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Application of Geostatistical Analysis for Evaluating Variation in Groundwater Characteristics

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Abstract: Knowing the temporal and spatial variation of groundwater quality is a necessary factor for implementing the optimal management of water resources. In order to investigate water quality this study was divided into two phases. At the first phase for evaluating the groundwater quality for irrigation, 76 wells were sampled in Bahadoran plain, in 2011. The SAR, EC and B^{3+} and Cl^- ions were analyzed as the evaluation indexes. Then using geostatistical methods the maps of each parameter were drawn. In the second phase, considering FAO criteria, these maps were overlaid and separate water quality maps were derived. EC map indicates that, respectively 48 and 52 % of the study area; groundwater lies in severe and slight to moderate restriction class for irrigation purposes. Moreover, the thematic map of infiltration restrictions indicates that the groundwater has no restriction at the rate of 66 % of the area while 11% of groundwater cause low to moderate and 23 % cause severe limitation. In terms of water toxicity, Boron and Chloride concentrations were investigated and according to the results their changes follow an exponential function in the study area.

Key words: Geostatistics · Kriging method · Zoning map · Spatial variation

INTRODUCTION

Agriculture largely depends on water resources of standard quality. In many areas, excessive use of good-quality water resources makes us use the lower-quality water resources. Low quality waters often contain plenty of soluble salts and long-term irrigation ignoring principles of water consumption, leads to the accumulation of soluble salts and sodium in the root zone and causes irreversible damages to crops, soil and environment [1]. Therefore, knowing the quality and quantity of groundwater as the most important sources of water supply is quite necessary [2]. Several methods have been developed to determine suitability of groundwater quality for irrigation purposes so far. For example, the FAO classification method presented in 1976 emphasized on long-term effects of water quality on crop production, soil condition and farm management. In this method, the salinity of water, soil water infiltration rate and toxicity of specific ions are investigated [3]. This kind of researches needs time-consuming field works and high-costing laboratory analysis. In the most of cases these two factors limit the number of sampled sites whereas values at unsampled sites usually are needed for analysis. In this casegeostatistical methods such as Kriging can be applied to estimate the values at unsampled sites and come up with this situation. Using this approach, groundwater variables would be estimated and applied in FAO classification method for analyzing the groundwater quality. So the primary objective of this study was to prepare zoning maps of groundwater quality in Bahadoran plain using geostatistical methods. The objective was achieved through the analysis of available water quality data, using Kriging method. The secondary objective was to investigate and evaluate the quality of groundwater for irrigation purposes based on FAO classification method.

MATERIALS AND METHODS

The study area lies between longitudes 54° 46’30”to 54° 59’30” East and latitudes 31° 16’55” to 31 31° 35’00” North and covers an area about 11,173.6 hectares. Its average altitude is 1461 meters and it falls into arid

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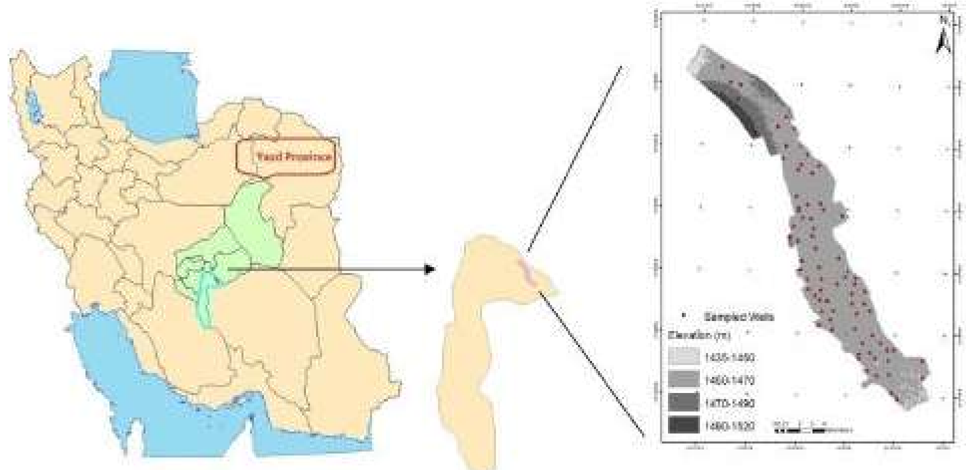

