SEASONAL CHANGES IN GROUNDWATER QUALITY AND ITS SUITABILITY FOR DRINKING AND IRRIGATION USES

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ABSTRACT: This study deals with evaluation of spatial and short-term temporal variation of groundwater quality during pre- and post-monsoon seasons in Jaipur district of Rajasthan by using statistical techniques, i.e. box and whisker plots, correlation matrices, and t-test, to the data collected for 153 sampling sites. In addition, this study assesses the groundwater quality to find its aptness for drinking and irrigation needs by comparing with drinking water standards prescribed by World Health Organization (WHO), and by plotting United States Salinity Laboratory (USSL) diagrams. Data of 13 groundwater quality parameters, i.e. calcium, magnesium, sodium, potassium, sulphate, chloride, nitrate, carbonate, bicarbonate, fluoride, total dissolved solids (TDS), electrical conductivity (EC) and pH, were analyzed for two seasons of four-year (2006-2009) period. The box and whisker plots revealed presence of non-normality in spatial series of almost all the parameters due to right-skewed distributions in both seasons. The box-whisker plots also revealed linkages between the water quality parameters and rainfall recharge occurring in aquifer system. Correlation matrices depicted a very strong linear relationship between seven pairs of the groundwater quality parameters, i.e. EC-TDS, EC-sodium, EC-chloride, TDS-sodium, TDS-chloride, pH-carbonate, and sodium-chloride during both seasons. However, magnitude of correlation was relatively less during the post-monsoon season as compared to pre-monsoon season. Results of t-test revealed a significant change in the mean concentrations of six parameters, i.e. pH, sodium, calcium, bicarbonate, nitrate, and fluoride at 5% significance level during pre-monsoon season in 4-year period. On the other hand, during post-monsoon season, only nitrate showed a significant change in 4-year period. Moreover, the groundwater quality in the area is not found safe for drinking purpose based on WHO standards as well as for irrigation use based on USSL diagrams. This finding emphasizes the need of formulating adequate policies in order to preserve and improve the groundwater quality in the area.

Key words: Correlation matrix; Drinking; Groundwater quality; Irrigation; Normality; Seasonal variability; t-test, US Salinity Laboratory diagram, World Health Organization.

1. INTRODUCTION

Groundwater, the vital source for drinking, irrigation and industrial purposes especially in arid and semi-arid regions of the world, is currently fast-depleting along with deteriorated quality due to its overexploitation at alarming rates. The groundwater quality is affected by natural factors as well as by anthropogenic activities (Helena *et al.*, 2000; Chan, 2001; Machiwal and Jha, 2015). Assessment of groundwater quality at both spatial and temporal scales is imperative for managing this vital resource in water-short regions. Several tools/techniques are described in standard textbooks on groundwater/hydrogeology to understand spatial and temporal distribution of groundwater quality (Karanth, 1987; Sara and Gibbons, 1991). Machiwal and Jha (2010) presented state-of-the-art techniques for water quality interpretation. Elci and Polat (2011) evaluated seasonal changes in groundwater quality by applying statistical tests in a karstic aquifer system near Izmir-Turkey, and found that except an increase in electrical conductivity (EC) and aluminium, none of the parameters changed significantly. Machiwal *et al.* (2011) employed long-term and multi-site annual data to assess groundwater quality in Udaipur, Rajasthan by using geographic information system (GIS) technique, and found it to be suitable for drinking and irrigation purposes. Dhak *et al.* (2012) evaluated groundwater suitability for drinking and irrigation uses using conventional techniques. Agca (2014) determined physicochemical properties of groundwater and their spatial variability in Amik plain of South Turkey by using t-test. It was found that calcium, magnesium, sulphate and hardness were significantly low during June compared to those in September month. Adhikari *et al.* (2014) characterized groundwater quality of Delhi, India and developed spatial distribution map of fluoride (F) using GIS-based kriging technique. The results indicated a definite pattern in F distribution with low values over river sides. Adhikary and Biswas (2011) suitably applied ordinary kriging for spatial assessment of groundwater quality in Datia district of Bundelkhand, which suggested that groundwater pollution was very low to medium in the southern and western portions, and comparatively good groundwater quality in the northern portion.

The groundwater is the major source of irrigation supplies in arid and semi-arid regions of India, and is vulnerable to salinity and sodicity problems reducing the crop productivity (Kamra *et al.,* 2002). In Rajasthan, the groundwater resources are under severe risk of fast depletion and degradation due to its indiscriminate withdrawal at large scale. Jaipur district (study area) of Rajasthan, is currently facing rapid urbanization and industrialization (Tatawat and Chandel, 2008), which along with increased population growth during the last few decades has resulted in crumbling of existing groundwater supply and sanitation systems. In past, most of the urban drinking water requirements were generally met by surface water sources, e.g. Ramgarh Lake. However, at present, more than 95% of urban water supplies are contributed by groundwater sources resulting in continuous lowering of groundwater levels and degradation of water quality (CGWB, 2007). No systematic study is carried out till now to evaluate quality of the groundwater resources in the area. Looking at the groundwater problems of the study area, the present study was undertaken to explore seasonal variations of the groundwater quality by using statistical techniques and to find its suitability for drinking and irrigation uses by employing water quality standards and US Salinity Laboratory diagrams.

2. MATERIALS AND METHODS

Study Area

Jaipur district (study area) is situated in northeast part of Rajasthan, which is the largest and driest state of India (Fig. 1). It is located between 26°25´ and 27°51´ North latitude and 74°55´and 76°10´ East longitude covering an area of about 10878 km^2. The district consists of 13 blocks and covers about 3.23% area of the state. Climate of the study area is dry and semi-arid, having extremes of cold and heat during winter and summer seasons, respectively with the mean minimum, maximum and mean air temperatures of 3°C, 45°C, and 24°C, respectively. The mean annual rainfall in the district is 548.2 mm, about 90% of which is received during the rainy season from June-September. Total annual potential evapotranspiration is 1744.7 mm (CGWB, 2007). In the study area, irrigated cultivation takes place in about 35.27% area. Depth of wells in the study area generally varies from 50 to 100 m in alluvium and 50 to 200 m in consolidated formation areas. Specific capacity of wells varies from 58 to 500 liters per minute per meters. Transmissivity value and storage coefficient varies from 10 to 850 m^2 day^{-1} and 4.70×10^{-5} to 1.05×10^{-3}, respectively (CGWB, 2007).

