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Variability of soil–water quality due to Tsunami-2004 in the coastal belt of Nagapattinam district, Tamilnadu

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Abstract

In this study, the Tsunami-caused deterioration of soil and groundwater quality in the agricultural fields of coastal Nagapattinam district of Tamilnadu state in India is presented by analyzing their salinity and sodicity parameters. To accomplish this, three sets of soil samples up to a depth of 30 cm from the land surface were collected for the first six months of the year 2005 from 28 locations and the ground water samples were monitored from seven existing dug wells and hand pumps covering the study region at intervals of 3 months. The EC and pH values of both the soil and ground water samples were estimated and the spatial and temporal variability mappings of these parameters were performed using the geostatistical analysis module of ArcGIS®. It was observed that the spherical semivariogram fitted well with the data set of both EC and pH and the generated kriged maps explained the spatial and temporal variability under different ranges of EC and pH values. Further, the recorded EC and pH data of soil and ground water during pre-Tsunami periods were compared with the collected data and generated variability soil maps of EC and pH of the post-Tsunami period. It was revealed from this analysis that the soil quality six months after the Tsunami was nearing the pre-Tsunami scenario (EC$<$ 1.5 dS m^{-1}; pH$<$8), whereas the quality of ground water remained highly saline and unfit for irrigation and drinking. These observations were compared with the ground scenarios of the study region and possible causes for such changes and the remedial measures for taking up regular agricultural practices are also discussed.

Keywords: Tsunami; Geostatistics; Soil–water quality; Spatial variability; EC and pH; Groundwater; ArcGIS®

1. Introduction

Tsunami-2004 caused the massive inflow of seawater that got impounded over the coastal inland agricultural system (CIAS), and severely affected the soil and water sources of the entire coastal stretches of Tamilnadu district in India (Chandrasekharan et al., 2005). Nagapattinam district was one of the severely affected tsunami-affected regions of Tamilnadu that faced the threat of deterioration of soil and ground water quality. Prior to the Tsunami, the soil–water systems of the Nagapattinam region were suitable for intensive agriculture, and rice, groundnut and vegetable crops were the major crops grown in these areas. It has been observed that the quality of soil deteriorated very fast due to seawater inundation and deposits of sea sediments at discrete locations. However, the soil quality of these regions indicated faster improvement after a good rainfall during March 2005 (Chandrasekharan et al., 2005; DOA, 1998). On the other hand, qualities of both surface and shallow groundwater sources were observed to be unfit for irrigation and domestic purposes. These observations of the soil and ground water quality of the Tsunami-affected regions necessitated collection of the representative samples and spatio-temporal analysis to understand the suitability of land for agriculture and the reclamation period of the Tsunami-affected areas.

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Understanding spatial variability of soil parameters over the land surface requires closely spaced field data and mapping the same on a suitable scale. However, the cost, efforts and time required for collection and analysis of a large number of data sets are not always practicable and economically viable. Development of spatial variability map requires a continuous surface with spatial data values at various locations that can be distributed over closer intervals using a suitable interpolation technique. There are two main groups of interpolation techniques to produce a continuous surface from point measurements; (a) deterministic and (b) geostatistical. Deterministic interpolation techniques create surfaces from measured points using mathematical functions, which are based on either the extent of similarity (e.g., inverse distance weighted, IDW) or the degree of smoothing (e.g., radial basis functions, RBF). Geostatistical interpolation techniques utilize both the mathematical and the statistical properties of the measured points. The basic assumption in using geostatistics to characterize heterogeneity in earth systems is that the properties in the earth are not random, but have some spatial continuity or are correlated over some distance. This implies that a parameter measured at one location provides information about parameter values at other adjacent locations. These concepts in geostatistics are used in modeling the spatial structure of various physical parameters using different semivariogram models. The best fitted semivariogram model is further used in kriging to obtain best linear unbiased estimators of spatially dependent data. Therefore, it is convenient from both the conceptual and the practical standpoints, to deal with regionalized variables such as hydraulic conductivity, water table depth, and soil salinity by using the probabilistic theory of random functions. Also, the geostatistical techniques quantify the spatial autocorrelation among measured points and account for the spatial configuration of the sample points around the prediction location. Recently, geostatistical tools have been applied to the modeling of spatio-temporal distributions in many disciplines such as environmental sciences, ecology, hydrology and soil sciences (Goovaerts et al., 2005; Burrough and McDonnell, 2000). These tools are increasingly coupled with GIS capabilities for applications that characterize space–time structure (semivariogram analysis), spatially interpolate scattered measurements (kriging) to create spatially exhaustive layers of measured parameters. In a review of the research works on spatial variability of the quality aspects of soil and water resources, Lauzon et al. (2005) reported that the spatial variability of soil test Phosphorus (STP), soil test Potassium (STK) and the soil pH for 23 Ontario farm fields could be accurately assessed with the sampling intensity of just 11 samples per hectare or less. They revealed that higher grid sizes resulted in poor prediction of spatial variability. To arrive at this conclusion, they used the GS+ analysis tool to develop semi-variogram models and Surfer to map the variability of STP, STK and Soil pH with different grid spacings. However, they did not use the ArcGIS capability to perform the geo-processing and generation of the variability maps. Sarangi et al. (2005a) used ordinary kriging and co-kriging techniques of geostatistics using the ArcGIS® and GS+ tools to generate the rainfall spatial variability map of St Lucia. Javed et al. (2005) used geostatistical method to determine the degree of spatial variability of soil properties and variance structure, and to model the sampling interval of alluvial floodplain soils. Geostatistical analyses illustrated that the spatially dependent stochastic component was predominant over the nugget effect. Structured semi-variogram functions of each variable were used in generating fine scale kriged contour map. It was observed that a 400 m sampling range would be adequate for detection of spatial structure of sand silt and clay and 100 m for soil hydraulic conductivity. Their study showed that the geostatistical approach resulted in better prediction of soil properties. Sarangi et al. (2005b) applied the geostatistical methods to map the variability of soil phosphorous saturation percentage (P_{sat}%) over the St. Esprit watershed of Quebec, Canada and generated the possible pathways of phosphorous transport using the ArcGIS® tool. It was revealed from their study that 23.5% of the watershed cropped area has reached higher phosphorous saturation level which necessitates judicious phosphorous input management. Elango et al. (2006) developed spatial variability maps using geostatistical concepts to study the variability of the ground water levels and the quality paratmeters (viz. Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_{3-}, HCO_{3-}, Cl^- and EC) of Tsunami-affected coastal areas of Tamilnadu. Their study revealed that the higher concentration of salinity parameters in ground water was observed when the monthly rainfall exceeded 100 mm, which was caused due to leaching of the salts through the vadose zone. However, they have not conducted any variability study related to salinity and pH of the soil in the agricultural fields of Coastal Tamilnadu before and after Tsunami. Keeping in view of the above, the present investigation aims at analysis of the soil and water quality parameters of the Tsunami affected Nagapattinam district of Tamilnadu and development of spatial variability maps for assessment of the cropped areas suitable for taking up agricultural crops after Tsunami.