Fig. 1: The location of sampled wells in the study area on digital elevation model (DEM).

climate zone with the average annual rainfall of about 66.8 mm. The maximum and minimum temperatures that have been recorded were 43 and -12°C, respectively. In Figure 1, the study area and location of sampled wells are shown on digital elevation model (DEM).

In this study to predict the spatial and temporal variations of groundwater quality parameters, a 5-year period (2006-2011) was considered and the study was divided into two phases. In the first phase, to evaluate the quality of groundwater, 76 wells were sampled and chemical characteristics including EC, SAR, TDS, Cl, B, Na, Ca and Mg were determined. The 76-surveyed wells with GPS data were used to produce the map. In terms of statistical analysis, the mean, standard deviation (SD), minimum-maximum values, skewness and kurtosis were calculated for considered variables. Logarithmic transformations were used to normalize the data and The Kolmograph - Smirnov normality test was conducted to analyze the normality of transformed data. The location of wells along with their measured properties was inserted as a point layer in the GIS environment and histogram, Normal QQ plot and the trend of data were analyzed to draw the zoning maps using geostatistical methods.

Kriging Method: The presence of a spatial structure where observations close to each other are more alike than those that are far apart, such structure (spatial autocorrelation) is a prerequisite to the application of geostatistics [4,5]. The experimental variogram measures the average degree of dissimilarity between unsampled values and a nearby data value [6] and thus can depict autocorrelation at various distances. The value of the experimental variogram for a separation distance of h (referred to as the lag) is half the average squared difference between the value at z (xi) and the value at z (xi+h) [7,4]:

$$\gamma(\mathrm{h}) = \frac{1}{2\mathrm{h}(\mathrm{h})} \sum_{\mathrm{i-1}}^{\mathrm{n(h)}} \left[Z(\mathrm{xi}) - Z(\mathrm{xi+h}) \right]^2 \qquad (1)$$

Where N (h) is the number of data pairs within a given class of distance and direction. If the values at z (xi) and z (xi + h) are auto correlated the result of Eq. (1) will be small, relative to an uncorrelated pair of points. From analysis of the experimental variogram, a suitable model (e.g. spherical, exponential) is then fitted, usually by weighted least squares and the parameters (e.g. range, nugget and sill) are then used in the Kriging procedure. Once the trend is removed, the statistical analysis will be performed on the residuals or the short-range variation component of the surface. Consequently the better prediction maps will be drawn. Then, after trend removing, zoning maps of EC, Cl, B and SAR were plotted using the spherical model and Kriging method. Finally according to FAO Instructions for water quality classification, zoning maps of groundwater based on restrictions that they can cause was produced. The map of salinity and toxicity of specific ions restriction was interpolated and consequently, EC and SAR maps were overlaid to produce the map of infiltration restriction.

RESULTS AND DISCUSSION

Statistical Analysis: An assessment of the normality of data is a prerequisite for many statistical tests as normal data is an underlying assumption in parametric testing.

Table 1: The results of statistical analysis on characteristics of groundwater

Characteristics of groundwater	Minimum	Maximum	Mean	Standard deviation	Kurtosis	Skewness	K-S (transformed data)
B (me/l)	008/0	3.51	9/0	76/0	4.91	1.36	0.054
Cl (me/l)	4.1	322	59.1	64.61	6.15	1.78	0.058
EC(ds/m)	0.97	8.97	3.08	1.97	3.7	1.28	0.062
SAR	35/4	57/45	15/15	9/55	3.23	1.02	0.068

To overcome the difficulties arising from departures from normality we can attempt to transform the measured values to a new scale on which the distribution is more nearly normal. We should then do all further analysis on the transformed data and if necessary transform the results to the original scale at the end [8]. skewness is an appropriate index to examine the normality of data, In fact, when this index is less than 0.5, data conversion is not necessary, but if it is more than 0.5, the logarithmic transformation should be used for data normalization [9]. According to the statistical summary of water quality data which is given in Table 1, skewness index in all characteristics of groundwater quality is more than 0.5 so they considered as abnormal data and the logarithmic transformations was used to transform the measured values to a new scale on which the distribution is more nearly normal.