Data Collection

Groundwater samples were collected from 153 sites during pre- and post-monsoon seasons of four years (2006-2009). The samples were analyzed for 13 water quality parameters, i.e. calcium, magnesium, sodium, sulphate, chloride, nitrate, carbonate, bicarbonate, fluoride, total dissolved solids (TDS), electrical conductivity (EC), and pH. The data were collected from the Central Ground Water Board, Western Regional Office, Jaipur. The data were not available for post-monsoon seasons of 2007 and 2008. All the collected data were checked for regularity without any gaps and error-free groundwater quality parameters were used for subsequent analyses.

Exploring Distribution of Groundwater Quality Parameters over Space and Time

Box and whisker plots for spatial series of 13 groundwater quality parameters were drawn for pre- and post-monsoon seasons of four years (2006-2009). A box and whisker plot is useful for visualizing important statistical qualities of a time series. Box plots are useful in situations where it is not necessary or feasible to portray all the details of a time series distribution. A box and whisker plot is composed of a central box with a square and a line in the box and two lines extending out from each end of the box called whiskers. The square or line within the box represents the median. The bottom and top horizontal lines in the box indicate the 25th and 75th percentile, respectively, of the statistics computed from the observed data. The length of the central box indicates the spread of the bulk of the data (the central 50%) while the length of the whiskers show the extent of the rest of the data. Details about the box and whisker plots can be found in USEPA (2006) and Machiwal and Jha (2012).

Evaluating Relationships between Water Quality Parameters

Linear relationships between all pairs of 13 groundwater quality parameters were evaluated by computing correlation matrix. The correlation matrix is a bivariate method, which measures the closeness of the relationship between chosen independent and dependent variables in terms of Spearman correlation coefficient (Machiwal and Jha, 2010). If the correlation coefficient is nearer to +1 or -1, it shows the probability of linear relationship between two variables x and y. In literature, correlations among water quality parameters are computed in order to provide a mechanism for prediction or forecasting (Kumar and Sinha, 2010; Patil and Patil, 2010; Jothivenkatachalam et al., 2010). For any two parameters, of n sample size, with $\bar{x}_1$ and $\bar{x}_2$ as their respective means, and s_1 and s_2 as their standard deviations, respectively, the correlation coefficient is computed as:

$$R = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}(x_i - \bar{x}_1)(x_j - \bar{x}_2)}{(n-1)s_1 s_2} \quad (1)$$

Analyzing Changes in Seasonal Groundwater Quality over four-Year Period

Four-year changes separately for pre- and post-monsoon seasons' groundwater quality from 2006 to 2009 period were analyzed in 13 parameters by applying student's t-test. For any water quality parameter, values during two years, i.e. 2006 and 2009, over number of sites are x_i ($i = 1, 2, \ldots, n_1$) and x_j ($j = 1, 2, \ldots, n_2$), respectively. The sample size for the two spatial series were n_1 and n_2 such that $n = n_1 + n_2$. The first series x_i ($i = 1, 2, \ldots, n_1$) had a mean μ_1, and standard deviation s_1, and the second subseries x_j ($j = 1, 2, \ldots, n_2$), had the mean μ_2 and standard deviation s_2. The simple t-test was used to examine the null hypothesis $\mu_1 = \mu_2$ when the two water quality series of the years 2006 and 2009 had the same standard deviation. Rejection of the null hypothesis was considered as significant change in the groundwater quality for a particular parameter. The test-statistic for t-test is defined as (Snedecor and Cochran, 1980):

$$ts = \frac{|\bar{x}_2 - \bar{x}_1|}{S\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{2}$$

where $$S = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n - 2}} \tag{3}$$

where, $\bar{x}_1$, $\bar{x}_2$, s_1^2 and s_2^2 are the estimated means and variances of the 2006 and 2009 groundwater quality series, respectively. Critical values of this test-statistic were taken from standard tables of student's t-distribution for 'n-2' degrees of freedom at 5% significance level. If the computed value of the test-statistic was greater than its critical value, then the null hypothesis, of both the seasonal water quality series belong to the same population, was rejected.

Assessment of Groundwater Quality for Drinking and Irrigation Uses

The groundwater quality in the study area was assessed to find its suitability for the drinking and irrigation purposes. The World Health Organization (WHO, 2006) has prescribed certain values for the maximum desirable limit (MDL) and the maximum permissible limits (MPL) of salient water quality parameters such as calcium, magnesium, sodium, chloride, sulphate, and bicarbonate. The percentage sites having the water quality parameters within MDL and MPL, and exceeding MPL/MPL are computed to find suitability of the groundwater for drinking purpose. Likewise, suitability of the groundwater for irrigation is determined by adopting criteria proposed by US Salinity Laboratory (USSL, 1954) that is based on sodium and salinity hazard. The sodium hazard in irrigation water is evaluated by determining SAR, which is given as (Karanth, 1987):

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{(\mathrm{Ca} + \mathrm{Mg})/2}} \tag{4}$$

where the concentrations are expressed in meq/L (milliequivalents per litre).