2. Materials and methods

2.1. Study area and data acquisition

The coastal line of Nagapattinam district extends from *Vedaranyam* (on south) to *Kollidam* (on north) with 100 km distance of separation and located within 79° 50′ 17.9″ E longitude and 10° 30′ 51.3″ N latitude at an elevation of about 35 m above mean sea level (Fig. 1). The annual precipitation of 1200 mm is distributed with 76% and 24% due to the effect of north-east monsoon and during other seasons, respectively. At times, the northeast monsoon brings excess rain causing cyclonic storm once in two or

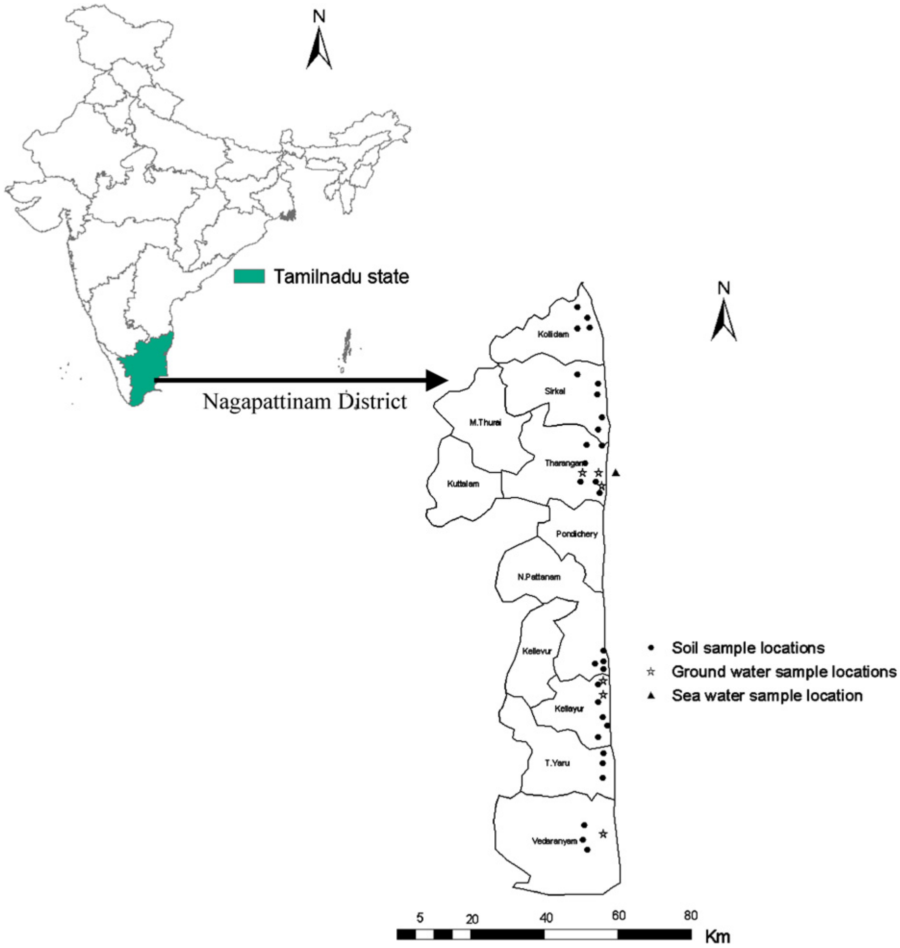

Fig. 1. The location map of the study area along with soil and ground water sampling points in the Tsunami-affected coastal belt of Nagapattinam district, Tamilnadu.

three years causing a rise in the sea level to more than a meter that affects the inlands through backwater channels. Such inland intrusion often extends to a few kilometers and retained for several days till receding of the cyclonic storm. Under these conditions, not only the adjoining agricultural fields are contaminated with salinity and sodicity problems but also the shallow ground water table is affected. The ground water is used for both drinking and irrigation purposes. The recent efforts of prawn culture in these areas also add to such problems.