The geometric mean of a set of data is

$$\bar{g} = \left\{ \prod_{i=1}^{N} Z_i \right\}^{1/N} \tag{2}$$

So that

$$\log \bar{g} = \frac{1}{N} \left\{ \sum_{i=1}^{N} \log Z_i \right| \tag{3}$$

in which the logarithm may be either natural (ln) or common (log10). If by transforming the data zi, i =1, 2,...,N, we obtain log z with a normal distribution then the variable is said to be log normally distributed.

After data transformation, Kolmogorov-Smirnoff test was used to examine the normality of transformed data. In statistics, the Kolmogorov-Smirnov test (K-S test) is a nonparametric test for the equality of continuous, one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution (one-sample K-S test), or to compare two samples (two-sample K-S test). The Kolmogorov-Smirnov statistic quantifies a distance between the empirical distribution function of the sample and the cumulative distribution function of the reference distribution, or between the empirical distribution functions of two samples. The null distribution of this statistic is calculated under the null hypothesis that the samples are drawn from the same distribution (in the two-sample case) or that the sample is drawn from the reference distribution (in the one-sample case). In each case, the distributions considered under the null hypothesis are continuous distributions but are otherwise unrestricted. If the K-S value of the Test is greater the 0.05 then the data is normal. If it is below 0.05 then the data significantly deviate from a normal distribution [5]. As shown in table 1, the K-S value of all transformed data is greater the 0.05 then the data is normal. Table 1 shows the results of statistical analysis of water quality data.

Geostatistical Analysis: Tables 2, 3 and 4, respectively, show criteria used to prepare zoning maps of potential irrigation problems such as salinity, soil infiltration restriction and toxicity of specific ions. After data normalizing, experimental variogram was computed. It was concluded that the best model for fitting on experimental variogram can be spherical model. Table 5 shows variogram model and parameters of the considered variables. Spherical model was provided the best fit to experimental semivariograms for $Lg_{10}Cl$, B, EC and SAR. The ratio of nugget variance to sill expressed in percentages can be regarded as a criterion for classifying the spatial dependence of ground water quality parameters. If this ratio is less than 25%, then the variable has strong spatial dependence; if the ratio is between 25 and 75%, the variable has moderate spatial dependence and greater than 75%, the variables shows only weak spatial dependence [10].

EC analysis shows that in the most parts of northern and northeastern regions, groundwater has been severely restricted. Overall, in 52 and 48 percent of the study area, groundwater cause low to moderate and severe restrictions, respectively. The results of overlaying maps of EC and SAR indicate that 66 percent of the groundwater has no limitation. While, 11 percent has low to moderate limitations, 23 percent has a severe limitation. In Figures 2 and 3 respectively, the zoning maps of ground water infiltration restriction and groundwater salinity is presented.

Table 2: Criteria used to prepare groundwater Salinity map and its spatial distribution in the study area

Potential Irrigation Problem	Criteria	Range	Degree of Restriction on Use	(ha)Area	Area percentage
Salinity	EC (ds/m)	3-0.7	Slight to Moderate	5757	52
		>3	Severe	5412	48

Table 3: Criteria used to prepare groundwater infiltration restriction and its spatial distribution in the study area