3. RESULTS AND DISCUSSION

Spatial and Temporal Variation of Groundwater Quality Parameters

Box and whisker plots of 13 groundwater quality parameters were drawn for pre- and post-monsoon seasons of years as shown in Fig. 2. It is seen from Fig. 2 that there exists large variation in spatial distribution of almost all the quality parameters over different seasons and years. An important finding of the box and whisker plots is presence of outliers and extremes towards the upper whisker for all the parameters, which indicates that the spatial series of all the parameters are right-skewed. This finding clearly suggests that spatial series of all the groundwater quality parameters do not follow normal distribution. It is further depicted from Fig. 2 that length of the upper whisker is larger than that of the lower whisker, which reveals that the distribution density of the first 25% of the data is more compared to density of the data distribution in the last quartile, i.e. 75-100%. This finding further supports the presence of non-normality in groundwater quality parameters.

On comparing median values and distribution of middle 50% of the data (as indicated by size of the boxes) of the parameters over different seasons and years, it can be seen that pattern of the box plots is almost similar over different seasons for all the groundwater quality parameters except pH, potassium, calcium and fluoride. These four parameters require careful attention in monitoring of the groundwater quality due to greater temporal variation.

It is discernible from Fig. 2 that median values or box size of concentration of almost all parameters remain low during post-monsoon season compared to those during pre-monsoon season in the year 2006. This may be attributed to large quantities of freshwater recharge resulting in response to heavy rainfall (978.6 mm) received during the rainy season, which lowered the concentration of the most parameters in the underlying aquifer. On the contrary, the parameter concentration and median values remained lower in pre-monsoon season of 2009 and increased or remained stable during the post-monsoon season. This is most-likely due to very less rainfall (250.4 mm) received during the rainy season of 2009 leading to extraction of huge quantities of the groundwater for providing life-saving irrigation to Kharif season crops. Withdrawal of the groundwater at large scale resulted in significant decline in the groundwater levels and deterioration of the groundwater quality.

Linear Correlations among Groundwater Quality Parameters

Two correlation matrices showing values of the correlation coefficients (r) between pairs of groundwater quality parameters during pre- and post-monsoon seasons of four years are presented in Tables 1 and 2, respectively. Both the matrices indicate magnitude of the linear relationships between pairs of 13 water quality parameters namely EC, TDS, pH, Na, K, Ca, Mg, Cl, SO_4, CO_3, HCO_3, NO_3, and F. The relationship between the parameters was classified into three classes according to r-values as (i) strong ($1>r>0.75$), (ii) moderate ($0.5<r<0.75$), and (iii) weak ($r<0.25$).

It can be seen from Table 1 that strong positive correlation during the pre-monsoon season occurred between pairs of EC-TDS, EC-sodium, EC-chloride, TDS-sodium, TDS-chloride, pH-carbonate, and sodium-chloride. The strong positive correlation between EC and TDS is well-known as EC is computed by using amounts of total dissolved solids in the groundwater. The strong positive relationships of EC with both sodium and chloride indicate abundance of sodium chloride in the groundwater, which is further confirmed by the strong positive relationship between sodium and chloride. The strong linear relationship of EC with sodium and chloride in the groundwater indicates that salinity of the groundwater is mainly due to the presence of sodium chloride. The moderate relationship exists for the pairs of EC-magnesium, EC-sulphate, TDS-sulphate, Na-sulphate, Na-bicarbonate, Na-fluoride, and magnesium-chloride. The moderate relationship of sulphate with EC, TDS and sodium indicates dissolution of weathered rocks in hard-rock terrain of the area. Also, moderate relationship of EC and TDS with sulphate indicates that presence of sulphate may reasonably responsible for salinity of the groundwater.

Results summarized in Table 2 shows a strong positive relationship during the post-monsoon season between pairs of EC-TDS, EC-sodium, EC-chloride, TDS-sodium, pH-carbonate, and sodium-chloride. It is clearly seen that pairs of the water quality parameters having the strong positive relationship remains almost unchanged over the years and do not change from pre-monsoon to post-monsoon season in the study area. During post-monsoon season, the moderate relationship exists for the pairs of EC-magnesium, EC-sulphate, TDS-chloride, TDS-sulphate, pH-bicarbonate, sodium-sulphate, magnesium-chloride, magnesium-sulphate, chloride-sulphate, carbonate-bicarbonate, and bicarbonate-fluoride. It is apparent that the salinity of the groundwater during post-monsoon season is due to sodium chloride and magnesium sulphate. Similar findings were observed for the pre-monsoon season. Generally, the post-monsoon season in a particular year seem to be characterized by a dilution in comparison to pre-monsoon season, if adequate (more than mean) annual rainfall, is received in that year.

Changes in Seasonal Groundwater Quality

Results of the t-test indicating significant/non-significant changes in 13 groundwater quality parameters over a period of four years (2006-2009) separately for pre- and post-monsoon seasons are presented in Tables 3 and 4, respectively. It is revealed from Table 3 that during the pre-monsoon season, the computed test-statistic value is more than the critical test-statistic value for six groundwater quality parameters (pH, sodium, calcium, bicarbonate, nitrate, and fluoride). Hence, null hypothesis of no significant change is to be rejected and it is concluded that the mean concentrations of the above six groundwater quality parameters have changed significantly over three-year period during the pre-monsoon season in the area at 5% significance level. However, temporal change in the mean parameter concentrations over three years was observed to be non-significant for the remaining seven parameters (EC, TDS, potassium, magnesium, chloride, sulphate, and carbonate) at 5% significance level. It is also clear from Table 4 that during the post-monsoon season, the computed test-statistic values are less than their critical values at 5% significance level for all the groundwater quality parameters except for nitrate. For the nitrate, the computed test-statistic value is higher than the critical test-statistic value. Thus, except nitrate, the mean values of all other 12 groundwater quality parameters did not change significantly during the post-monsoon season over three-year period.