Accordingly, to understand the spatial variability of soil and water sources, the representative samples from land surface and dug wells were collected during January, April and June 2005 for measurement of specific chemical parameters viz., EC and pH. More than one hundred surface soil samples and 44 water samples (comprising sea, surface and groundwater (dug well and hand pumps)) were collected along the coastal line and analyzed for certain chemical parameters. While collecting samples, the location of the sample acquisition points were recorded by using a hand held geo positioning system (GPS). The geo-locations (latitude and longitude) information acquired through GPS for the investigated locations containing the measured EC and pH values were acquired in the geographic coordinate systems. The geographic coordinates represented in the form of latitude and longitude was then transformed to projected coordinates using the polyconic projection system that encompasses the study region. The Arc Map module of ArcGIS® (Ver. 8.3) was used to perform these transformations, display and edit all the attribute feature classes of the study area. This was done so as to represent the actual spatial distance between points on the study site and use this information for geostatistical analysis. The polygon feature classes representing the district and block boundaries encompassing Nagapattinam and the attribute information of land use, soil type, EC and pH values of the collected samples after the Tsunami-2004 of both soil and ground water locations were added to the map layer (Fig. 1). Subsequently, the generated GIS feature classes having attribute tables populated with EC and pH values were subjected to geostatistical analysis. The recorded EC and pH data of the soil and ground water of pre-Tsunami period were obtained from the report of department of agriculture, Nagapattinam (DOA, 1998) and entered in the Excel spreadsheet for comparison with the post-Tsunami results.

2.2. Geostatistical analysis

The preliminary step of geostatistical analysis was exploratory data analysis (EDA), in which the normality and trend of data, voroni mapping to identify the outliers and semivariogram cloud of the raw data were observed. These steps are essential before using the data for generation of the semivariograms and the kriged maps. The presence of global or local outliers and skewed data distribution generally lead to inaccurate estimation of spatial variability (Burrough and McDonnell, 2000). Therefore, in this study, the collected data were subjected to EDA through data transformations and outlier removal techniques. Using the Arc Map module of ArcGIS®, the polygon feature class of the Nagapattinam district along with the point feature class representing the measured EC and pH values were projected and geo referenced to generate the GIS coverage for subsequent analysis. The EDA techniques carried out using the geostatistical module of ArcGIS® revealed that the data set needed logarithmic transformation to attain normality and there were no outliers present in the data sets. Out of different kriging techniques, the ordinary kriging (OK) methods were used in the present study due to its simplicity and prediction accuracy (Isaaks and Srivastava, 1989; Burrough and McDonnell, 2000; Webster and Oliver, 2001; Johnston et al., 1996). Moreover, it was observed that the OK of a single variable is frequently used to account for data fluctuations over the study region (Burrough and McDonnell, 2000; Webster and Oliver, 2001). Again, due to less number of EC and pH measurement values limiting to 44 data values, the omni directional variogram was adopted in the present analysis which assumed the spatial variability to be identical in the X, Y and Z directions.

The objective of kriging is to predict parameter values at unmeasured locations, x_0, within the system domain D, using information available elsewhere in D (x_1, x_2, …, x_n). This can be carried out by expressing $Z(x_0)$ {where, $Z(x)$: $x \in D$} as a linear combination of the data $Z(x_1)$, $Z(x_2)$, …, $Z(x_n)$, such that

$$\ddot{Z}(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_0), \tag{1}$$

Where, $\lambda_1$is the kriging weight of the parameter value at $Z(x_0)$ for "n" number of nearby sample points to be used in estimation. The optimal weight, λ_1 is calculated such that the estimation of $\ddot{Z}(x_0)$ by $Z(x_0)$ is unbiased and the sum of squares of error is minimized. Ordinary kriging is based on two assumptions. First, the mean of the process is assumed constant and is invariant within the spatial domain. This is expressed as

$$E[Z(x+h) - Z(x)] = 0, \tag{2}$$

where, E is the expectation and $x \in D$ and $x+h \in D$, h being the distance between two points.

Second, the variance of the difference between two values is assumed to depend only on the distance h between the two points, and not on the location x. The variance is given by

$$\mathrm{var}[Z(x+h) - Z(x)] = 2\gamma(h), \tag{3}$$

Where, the function $\gamma(h)$ is the semi-variogram.

Based on these assumptions, the kriging equation is given as (Deutsch and Journel, 1992; Burrough and McDonnell, 2000)

$$\gamma(h,\alpha) = \frac{1}{2N(h,\alpha)} \sum_{i=1}^{N(h)} [Z(x_i+h) - Z(x_i)]^2, \tag{4}$$

Where, $\gamma(h, \alpha)$ = semivariance as a function of both the magnitude of the lag distance or separation vector (h) and its direction (α), $N(h, \alpha)$ = number of observation pairs separated by h and direction α used in each summation, and $Z(x_i)$ = random variable at location x_i.

