

## **Spatio-Temporal Variability Analysis of Groundwater Level in Coastal Aquifers Using Geostatistics**

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### **Abstract**

Over exploitation of coastal aquifers often lead to reversal of hydraulic gradient and seawater intrusion in coastal areas. Information on spatial variability of groundwater level can help in identifying the critical region and deciding appropriate management strategies for augmenting groundwater table and controlling seawater intrusion. In the present study, spatial and temporal behavior of groundwater level in the coastal aquifers of Minjur in Tamilnadu, India was studied using the GS+ and geostatistical module of Arc GIS 9.3 softwares. The variograms and krigged spatial maps were generated for pre monsoon and post monsoon seasons of 1999 and 2008. The variogram analysis of water level showed a nugget to sill ratio of  $< 0.25$ , indicating that the groundwater level has very strong spatial dependence. The average range of variograms for spatial analysis was about 10.5 km. The spatial variability analysis of groundwater level indicated that the water level was below mean sea level and reverse hydraulic gradient existed in both the aquifers, which is the main reason for intrusion of sea water into these aquifers. It was observed from the spatial variability maps that there was a considerable decline in the water level over a period of 10 years and groundwater level improved during post monsoon in both aquifers. Further, the study showed that geostatistical analysis is helpful in delineating the critical regions where measures like controlled pumping and artificial groundwater recharge are to be implemented to improve groundwater level.

**Keywords** - Groundwater level; Variograms; Geostatistics; Kriging; Spatial variability

## 1. Introduction

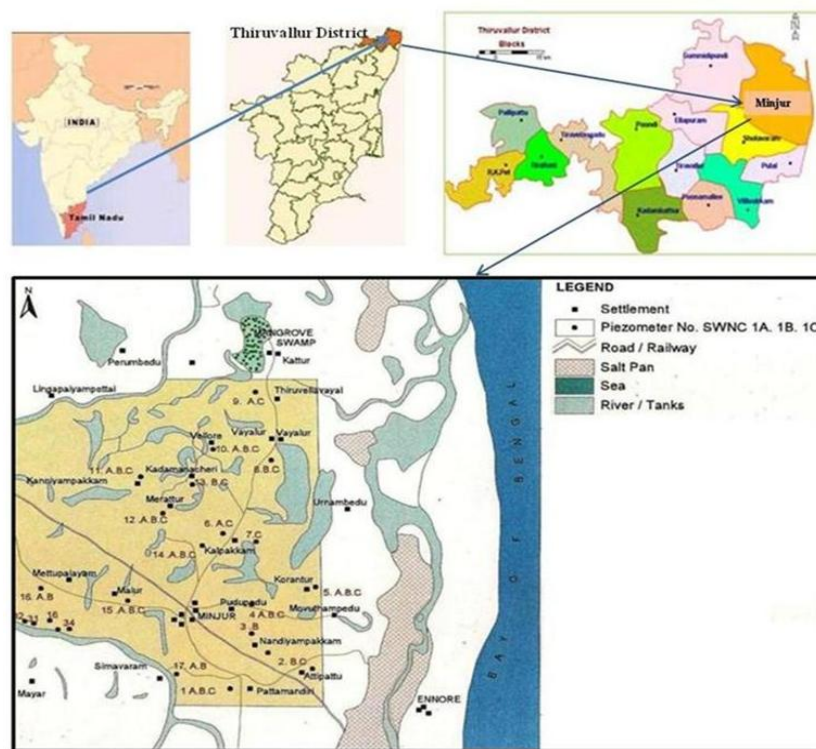
Groundwater is the major source of water to meet the irrigation, domestic and industrial requirements in coastal region worldwide. With rapid increase in population and industries in coastal region, pressure on groundwater has increased tremendously. This has led to the over exploitation of groundwater and sea water intrusion into freshwater aquifers. Groundwater level in selected observation wells in the affected area is being monitored at regular interval to understand the fluctuations in water level due to extraction. The limitation of such point sampling is that the data are collected from very limited observation wells and they do not provide detailed information on extent of area affected. This necessitates the use of spatial interpolation methods like geostatistics for generating the spatial variability maps of groundwater level.