It is clear from the above discussion that over a period of four years, more number of parameters showed a significant change in their mean concentration values during pre-monsoon season as compared to that during the post-monsoon season. During post-monsoon season, the groundwater levels are generally situated at relatively shallow depths after being augmented from the recent rainy season groundwater recharge. The recharge of the groundwater usually reduces the concentrations of the chemical parameters. As the season proceeds towards the dry season (pre-monsoon season), the groundwater levels starts declining due to pumping, leading to increase in the concentrations of the groundwater quality parameters. The significant change in the mean concentrations of the more quality parameters during the pre-monsoon season reflect deeper groundwater levels in the study area. This suggests a further study in this direction in the study area to confirm the results.

Suitability of Groundwater for Drinking and Irrigation Needs

Percentage sites having values of six groundwater quality parameters within the MDL and MPL, and exceeding MDL/MPL over pre-monsoon (2006-2009) and post-monsoon (2006 and 2009) seasons are shown in Table 5. It is seen from Table 5 that the calcium concentration at more than 96% sites remains within the MDL of 3.74 meq/l prescribed by WHO (2006) for drinking water standards, and at rest 4% or less sites, the Ca concentration is within the MPL of 9.98 meq/l in the area. Similarly, the concentration of sulphate remains within the MPL (8.33 meq/l) at more than 97% sites, and exceeds the MPL for 3% sites at the maximum. The concentration of magnesium also remains within the MPL (12.34 meq/l) at more than 96% of the sites. Sodium and chloride concentrations remain within the MDL of 8.7 and 5.64 meq/l at 35-54% and 49-60% of the sites, respectively. However, the chloride concentration exceeds the MPL at 16-19% of the sites. Bicarbonate concentration exceeds the MDL (4.92 meq/l) at 27-43% of the sites. From the above results, it is revealed that calcium, magnesium and sulphate do not exceed the permissible limits of the drinking water at almost all the sites. However, sodium, chloride and bicarbonate exceed their maximum permissible limits at considerable number of sites. Therefore, the entire groundwater in the study area may not be considered as safe for drinking purpose.

The USSL diagrams for the groundwater sites for 4 pre-monsoon and 2 post-monsoon seasons are shown in Figs. 3 (a-f). It is depicted from this figure that relatively large number of sites exists in C4-S4 class in all the seasons, which indicates that the groundwater at most of the sites contains ‘very high salinity’ and ‘very high sodium’. Distribution pattern of the groundwater quality sites on the USSL diagrams is more or less identical over the years. However, proportion of the sites in the worst water quality class (C4-S4) slightly decreases over the seasons. On comparing salinity and sodium hazards over the seasons, it is observed that sites having ‘medium’ sodium hazard increases from 25% in pre-monsoon to 36% in post-monsoon season of the year 2006 whereas the sites with ‘low’ sodium hazard decreases from 50% to 40%. On the contrary, in the year 2009, sites having ‘medium’ sodium hazard decreased from 27% to 23% with corresponding 3% increase in sites with ‘low’ sodium hazard. Likewise, the ‘very high’ salinity hazard decreased from 41% sites in pre-monsoon to 34% sites in post-monsoon in the year 2006; however, the sites having ‘very high’ salinity hazard increased from 28% in pre-monsoon to 31% in post-monsoon season of the year 2009. The above results suggest high variability in the groundwater quality parameters over different years. Furthermore, the groundwater quality is not found to be suitable for irrigation purpose at large number of sites in the area. Therefore, the groundwater quality is not safe for drinking as well as irrigation purposes, and there is need to frame adequate policies and to implement suitable strategies for managing the groundwater quality in the area.

4. CONCLUSIONS

The main intent of this study was to explore spatial and temporal variations in pre- and post-monsoon groundwater quality, and to assess its suitability for drinking and irrigation purposes in Jaipur district of Rajasthan. A total of 13 groundwater quality parameters were analyzed by statistical techniques such as box and whisker plot, correlation matrix method and t-test, to study the spatial and temporal variability of the groundwater quality. The box and whisker plots revealed the spatial distribution of almost all groundwater quality parameters to be right-skewed; reflecting non-normality in the data over space. The box plots also depicted that the groundwater quality is largely controlled by the rainfall in the area. Dilution of salts in groundwater occurred due to freshwater recharge from surplus rainwater in the year 2006. However, in the year 2009, very less rainfall occurred over the area, which resulted in reduced groundwater recharge and enhanced groundwater pumping during Kharif season which ultimately led to deterioration of groundwater quality. Amongst 13 parameters, a strong correlation in the pre-monsoon season was observed between EC and TDS, sodium and chloride, TDS with sodium and chloride, pH with carbonate, sodium with chloride. On the other side, in post-monsoon season, a strong correlation existed in EC with sodium and chloride, TDS with sodium, pH with carbonate and sodium with chloride. It was apparent that sodium chloride and magnesium sulphate were responsible for salinity of the groundwater. Results of t-test revealed a statistically-significant decrease in the value of pH, sodium, calcium, bicarbonate, nitrate and fluoride at 5% significance level during pre-monsoon season over a period of three-year period (2006 to 2009). However, in the post-monsoon season, nitrate was found to be significantly changing over three-year period. The findings of this study are very useful for the planners and decision-makers in the area to formulate appropriate strategies to protect the precious groundwater resources from deterioration. Finally, this study illustrates that statistical methods are an excellent exploratory tool for interpreting complex groundwater quality data sets and for understanding spatial and temporal variations, which are useful and effective for water quality management. Furthermore, the parameters of calcium, magnesium and sulphate were found to be within the maximum permissible limits prescribed by the World Health Organization at almost all the sites. However, three parameters, i.e. sodium, chloride and bicarbonate exceeded the desirable/maximum limits at relatively large number of sites. The US Salinity diagrams represented a large number of sites having 'very high' salinity and sodium hazards. Therefore, the groundwater quality in the area is not found safe for drinking as well as irrigation uses. This finding emphasizes the need of formulating adequate policies in order to preserve and improve the groundwater quality in the area.