For OK, the weighing parameter λ_i shown in Eq. (1) is determined to fulfill conditions as presented in Eqs. (2) and Eq. (3) by solving a system of linear equations such as

$$\begin{cases} \sum_{i=1}^{n(x)} \lambda_i(x)\gamma(x_j - x_i) - \mu(x) = \gamma(x_j - x) \ \ j = 1, 2 \ldots n(x), \\ \sum_{i=1}^{n(x)} \lambda_i(x) = 1, \end{cases} \tag{5}$$

Where, $\mu(x)$ is the Lagrangian parameter accounting for the constraint on the weights. The information needed for Eq. (5) is the semivariogram values of γ, which are estimated using Eq. (4). In similar type of studies to estimate the spatial variability of soil parameters, the spherical model is the most widely used semivariogram model and is characterized by the linear behavior at the origin (Deutsch and Journel, 1992; Goovaerts, 2000). The spherical model is given by

$$\gamma(h,\alpha) = \begin{cases} S\left(1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right), & h \leqslant a, \\ S, & h > a, \end{cases} \tag{6}$$

Where $\gamma(h,\alpha)$ is the spherical semivariogram with range parameter, a, and sill, S, for lag distance h.

In this study, the selection of a best semi-variogram model using ArcGIS® was achieved by visual interpretation and confirmation of the model through cross validation statistics. Different combinations of the active lag distance and lag class sizes were tried for getting a best-fit semivariogram model with the fitting statistics (Goovaerts, 2000; Isaaks and Srivastava, 1989). The variogram model was generated and different combinations of active lag distance and lag sizes were tried to arrive at a better fitted variogram model with highest coefficient of determination (R^2) and minimum residual sum square (RSS) value. The best semi-variogram model obtained for the measured locations were used to predict the EC and pH values for the rectangular zone encompassing the measured points and generate the spatial variability maps. The spatial variability maps thus obtained from kriging were partitioned to uniform EC (i.e. EC < 1.5 dSm^{-1}; 1.5 dSm^{-1} < EC < 4 dSm^{-1}; EC > 4 dSm^{-1}) and pH (pH < 7; 7 < pH < 8; pH > 8) ranges for comparison and subsequent geo-processing analysis. The GIS thematic coverage feature classes of EC and pH variability were carried for the measured data values before Tsunami, during January-2005 and during April-2005 to understand the aftermaths of Tsunami on the spatial variability of EC and pH values along the costal blocks of Nagapattinam district.

3. Results and discussion

3.1. Variability of soil parameters

The mean values of measured EC and pH data of soil samples of pre-Tsunami, January-2005, April-2005 and June-2005 for the four severely affected locations are shown in Fig. 2. With reference to pH values, there were slight increase in some locations but in general those variations were not significant. The locations having high pH after tsunami (*Erukkattancheri, Sathangudi, Vellapallam*) may require some amount of gypsum (500–1000 kg/ha) to lower the pH and create a soil environment having calcium and sulphate instead of the deleterious sodium and chloride ions. It was also observed that there was significant increase of the soil EC values immediately after Tsunami in comparison to the pre-Tsunami period. The high salinity was due to sea water ingress, but, due to the rainfall during March-2005, there was flushing of the surface salts that resulted in lowering of EC of the surface soil. Thus the surface soil was suitable for agriculture during April-2005. Moreover, in some fields, the farmers with the help of NGOs have scrapped the thick sediment layer (2–20 cm thickness) like the one at *Vellapallam* and kept as small heaps in the field itself as shown in Fig. 3. Initially it was felt that these have to be thrown back to the sea since the sediments have very high EC and are not suitable for cultivation. Subsequently it was decided to use the pilled sediments for agriculture by spreading over the fields. The decision was taken due to its

