$
Mean absolute error (MAE)	$\mathrm{MAE}_M = \dfrac{\sum_{i=1}^{n} |V_O - V_M|}{n}$
Mean bias error (MBE)	$\mathrm{MBE}_M = \dfrac{\sum_{i=1}^{n}(V_M - V_O)}{n}$
Mean absolute percent error (MAPE)	$\mathrm{MAPE}_M = \dfrac{\sum_{i=1}^{n} \left| \dfrac{V_O - V_M}{V_O} \times 100 \right|}{n}$
Average index ratio (IR)	$\mathrm{IR} = \dfrac{V_M}{V_O}$
Percent of error (PE)	$\mathrm{PE} = \sum \left(\dfrac{V_M - V_O}{V_O} \right) \times 100$

V_O, observed value and V_M model value

2.4 TDS Zoning Map

After generation and validation of model, we have used model to predict TDS value of 47 points using ρ from VES survey. These predicted TDS values were interpolated within study area using ArcGIS-10.1 [10–14] for creating TDS zoning map of study area.

3 Result and Discussion

Twenty-three (7 + 16) bore wells water samples were collected for TDS measurements while seventy ρ from VES across study area were carried out and used to establish and validate the existing relationship between ρ and TDS. TDS hydrogeochemical parameter tested by using QLSR coefficients (a, b and c) driving by Eqs. 4–11. Results of the QLSR coefficients revealed that TDS has good correlation. Thus, Eqs. (2)–(9) were used to establish relationship that relates TDS of groundwater to ρ of groundwater as Eq. 12:

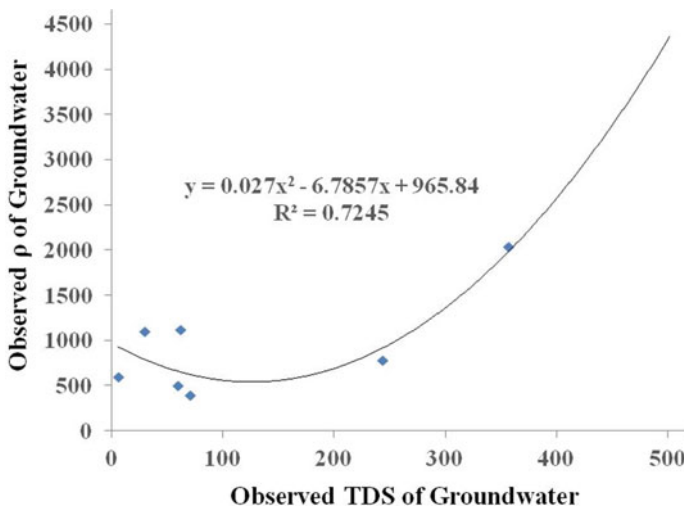$$\text{TDS} = 0.027 \times \rho^2 - 6.7857 \times \rho + 965.84 \tag{12}$$

Fig. 2 Correlation between observed TDS and ρ of groundwater

where, TDS is Total dissolved solid of groundwater and ρ is apparent resistivity of groundwater while $a = 0.027$, $b = -6.7857$; and $c = 965$.

Equation 12 and Fig. 2, is showing a good R^2 value of 0.72 which revealed that ρ and TDS of groundwater are strongly correlated and both can be used to translate ρ into TDS or TDS into ρ of groundwater.

3.1 Empirical Models Validation

Equation 12 has been used to predicate TDS for study area. It has been decided by statistical tests only therefore we have applied statistical test over 16 model-predicted and observed TDS value of 16 fixed points (Table 3). Table 3 shows TDS value comparison between $TDS_{Observed}$ and TDS_{Model} using statistical test. The statistical analysis gives level of accuracy of developed empirical models TDS_{Model} with respect to $TDS_{Observed}$. Based on statistical parameters RMSE, R-RMSE, MAE and MBE statistics test, TDS_{Model} is more closer to $SM_{Observed}$ due to low value of error indexes (RMSE = 89.37, R-RMSE = 0.10, MAE = 55.17, MBE = 35.20 and SEE = 0.16, Table 3). Higher value of R^2, Adj R and Multi R test (Table 3) revealing that TDS_{Model} values how much closer to $TDS_{Observed}$ and also TDS_{Model} value can be translated into $TDS_{Observed}$ value due to high value of R^2 0.899 ($\approx$0.9, Fig. 3) (TDS_{Model} with

Table 3 Statistical test result or validation of developed model

Sl.No	$TDS_{Observed}$	TDS_{Model}	Statistical test	Statistical values
1	624.27	604.95	RMSE	89.37
2	947.01	826.69	R-RMSE	0.10
3	757.60	577.48	MAE	55.17
4	927.33	882.09	NRMSE	0.10
5	793.75	781.30	MBE	35.20
6	804.08	779.40	MAPE	0.40
7	935.12	812.80	RMSE%	0.64
8	653.68	614.91	IR (average index ratio)	0.94
9	886.82	897.01	PE (% Error)	−6.94
10	693.09	667.26	R^2	0.90
11	1031.48	911.02	p (at 95%)	0.01
12	1001.93	997.93	Multi R	0.95
13	696.05	549.82	Adj. R	0.89
14	1333.06	1372.97	Standard error	66.77
15	800.00	814.99	t-test	1.66
16	1039.12	951.02	SEE	0.16
17	–	–	VE	0.09