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Table 1. *Correlation matrix for groundwater quality parameters of pre-monsoon season*

	EC	**TDS**	**pH**	**Na**	**K**	**Ca**	**Mg**	**Cl**	**SO_4**	**CO_3**	**HCO_3**	**NO_3**	**F**
EC	1												
TDS	**0.93**	1											
pH	0.26	0.20	1										
Na	**0.95**	**0.94**	0.30	1									
K	0.16	0.16	-0.05	0.13	1								
Ca	0.19	0.17	-0.08	0.07	0.15	1							
Mg	0.51	0.48	-0.08	0.35	0.14	0.36	1						
Cl	**0.91**	**0.88**	0.08	**0.87**	0.16	0.25	0.64	1					
SO_4	0.51	0.58	-0.04	0.53	0.22	0.14	0.32	0.45	1				
CO_3	0.36	0.33	**0.86**	0.42	-0.01	-0.10	-0.08	0.14	0.03	1			
HCO_3	0.46	0.42	0.28	0.54	-0.04	-0.07	-0.11	0.20	0.14	0.37	1		
NO_3	0.05	0.04	0.04	0.07	0.02	0.01	-0.03	-0.01	-0.07	0.03	0.21	1	
F	0.44	0.47	0.27	0.52	0.04	-0.02	-0.05	0.32	0.27	0.32	0.50	0.05	1

Note: Figures in bold face indicate very strong correlation.

Table 2. *Correlation matrix for groundwater quality parameters of post-monsoon season*

	EC	**TDS**	**pH**	**Na**	**K**	**Ca**	**Mg**	**Cl**	**SO_4**	**CO_3**	**HCO_3**	**NO_3**	**F**
EC	1												
TDS	**0.75**	1											
pH	0.06	0.06	1										
Na	**0.83**	**0.76**	0.27	1									
K	0.18	0.17	0.05	0.17	1								
Ca	0.22	0.18	-0.10	0.18	0.23	1							
Mg	0.54	0.44	-0.24	0.42	0.17	0.31	1						
Cl	**0.93**	0.69	-0.12	**0.77**	0.21	0.31	0.69	1					
SO_4	0.70	0.59	-0.01	0.67	0.22	0.27	0.61	0.69	1				
CO_3	0.22	0.19	**0.85**	0.38	0.07	-0.11	-0.18	-0.01	0.04	1			
HCO_3	0.17	0.18	0.52	0.36	-0.05	-0.13	-0.23	-0.07	-0.09	0.59	1		
NO_3	0.47	0.27	-0.15	0.078	-0.01	-0.07	-0.01	0.35	0.09	-0.02	-0.13	1	
F	0.20	0.14	0.42	0.32	0.07	-0.06	-0.22	0.03	0.03	0.45	0.61	0.01	1

Note: Figures in bold face indicate very strong correlation.

Table 3. *Results of t-test for pre-monsoon seasons of 2006 and 2009*

	EC	**TDS**	**pH**	**Na**	**K**	**Ca**	**Mg**	**Cl**	**SO_4**	**CO_3**	**HCO_3**	**NO_3**	**F**
$ts_{computed}$	-1.58	-0.8	-3.2	-2.2	0.34	-2.8	1.76	-1.1	-0.2	-0.3	-4.46	-4.13	-7.3
$ts_{critical}$	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96
Remark	ns	ns	s	s	ns	s	ns	ns	ns	ns	s	s	s

Note: ns = not significant; s = significant

Table 4. *Results of t-test for post-monsoon seasons of 2006 and 2009*

	EC	**TDS**	**pH**	**Na**	**K**	**Ca**	**Mg**	**Cl**	**SO_4**	**CO_3**	**HCO_3**	**NO_3**	**F**
$ts_{computed}$	0.65	1.01	0.28	0.79	1.23	1.15	-0.12	0.11	0.47	0.50	1.19	-3.32	1.67
$ts_{critical}$	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96
Remark	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	s	ns

Note: ns = not significant; s = significant

Table 5. *Percentage of sites having groundwater quality parameters within the recommended limits for drinking purpose*

Parameter	**Criteria**	**Season and Year**					
		Pre 2006	**Post 2006**	**Pre 2007**	**Pre 2008**	**Pre 2009**	**Post 2009**
Calcium	Within MDL	96	99	99	98	99	98
	Within MPL	4	1	1	2	1	2
	Exceeding MPL	0	0	0	0	0	0
Magnesium	Within MDL	65	65	48	56	47	44
	Within MPL	32	34	52	41	52	52
	Exceeding MPL	3	1	0	2	1	4
Sodium	Within MDL	54	54	53	50	44	35
	Exceeding MDL	46	46	47	50	56	65
Sulphate	Within MDL	92	90	90	94	91	87
	Within MPL	7	10	8	4	8	10
	Exceeding MPL	1	0	2	1	1	3
Chloride	Within MDL	55	59	58	60	49	50
	Within MPL	28	25	26	23	32	31
	Exceeding MPL	17	16	16	16	19	19
Bicarbonate	Within MDL	59	58	64	64	73	57
	Exceeding MDL	41	42	36	36	27	43