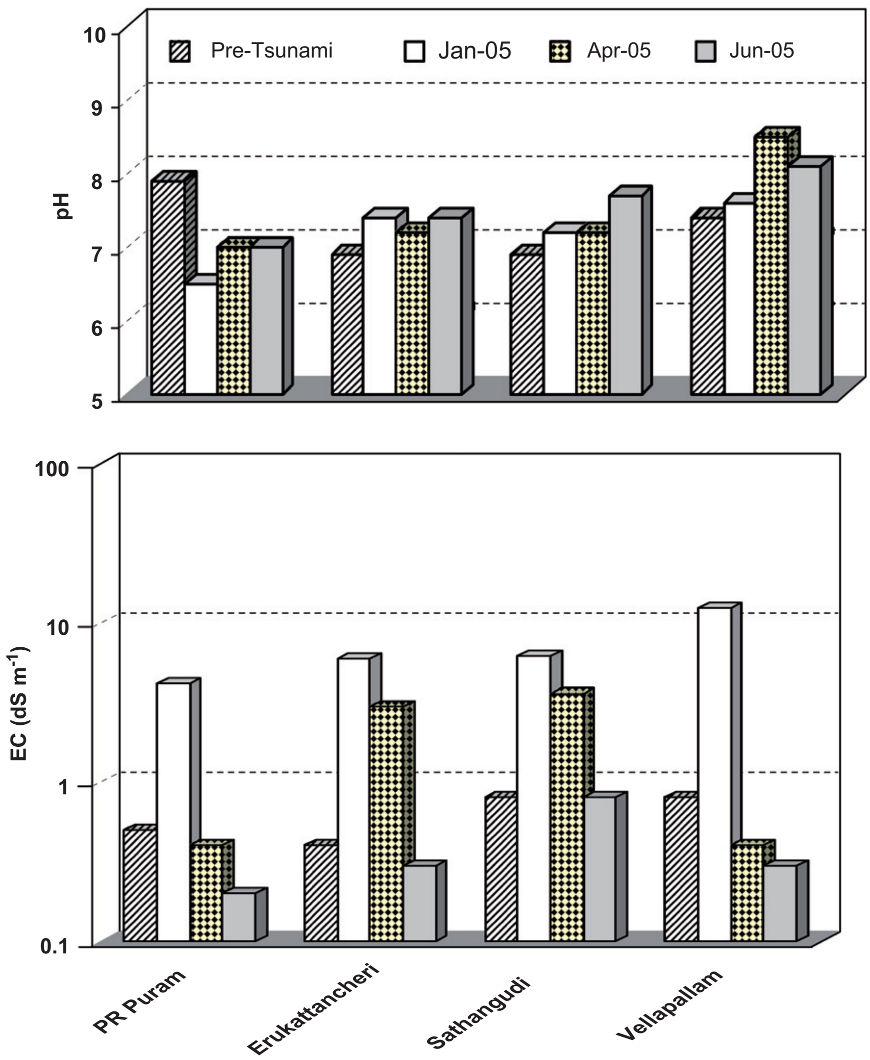

Fig. 2. Temporal variability of pH and EC in the surface soil of selected locations of coastal area of Nagapattinam district.

rich content of minerals and organic matter useful for cultivation besides high EC. Because, the high salinity can be controlled with washing and leaching of salts after heavy showers, which occur quite often in the Nagapattinam district during the north-east monsoon period.

The ArcGIS® assisted analysis for all the data sets of EC and pH revealed that the spherical semi-variogram model fitted well with the data having better fitting statistics ($0.87 < R^2 < 0.91$ and $0.001 < RSS < 0.002$). The spherical semivariogram resulting from the analysis of EC data is shown in Fig. 4. Further, the best fitted spherical semivariogram models for both EC and pH were used for generating the spatial variability maps of EC and pH as per the defined ranges for the data sets for the periods before Tsunami, during January-2005 and April-2005 to compare and study the effects of Tsunami on the soil EC and pH variability (Figs. 5 and 6). It is observed from the spatial variability maps that that pre-Tsunami EC values are less than $1.5\,\mathrm{dS\,m^{-1}}$ all along the coast. The data

Fig. 3. Accumulation of sea sediments deposited by tsunami 2004 over a rice field in Vellapallam, *Vedaranyam* (as on 12th June 2005).

corresponding to January 2005 revealed that a small location (north of *Kellay*) was severely affected (EC $>4\,\mathrm{dS\,m^{-1}}$). Otherwise, in all cases the spread was of EC $<4\,\mathrm{dS\,m^{-1}}$ and soils are generally suitable for agricultural purposes. Interaction with local farmers revealed that although the quality of soil is limping back to pre-Tsunami status, there is severe scarcity of water for irrigation. It is also observed that a part of the areas around *Kollidam*, Sirkali and Tarangambadi, which were having soil EC $<1.5\,\mathrm{dS\,m^{-1}}$ in January 2005 showed a higher ($4<$ EC $>1.5\,\mathrm{dS\,m^{-1}}$) at these locations in April 2005. This could be possible since the area is relatively at a higher elevation and also the fields were left fallow for the past six months.

In respect of pH variations, it was observed that the pre-Tsunami and the January 2005 samples did not show any significant variations (all values <8) and the soil was more or less neutral. However, during April 2005, the soils of southern part of Nagapattinam resulted in a higher pH (i.e. pH >8) and lower EC (i.e. EC $<4\,\mathrm{dS\,m^{-1}}$), which revealed that soils at these locations are becoming alkaline. Depending on soil types, the gypsum of appropriate quantities can be applied before taking up agricultural activities.

3.2. Ground water quality variation

As mentioned under materials and method, 44 water samples from sea, dug well (or *kutcha wells*), hand pumps/bore wells have been collected for the measurements of EC and pH. After computing average values of these parameters, the number of samples were reduced to 13 (seven for groundwater from hand pumps/bore wells and six for dug wells and sea water) and variations of EC and pH are shown in Figs. 7 and 8. The mean depths of water level from ground surface were measured to be at 5 m in dug wells and 10 m in hand pumps. Since there were no