The spatial and temporal variations in the groundwater table drop were investigated by many researchers. Finke et al (2004) and Ahmadi and Sedghamiz (2007) used kriging for mapping of groundwater level to identify critical area. Antonellini et al (2008) prepared salinity and water table maps using kriging for the coastal aquifer of the southern Po Plain, Italy to identify the causes and extent of seawater intrusion. Taany et al (2009) applied kriging technique to study the spatial and temporal variation of groundwater level fluctuation in Amman –Zarqa basin. The present study was planned to address the spatial and temporal variability of groundwater water level in coastal aquifer of Minjur using geostatistical methods.

## 2. Materials and Methods

### 2.1 Study Area Description

The study area is located in Minjur of Thiruvallur District in Tamil Nadu. It is located between  $13^{\circ}15'0''$  and  $13^{\circ}20'50''$  North Latitude and  $80^{\circ}12'40''$  and  $80^{\circ}18'05''$  East Longitude and has an area of  $143 \text{ km}^2$  (Figure. 1). The Bay of Bengal lies in the east of study area. The area is covered by alluvium of two rivers, which consists of sand, clay and sandy clay. The alluvium is underlain by tertiary formations followed by Gondwana clay which rests on the basement of Archaean rocks. The aquifer system in the area consists of three layers: the unconfined aquifer, aquitard and semi confined aquifer. Of these aquifers, farmers extensively pump water from the semi confined aquifer for irrigating paddy crops. Large scale pumping done by Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB) for meeting the industrial and drinking water requirements of Chennai city and groundwater pumping by farmers has resulted in water level decline.



**Figure. 1** Location of the study area

## 2.2 Geostatistics

The theoretical basis of geostatistics has been described by several researchers (Gooverts, 1997; Isaaks and Srivastava, 1989; Kitanids, 1997). Geostatistics is an effective tool for modeling the spatial structure of various physical parameters. It analyses the spatial variation using different semi variogram models and they are used in kriging to obtain best linear unbiased estimators of spatially dependent data (Sarangi et al, 2006; Dash et al, 2010). Semi variogram is defined as one-half of the variance of the difference between the attribute values at all points separated by a distance  $h$  and can be calculated using the equation (1)

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i + h) - z(x_i)]^2 \quad (1)$$

where,  $\gamma(h)$  is the experimental semi variogram for a given distance (lag)  $h$ ,  $h$  is the separation distance between the two data points,  $z$  is the value of the sample,  $x$  is the position of one sample in the pair,  $(x + h)$  is the position of other sample in the pair and  $N$  is the number of pairs in the calculation. The correlation between  $z(x)$  and  $z(x + h)$  expresses the spatial structure of the parameter under study. The calculated semi variogram is plotted on the Y axis against corresponding lag distance on the X axis. Then, fitting a theoretical model like circular, spherical, exponential, Gaussian is essential so that variogram can be computed for any possible sampling interval. The

most appropriate variogram model is chosen based on statistical measures. The adequacy and validity of the model can be tested by a technique called cross validation. Interpolated and actual values are compared, and the model that yields the most accurate predictions is retained. Then, the interpolation methods like kriging use them to interpolate the values at unknown points and produce spatial variability map (Isaaks and Srivastav, 1989; Gooverts, 1997; ESRI, 2004). Among the different kriging methods, ordinary kriging can be applied for spatial and temporal analysis, if datasets do not possess a trend. Webster and Oliver (2001) reported that the ordinary kriging of a single variable is most robust, simple and common kriging method in which the mean of the interpolated data,  $m$ , is assumed to be unknown. The ordinary kriging estimate,  $Z^*(x_0)$ , of an unsampled site is a linear sum of weighted observations within a neighborhood (Equation. 2)

$$Z^*(x_0) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (2)$$

where,  $Z^*(x_0)$  is the estimate of  $Z$  at  $x_0$ ,  $\lambda_i$  is the weight assigned to the  $i$  th observation, and  $n$  is the number of observations within the neighborhood. The weighing factors of  $\lambda_i$ 's are determined based on a variogram of  $Z$ .