Potential Irrigation Problem	Criteria and Range		Degree of Restriction on Use	(ha)Area	Area percentage
Infiltration	SAR=3-6	EC(ds/m)=1.3-2.9 and 2.9-5	None	7385.74	66.26
	SAR=6-12	EC(ds/m)=1.3-2.9 and 2.9-5			
	SAR=12-20	EC(ds/m)= 2.9-5 and >5			
	SAR=20-40	EC(ds/m)= >5			
	SAR=12-20	EC(ds/m)= 1.3-2.9	Slight to Moderate	1201.58	10.78
	SAR=20-40	EC(ds/m)=2.9-5			
	SAR=20-40	EC(ds/m)=1.3-2.9	Severe	2558.85	22.96

Table 4: Criteria used to prepare groundwater toxicity of specific ions and its spatial distribution in the study area

Potential Irrigation Problem	Criteria	Range	Degree of Restriction on Use	(ha)Area	Area percentage
Sodium (Na) toxicity	SAR	9-3	Slight to Moderate	2791.81	25
		>9	Severe	8374.05	75
Chloride (Cl) toxicity	Cl (me/l)	<4	None	168.54	1.51
		4-10	Slight to Moderate	734.16	6.58
		>10	Severe	10261.96	91.91
Boron (B) toxicity	B (me/l)	<0.7	None	5439.52	48.72
		0.7-3	Slight to Moderate	5597.00	50.14
		>3	Severe	127.28	1.14

Table 5: Variogram models and parameters of considered variables

Variables	Model	Nugget effect (Co)	Sill (C+Co)	Range (m)	(Co / C+Co)	R^2
LG_{10}(Cl)	spherical	0.19	0.56	6344.2	0.34	0.76
LG_{10}(B)	spherical	0.15	0.75	4653.5	0.2	0.9
LG_{10}(Ec)	spherical	0.24	1.24	7344.4	0.19	0.85
LG_{10}(SAR)	spherical	0.21	1.19	4546.5	0.18	0.83