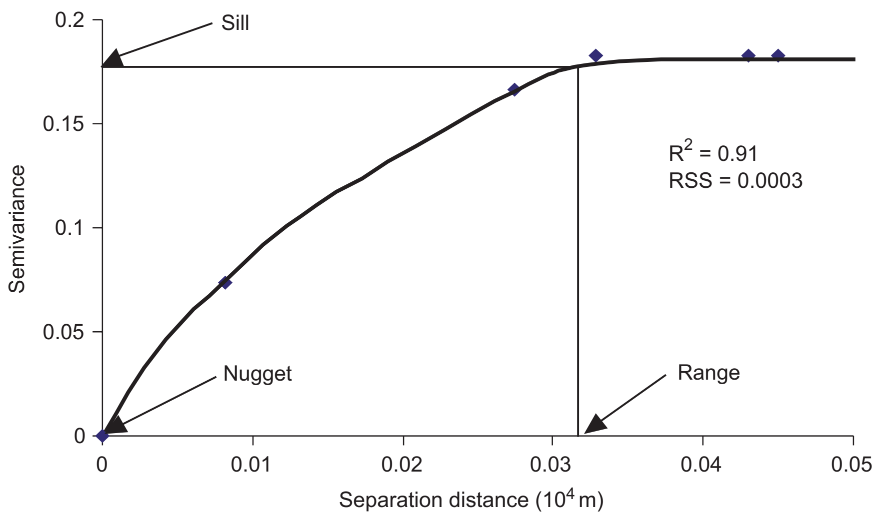

Fig. 4. The best fitted spherical semivariogram parameters representing the soil EC parameter of the study area.

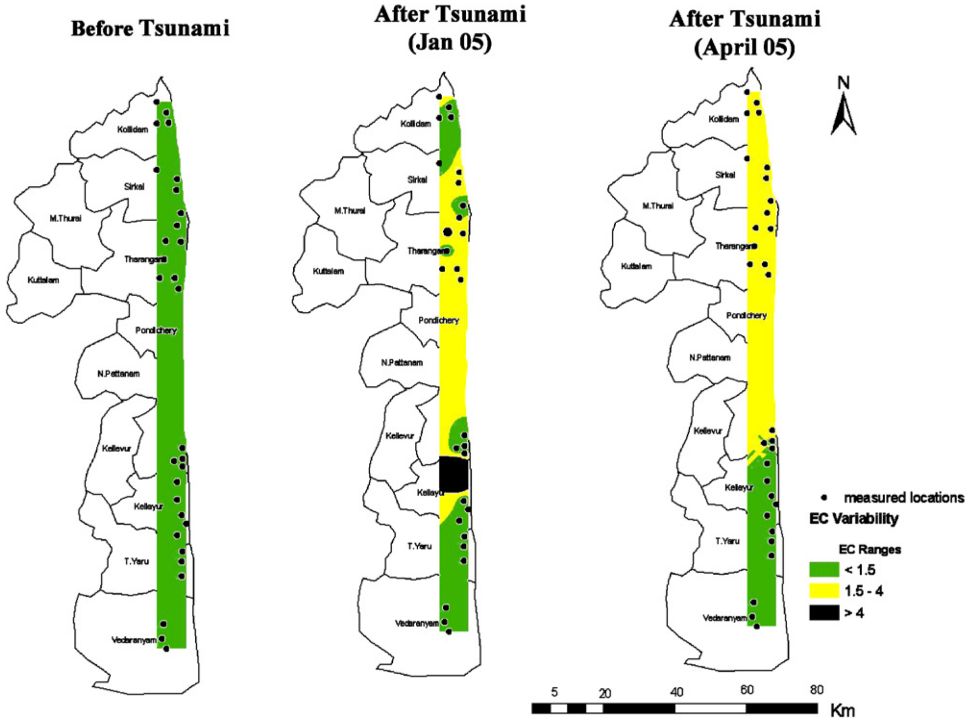

Fig. 5. Spatio-temporal variability of EC in $dS\,m^{-1}$ of surface soil along the Tsunami-affected Nagapattinam Coast of Tamilnadu, India.