Note: MDL = maximum desirable limit; MPL = maximum permissible limit

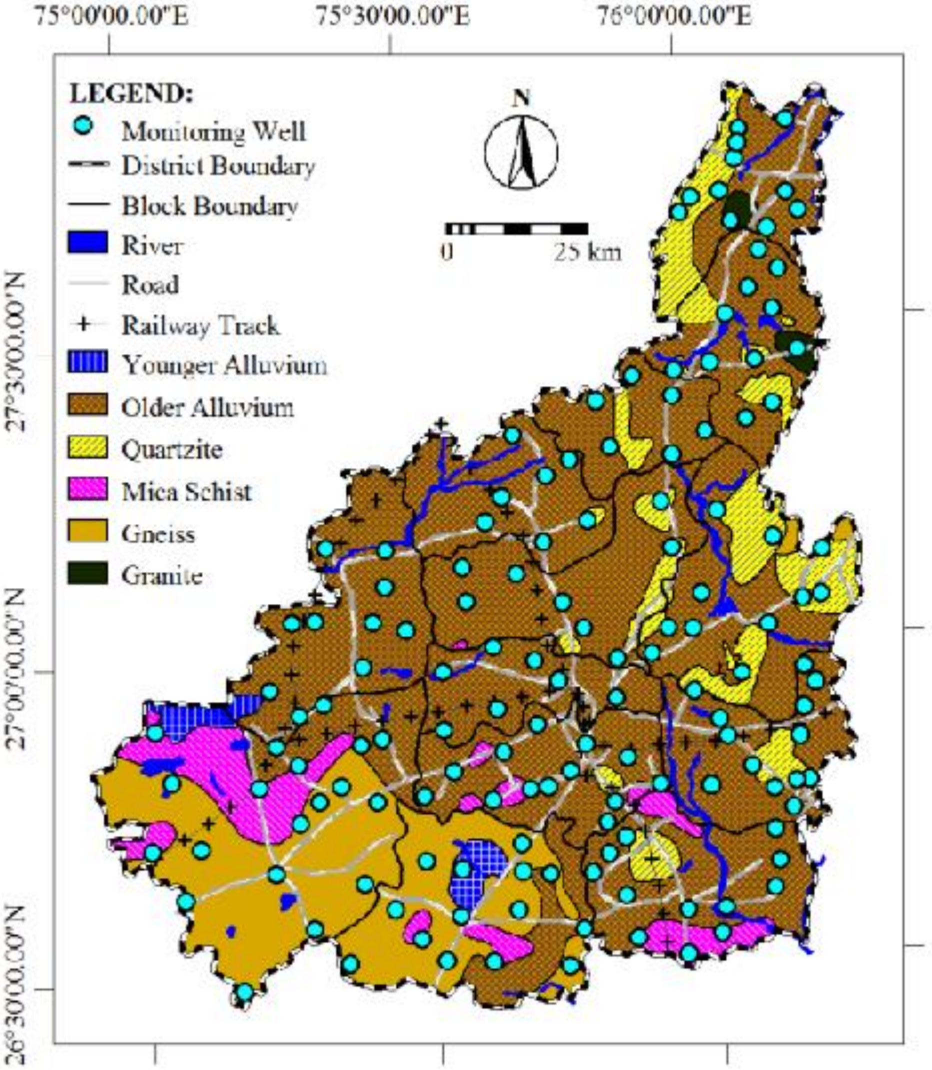
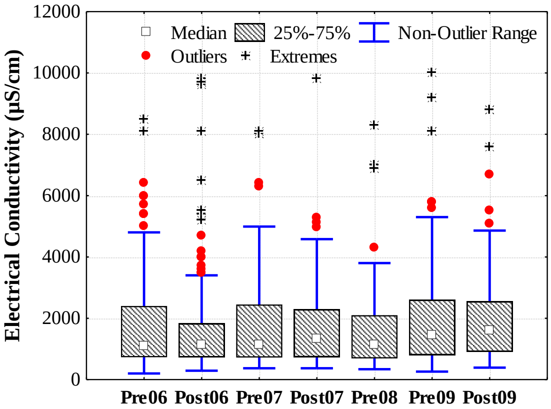
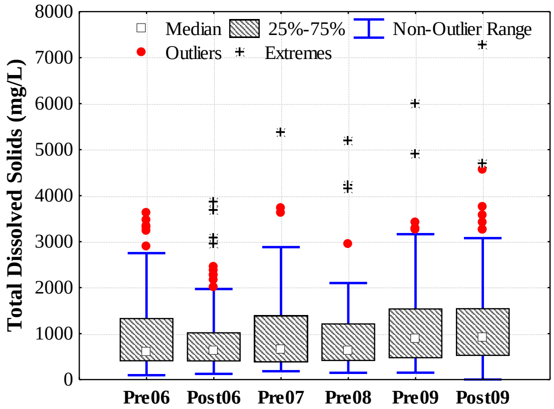
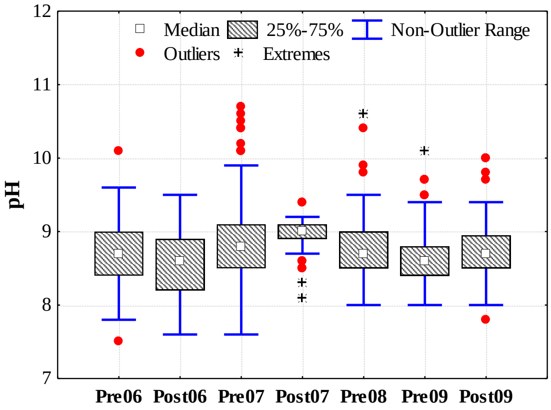
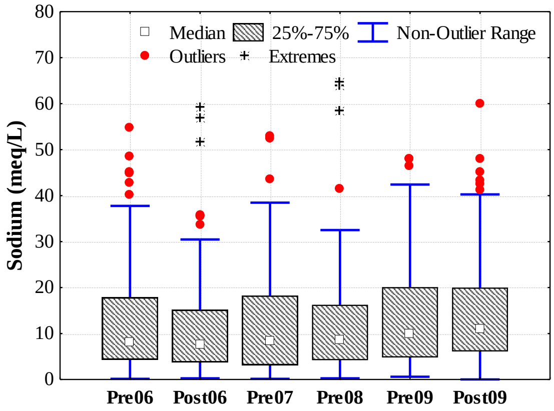