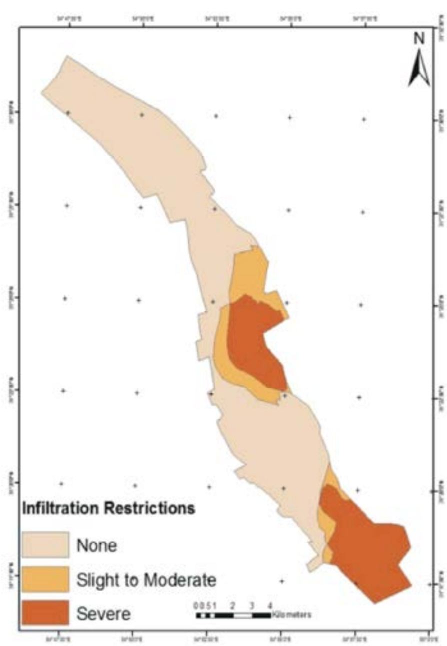

Fig. 2: Zoning map of groundwater infiltration

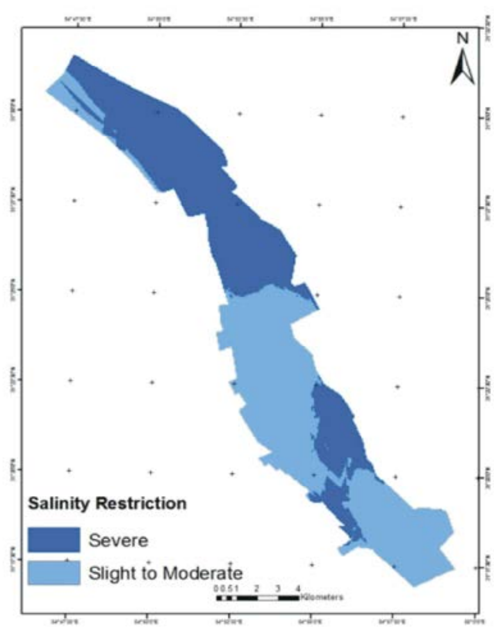

Fig. 3: Zoning map of groundwater salinity

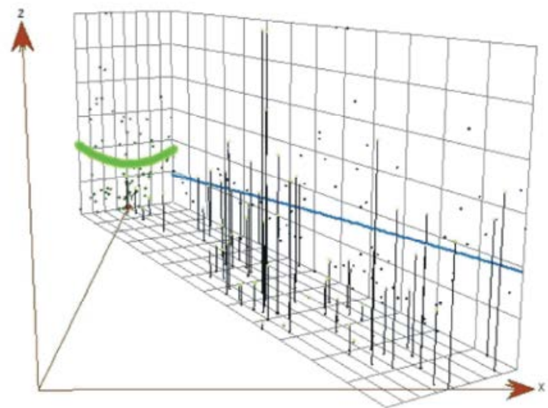

Fig. 4: The trend of spatial distribution of Boron

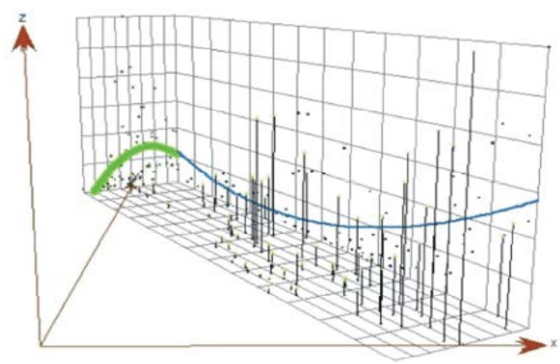

Fig. 6: The trend of spatial distribution of chloride

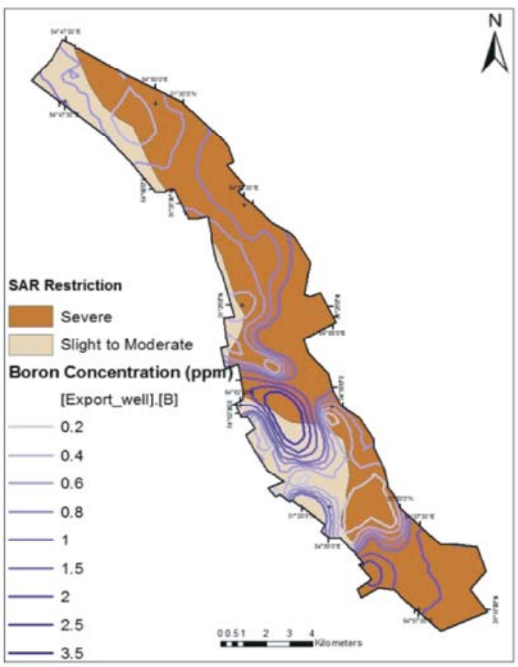

Fig. 5: Zoning map of Boron concentration and SARrestriction

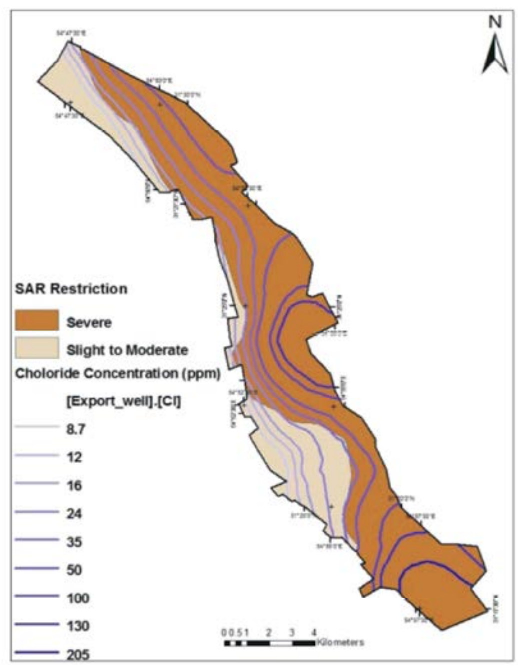

Fig. 7: Zoning map of Chloride concentration and SAR restriction

In Figure 4 the spatial variation of boron concentration in the study area is shown. The X- axis indicates the changes in the east - west direction, the Y-axis indicates the changes in the North - South direction and Z values indicate the boron concentration of samples. As shown in Figure 4, trend of spatial concentration of boron may follow an exponential function, in the western parts of the study area there was a high concentration of boron which decreases towards the central parts and increases again from central parts towards the eastern parts. On the figure 5 these changes are clearly visible on the SAR restriction map.