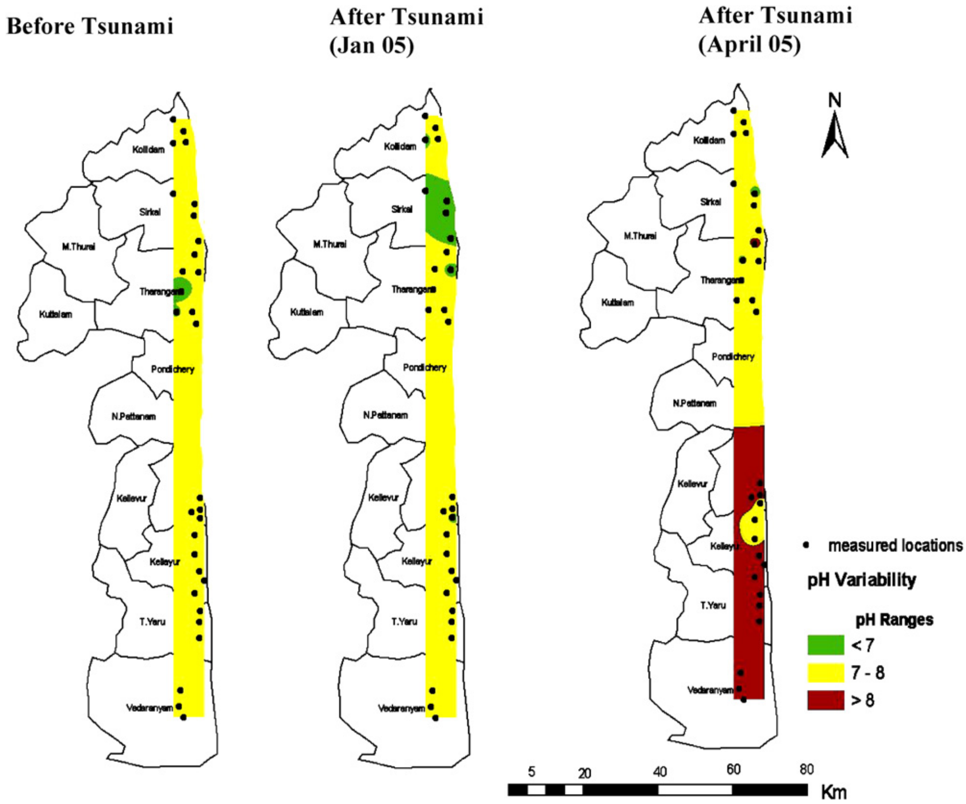

Fig. 6. Spatio-temporal variability of pH of surface soil along the Tsunami-affected Nagapattinam Coast of Tamilnadu, India.

secondary data prior to Tsunami, we do not have much information on water table depths and quality of ground water at these locations. However, from the secondary sources, it was reported that the ground water was fit for irrigation and drinking purposes before Tsunami. However, after Tsunami, the quality deteriorated (EC $>20\,dS\,m^{-1}$). Here, the EC of dug wells were about 5 to 10 times that of bore wells, which means that the quality of

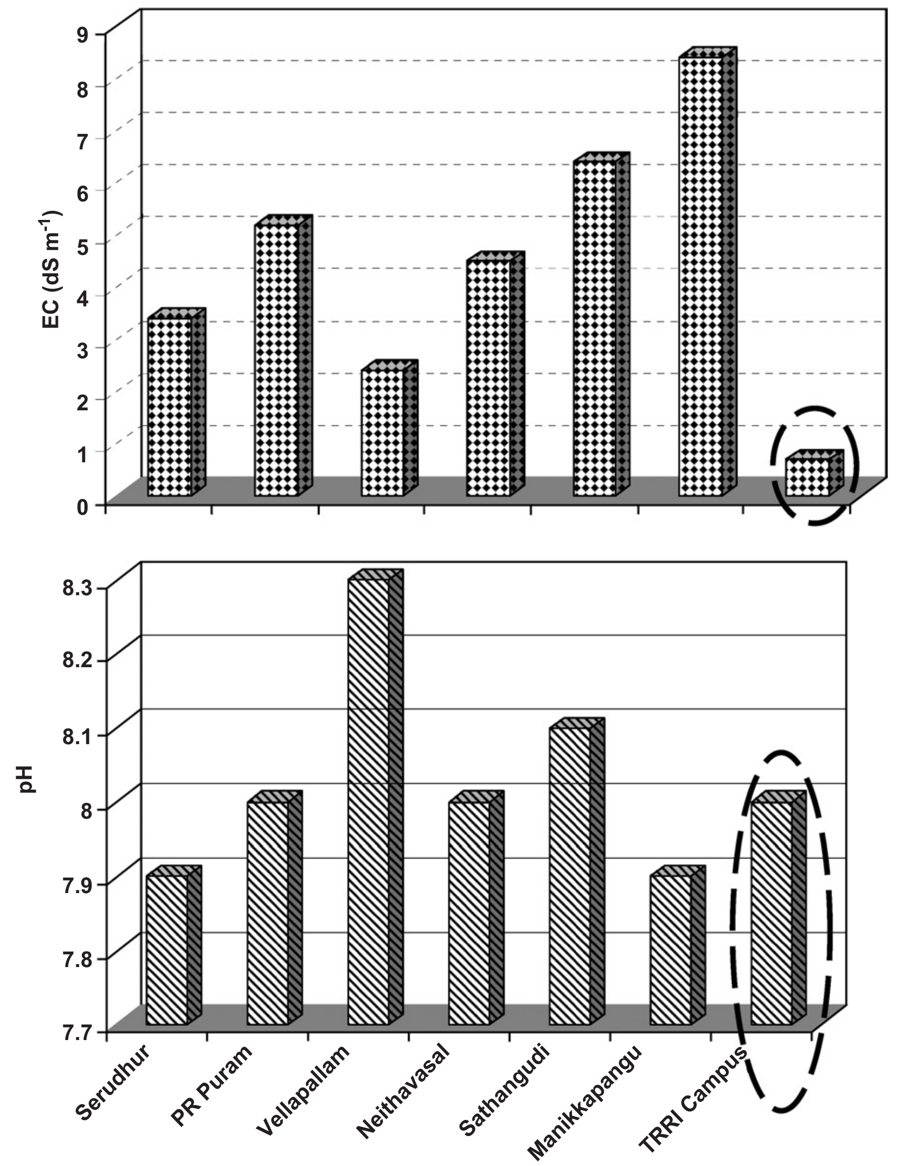

Fig. 7. EC and pH variations of ground water at selected locations (The TRRI campus location in both the figures represent the unaffected area).