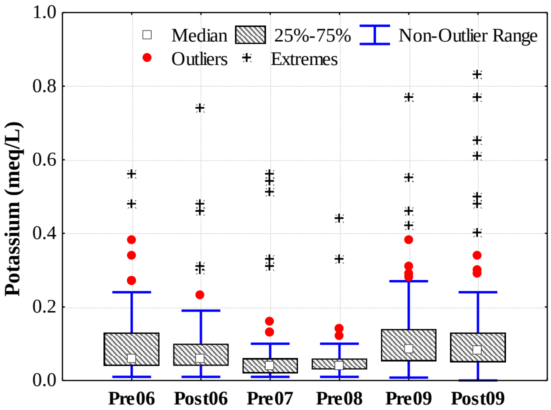
Fig. 1. Location map of study area along with groundwater sampling sites

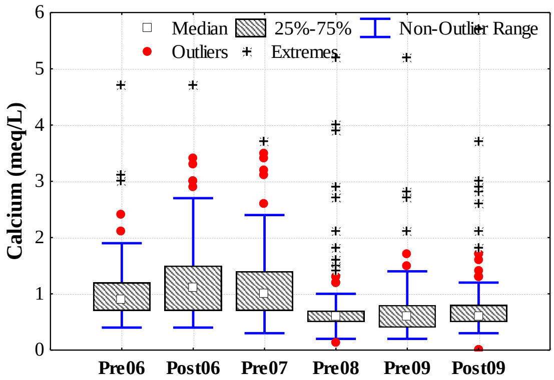

Electrical Conductivity (µS/cm)
0
2000
4000
6000
8000
10000
12000
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Post07 Pre08 Pre09 Post09

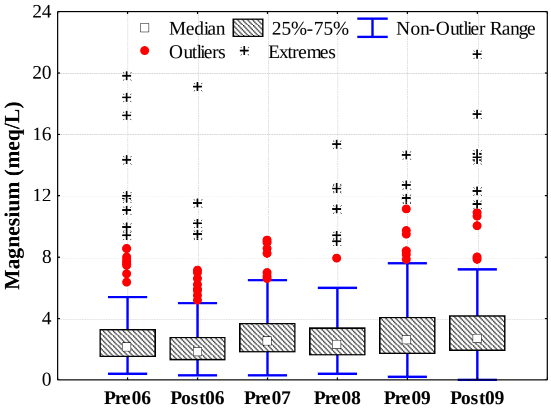

Total Dissolved Solids (mg/L)
0
1000
2000
3000
4000
5000
6000
7000
8000
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Pre08 Pre09 Post09

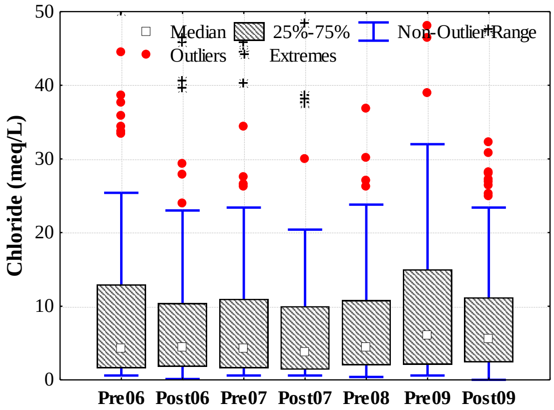

pH
7
8
9
10
11
12
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Post07 Pre08 Pre09 Post09


Sodium (meq/L)
0
10
20
30
40
50
60
70
80
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Pre08 Pre09 Post09


Potassium (meq/L)
0.0
0.2
0.4
0.6
0.8
1.0
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Pre08 Pre09 Post09


Calcium (meq/L)
0
1
2
3
4
5
6
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Pre08 Pre09 Post09


Magnesium (meq/L)
0
4
8
12
16
20
24
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Pre08 Pre09 Post09


Chloride (meq/L)
0
10
20
30
40
50
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Pre06 Post06 Pre07 Post07 Pre08 Pre09 Post09