Figure 6 shows the spatial concentration of chloride in the study area. As can be seen, the chlorine concentration increased gradually to the east and after reaching a certain point starts to decrease. Figure 7 shows the changes in chlorine concentration on the SAR restriction map.

Since groundwater is the most important source of water supply for agriculture in arid and semiarid regions, its quality must be investigated periodically to reduce the hazard of soil salinization and damage to crops. Up-dated reliable data is necessary for evaluating and monitoring groundwater quality. But in many cases, data collection from all over the area is time-consuming and costs a lot.

Therefore by using interpolation methods, significant savings in time and money can be provided. Geographic Information Systems (GIS) is a powerful tool for analysis of the spatial relationships among the data. This system can use various methods such as Kriging to Interpolate and determine spatial relationships among the data. Interpolation using Kriging techniques have been done in a variety of studies that indicates the good accuracy of this method to draw Interpolation maps. Taghizadeh *et al*. [11] examined the spatial variation of water quality characteristics using Kriging, Cokriging and IDW Interpolation methods in Rafsanjan, Iran. They concluded that Kriging and Cokriging methods were more suitable than IDW method. Ashraf *et al*. [12] investigated the chemical quality of well waters in Damghan, Iran and prepared zoning maps of salinity, infiltration and toxicity of specific ions using the FAO classification in Arc GIS environment. They concluded that over 98% of the study area had no restrictions in terms of infiltration. Rahimi and Saghfian [13] concluded that the fuzzy Kriging method for estimating the spatial variation of rainfall leads to decrease by 10% in estimation error. So in the present study the Kriging method was selected for ground water quality zoning and producing thematic maps; to evaluate the groundwater quality. According to the results, all parameters of ground water quality have strong spatial structure except Cl-. Also effective range of most parameters is close together and with the range of 4546.5 to 7344.4 m. in the present study, three problem categories: salinity, infiltration and toxicity are used for evaluation of water quality and the occurrence prediction of water quality-related problems. Toxicity problems occur if certain constituents (ions) in the soil or water are taken up by the plant and accumulate to concentrations high enough to cause crop damage or reduced yields [3]. The ions of primary concern are chloride, sodium and boron. Chloride ions are added continuously to the soil during irrigation process. Most fruit trees, grapes and nuts and ornamental plants are sensitive to chloride ions. The results of this study indicate that 91.91 percent of Bahadoran's groundwater can cause severe problems, so precautionary measures must be taken about their usage. Moreover, Boron is very dynamic in soil, so that both its deficiency and toxicity is important. Boron like sodium and chloride is water soluble ion and irrigation water containing high concentrations of boron is the main cause of its toxicity in the soil and plants [14]. According to the results, only 1.14 percent of the study area's groundwater cause severe restriction in terms of boron toxicity. On the other hand, sodium absorption ratio (SAR) is important factor that can both influence the rate of water infiltration in the soil and also can cause toxicity problems. The high SAR values increases the dispersion of clay particles and reduces the soil permeability [15, 16]. However, the higher EC can flocculate the soil particles and increase soil permeability [17]. According to the obtained results, most of the groundwater (about 48%) in the study area has a high EC therefore only about 22.96 percent of them result in severe infiltration restriction. But 75 percent of them have a severe problem in terms of the toxicity that they can cause. Overall, the results show that usage of the region's groundwater for irrigation purposes needs to have some precautionary measures. Furthermore accurate management should be considered to correct or delay the onset of the existing problem.

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