ground at intermediate depths (>10 m) was better than that at shallow depths (<5 m) in *kutcha wells*. This was because of the mixing of sea water with dug wells directly whereas hand pumps/bore wells tap water from confined aquifer with recharge zone at distant locations. A close look at Figs. 6 and 7 reveal that although EC of groundwater at *Aduthurai* is $<1\,dS\,m^{-1}$, the pH is >7.5 which indicated that the water is alkaline in nature. The same is true for *Vellapallam* village in *Vedaranyam* block. In any case, both *kutcha* wells and hand pumps located in the coastal areas were not suitable for both irrigation and drinking. It appeared that occurrence of high intensity precipitation events could flush out the dissolved salts or can dilute the water of dug wells. Moreover, it was reported that there was marginal decrease of salinity of water in a dug well near *Pratabaramapuram* village, after two periodic cleaning operations during the past three months. This could be due to the higher recharge of saline water into the well from the adjoining areas. As the quality of both surface soil and groundwater were not of good quality, certain remedial measures need to be undertaken by the farmers, NGOs and governmental agencies for bringing back the Tsunami affected agricultural fields under production process.

4. Conclusions

In this study, the soil and ground water samples from different locations of the Tsunami-affected coastal region of Nagapattinam district, Tamilnadu were collected in a gap of three months and the geostatistical techniques were employed to understand the spatio-temporal variability of the EC and pH parameters. It was revealed that the soil salinity and pH of the majority of agricultural regions were

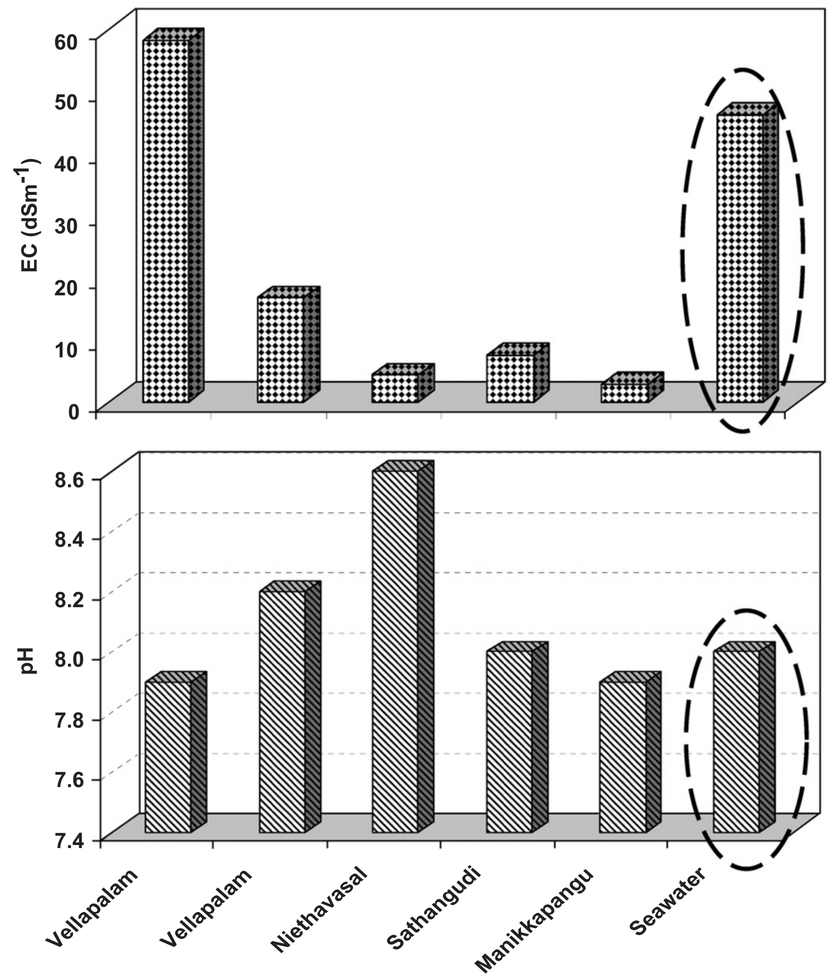

Fig. 8. Tsunami induced EC and pH variations of dugwell locations compared with seawater.

becoming suitable for agricultural production by June 2005. However, a couple of blocks were still observed to display EC value close to $4\,dS\,m^{-1}$, in which the salt tolerant varieties could be taken up to enhance the agricultural productivity. However, there was a significant increase in the pH of the soil towards the southern part of the district, which necessitated application of gypsum to reclaim the land for agricultural production. Moreover to reclaim the coastal agricultural belt from the aftermath of Tsunami-2004, effort should be made to adopt both the short term and long-term strategies. The short-term strategies include adoption of improved crop varieties and water management practices. In the case of long-term strategies, both new investment and renovation options are indicated. The major components under new investments should include construction of agricultural field drainage technologies, provision of water harvesting structures in non-command areas and construction of dug wells and drip and sprinkler irrigation systems for management of saline and sodic soils. Whereas, under renovation strategies, the measures include the renovations of defunct tanks and ponds, repair and maintenance of shutters, desilting of drainage channels and wells, tail end regulators of field channels and watercourses including the masonry works in the water conveyance, control and diversion structures. Nonetheless, considering the study objectives, the variability map generated using ArcGIS® based geostatistical approaches using minimal data could be used to devise the short and long term reclamation measures for the Tsunami-affected agricultural fields of Nagapattinam district, Tamilnadu.

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