y = 0.8494x + 177.93
R² = 0.8992
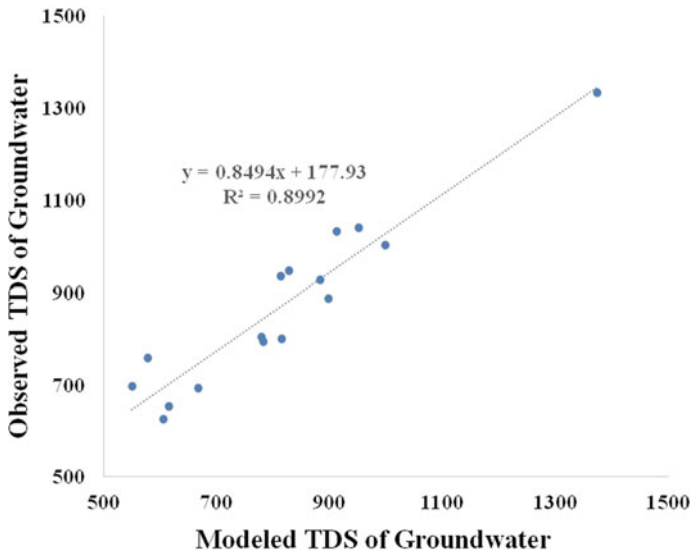
Fig. 3 Correlation between Observed and modelled TDS of groundwater

TDS$_{Observed}$, Table 3). Very good (or less) value of p-value test for TDS$_{Model}$ with TDS$_{Observed}$ has revealed that more probability of obtaining value from TDS$_{Model}$ similar to TDS$_{Observed}$. Lower value of RMSE% (=0.64) and VE (=0.09, Table 3) showed a good agreement of model based on TDS with respect to TDS$_{Observed}$. IR approach to ($\approx$1) one, which is revealed model-based predicted TDS (TDS$_{Model}$) can be shows 1:1 line properties (less noise in model-based TDS with respect TDS$_{Observed}$. Overall on the statistical tests (Table 3), developed model (Eq. 12) on the basis of ρ parameter for study area is well working. By using this model easily TDS value may be forecasted. Based on above statistics result (Table 3), it is inferred that present model (Eq. 12) performs good (with respect to observed TDS) for retrieval of TDS from ρ of groundwater.

3.2   TDS Zoning

TDS values to be less than 465 mg/l, an indication of very good quality of water and in TDS map such area (or red colour patches) are very less. TDS values that range from 465 to 965 mg/l, an indication of good quality water. In TDS maps such value covers nearly about 20% of the study area and have yellow colour patches. TDS values that range from 965 to 1620 mg/l, an indication of saline region (light blue to dark blue colour patches) and such type of area is almost 70% of the study area. WHO has recommended 600 and 1000 mg/l as the lower and upper limits of TDS acceptability for drinking use. In our case, the TDS maps have majority of area fall in upper limit of TDS (1000 mg/l<). Hence our study area groundwater is suitable for industrial and agricultural purposes, and this is logical also because one side of our study area is sea and another two side are two polluted rivers Adyar [15] and Koovam (or Cooum). Contour maps of the ρ at 100 mg/l interval has revealed that most part of the study area is affected by two directions as middle of upper (Adyar river a major source to contaminate to groundwater, [15] with 700 mg/l< contour values (Fig. 4) and middle-lower side (Koovam/Cooum river a major source to contaminate to groundwater, [1, 16, 17]) of study area with higher value of contour (Fig. 4). From sea direction slight salt/saline water intrusion (in aquifer) is also identified which is normal and natural process in coastal region.
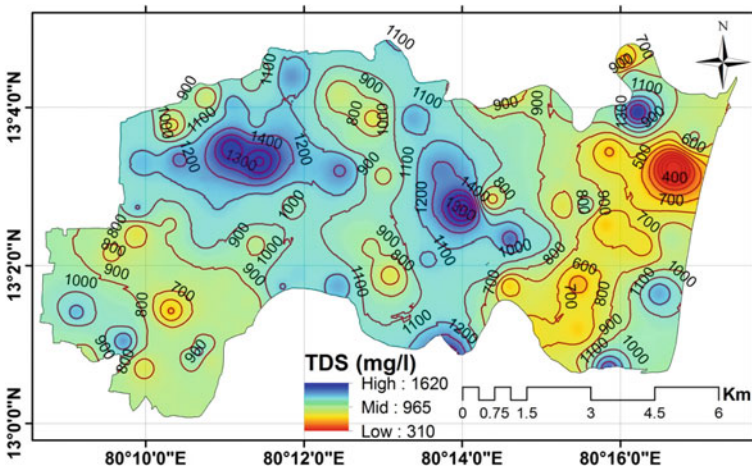

Fig. 4   TDS zoning of groundwater with TDS concentration contour at 100 mg/l interval

4   Conclusion

Results show a significance of present work and its ability to estimate the TDS from ρ data and to predict and map salinity of groundwater. Good prospects exist for freshwater development in the study area where the TDS values range from 465 to 604 mg/l (or >965 mg/l). The predicted TDS from TDS and ρ measurements is in good agreement with the TDS observed/measured values. The TDS value from ρ data gives reliable and logical estimate therefore ρ can be used to understand the salinity of groundwater. Based on the TDS and ρ (as a primary objective), three groundwater quality zones (>310 mg/l, 310–965 mg/l and 965–1620 mg/l) were mapped. Present research work has offered a better understanding of the groundwater system at study area and such type of relationship will be guided in development of future groundwater exploration strategies in the study area and also eradicate the problem of saltwater and abortive wells in the area.

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