### 2.3 Semi variogram analysis and kriging

Groundwater depth observed during pre and post monsoons of 1999 and 2008 were subjected to exploratory data analysis using histogram tool. Then different semi variogram models like circular, spherical, exponential, linear, Gaussian were tested using GS+ software. The semi variogram parameters like nugget, sill and range, coefficient of determination ( $R^2$ ) and residual sum of squares (RSS) were determined and the performance of each model was evaluated using cross-validation. Thereafter the model giving best results was selected. The spatial prediction maps of water table depths were prepared using ordinary kriging for the unconfined and semi confined aquifers for pre monsoon and post monsoon seasons using Geostatistical Analyst Extension Tool of Arc GIS 9.3 software.

## 3. Results and Discussion

### 3.1 Semi variogram models for groundwater level

Results of semi variogram analysis are provided in Table 1. Circular model fitted best in unconfined aquifer in all the cases, except for post monsoon of 1999. Whereas in semi confined aquifer, spherical model fitted best during 1999 and Gaussian model fitted well in the year 2008. The nugget to sill ratio as described by Tanny et al (2009) was used to analyze the spatial structure. A variable is said to have strong spatial dependence if the ratio is less than 0.25, and has a moderate spatial dependence if the ratio is in between 0.25 and 0.75; otherwise the variable has weak spatial dependence. In the present study, the nugget to sill ratio of groundwater level in all cases was less than 0.25 indicating that the groundwater level has strong spatial dependence in both the aquifers. The range is the distance within which the variables are spatially correlated. In the presented study, the average range of 10.5 km was obtained. The  $R^2$  values of 0.87 to 0.99 indicate that the variograms were chosen correctly and the

predictions were accurate.

**Table 1** Best-fit semi variogram model parameters

Year	Aquifer	Season	Best-fit model	Nugget/sill	Range (km)	R <sup>2</sup>
1999	Unconfined	Pre monsoon	Circular	0.008	8.5	0.91
		Post monsoon	Spherical	0.133	15.0	0.98
	Semi confined	Pre monsoon	Spherical	0.079	9.5	0.94
		Post monsoon	Spherical	0.192	10.3	0.99
2008	Unconfined	Pre monsoon	Circular	0.05	8.2	0.91
		Post monsoon	Circular	0.15	13.0	0.87
	Semi confined	Pre monsoon	Gaussian	0.002	9.2	0.94
		Post monsoon	Gaussian	0.03	11.3	0.92

### 3.2 Spatial variation of groundwater level

The spatial variability map of groundwater levels in both the aquifers during pre and post monsoon seasons of 1999 and 2008 were generated and are presented in Figure.2 and Figure.3 respectively. The area under different water table ranges is shown in Table 2. It was observed that the water table in most of the area remained below MSL. In general the slope of the hydraulic gradient was from sea to the land side indicating the reversal of hydraulic gradient. The resulting inflow of seawater towards the fresh water aquifer may be the main reason for the increased salinity of groundwater. There was a considerable increase in water table after the monsoon season. The depth to water table increased from 10.44 m below MSL during pre monsoon to 8.25 m below MSL during post monsoon. This clearly indicated that, in case of unconfined aquifer, water table responded quickly to recharge from rainfall. The spatial variability maps of water table in unconfined aquifer for pre monsoon season indicated that in 42.0% and 58.0% of the study area, water table remained within 4.0 m and between 4.0-8.0 m below the MSL. After the monsoon, the area under the above classes changed to 67.8% and 32.2% respectively.