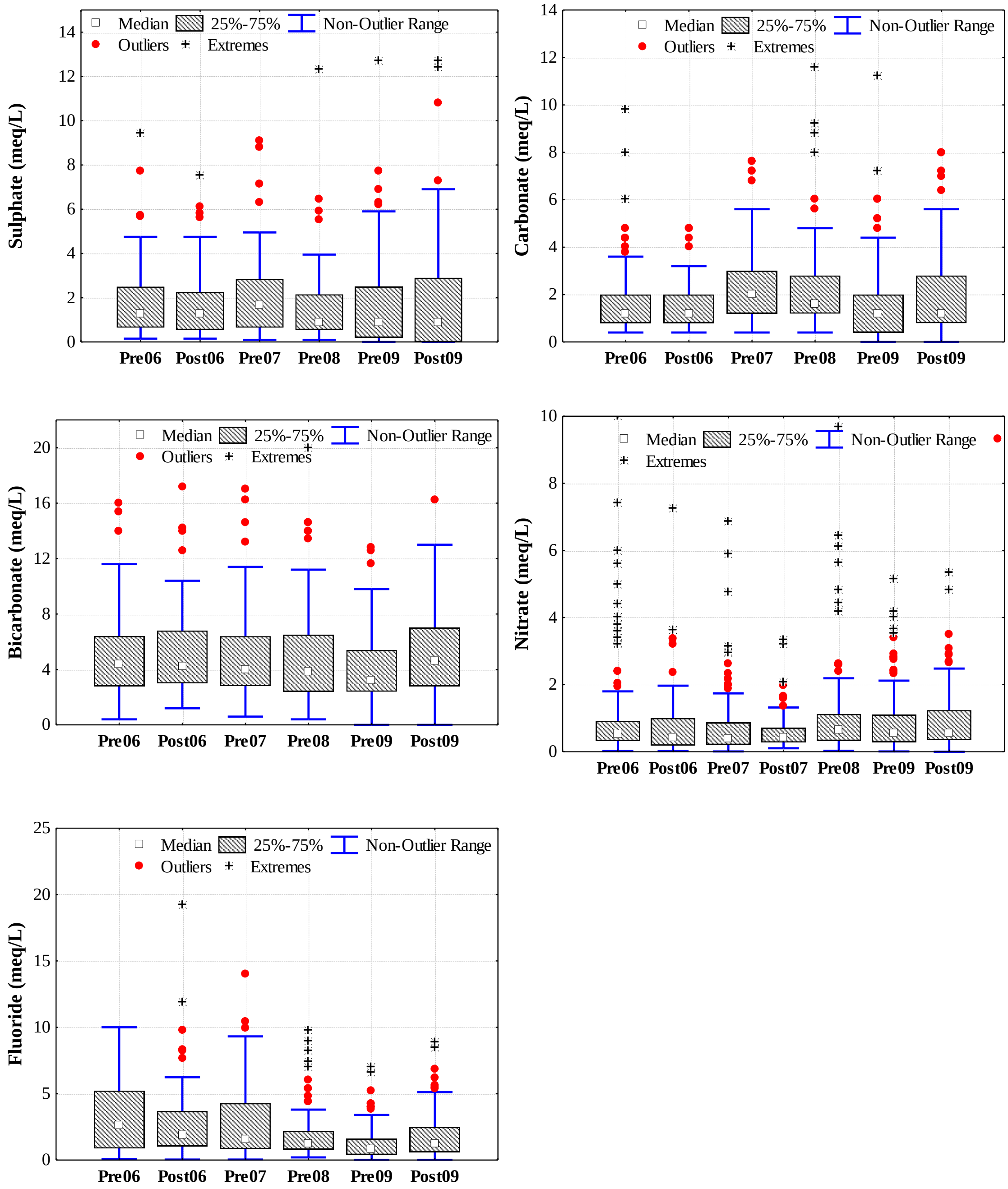


Fig. 2. Box and whisker plots of 13 groundwater quality parameters

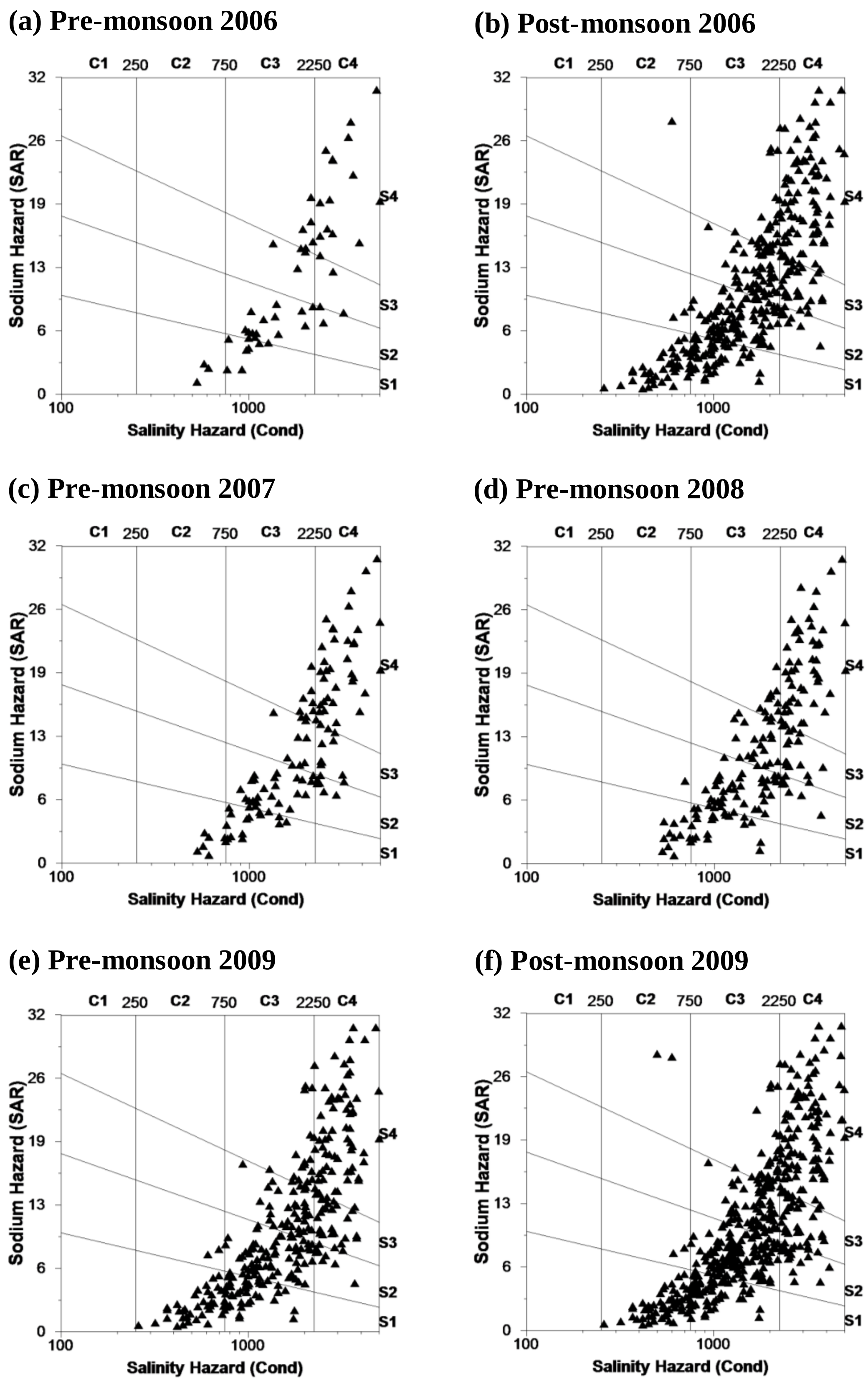


Fig. 3. USSL diagrams showing suitability of groundwater for irrigation **(Sodium hazard: S_1- Low, S_2- Medium, S_3-High, S_4- Very High; Salinity Hazard: C_1- Low, C_2- Medium, C_3- High, C_4- Very High)**