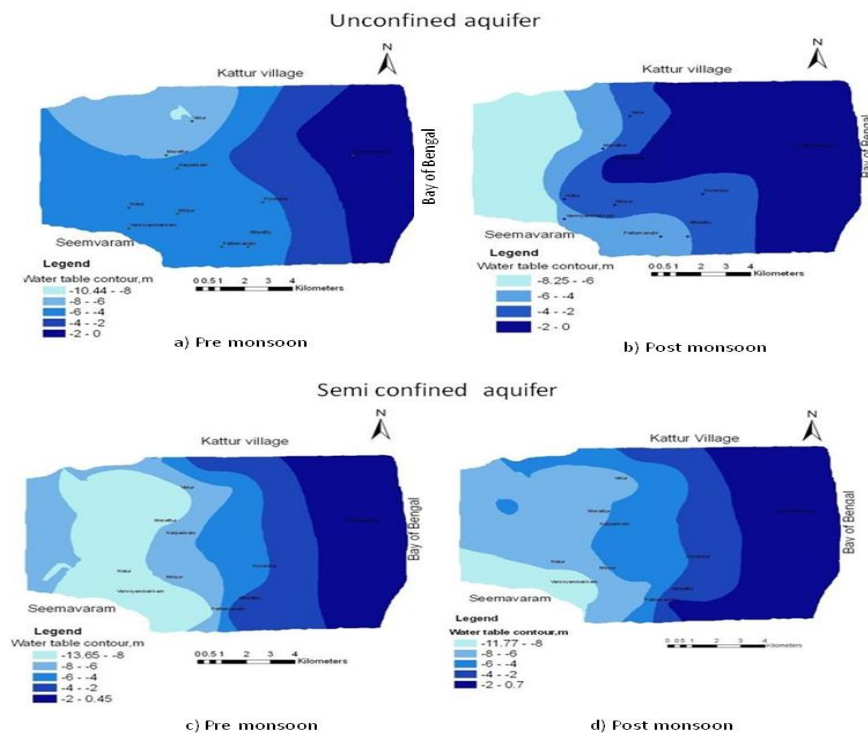
**Table 2** Delineated area under different depth ranges

Aquifer	Water table elevation, below MSL(m)	Area (%) - 1999		Area (%) - 2008	
		Pre monsoon	Post monsoon	Pre monsoon	Post monsoon
Unconfined	Upto 4.0	42.0	67.8	27.0	28.0
	4.0 to 8.0	58.0	32.2	21.0	47.0
	> 8.0	-	-	52.0	25.0
Semi confined	Upto 4.0	43.2	47.4	35.0	37.0
	4.0 to 8.0	31.6	46.0	19.0	26.0
	> 8.0	25.2	6.60	46.0	37.0

Similar analysis undertaken for semi confined aquifer showed that the reverse hydraulic gradient existed in the semi confined aquifer also with much steeper slope than the unconfined aquifer. The maximum depth to piezometric surface was

observed to be 13.65 m below MSL during pre monsoon, which increased to 11.7 m below MSL after the monsoon. The higher depth of piezometric surface in the semi confined aquifer could be attributed to the extensive withdrawal of water by farmers for irrigating crops and extraction by CMWSSB for meeting drinking and industrial needs of Chennai City. The steep gradient of piezometric surface formed by the extensive withdrawal of water was higher in the southern region of the study area. The spatial variability maps of semi confined aquifer during pre monsoon of 1999 showed that in 25.2%, 31.6% and 43.2% of the study area, piezometric surface remained below 8.0 m, within 8.0- 4.0 m and within 4.0 m below MSL respectively. In this aquifer also, the piezometric surface moved upwards after the monsoon season. The area where piezometric surface was below 8.0 m has decreased from 25.2% to 6.6 % after the monsoon season.

Analysis of variability maps of groundwater levels in both the aquifers in the year 2008 showed considerable drop in the groundwater level as compared to the year 1999. In unconfined aquifer, 52.0% of the area showed water table below 8.0 m below MSL, during pre monsoon. Whereas, in 1999, water table remained above this level everywhere. Similar results were also observed in semi confined aquifer. However, the magnitude of decline in the piezometric surface was less in comparison to unconfined aquifer. After monsoon, 37.0% of the study area showed piezometric surface below 8.0 m, in 26.0 % of the area it lied within 8.0- 4.0 m and in 37.0 % of the area, piezometric surface was within 4.0 m. The vertical leakage from the aquitard above the semi confined aquifer may be the reason for the rise in piezometric surface in this layer after the monsoon. Spatial and temporal analyses showed a considerable drop in ground table levels by 2008 compared to 1999.





groundwater management plan in the affected area.

### Acknowledgements

The authors wish to express their sincere thanks to the officials of State PWD, Tamil Nadu for providing the necessary data and help for the study.

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