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Analysis of groundwater quality in the northwest of Iran

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ABSTRACT

The aim of the study is to determine the spatial variability of groundwater depth and pollutant concentration levels in Ardabil plain in the northwest of Iran using geographical information systems. Ordinary kriging method was used to analyze the spatial pattern of groundwater depth and quality parameters, while indicator kriging (IK) method was utilized to analyze groundwater quality parameters equal to or greater than the pollution threshold values. The created spatial variability maps showed that in more than half (53%) of the study area, groundwater depth was less than 20 m from the ground surface. Quantity of salinity was higher than 2.5 dSm^{-1} in 2% of the study area and the nitrate concentration exceeded 50 mg l^{-1} in 8% of the region. The probability maps exhibited that about 3% of the area had the highest probability (0.8–1.0) of exceedance of the threshold nitrate concentration, but the area did not have any highest probability of exceedance of the threshold electrical conductivity value in the groundwater. Additionally, other parameters of groundwater quality, i.e. chloride (Cl), pH, sulfate (SO_4), bicarbonate (HCO_3), calcium (Ca), sodium (Na), magnesium (Mg), and total hardness (TH) had a good quality and their concentrations were lower than the corresponding threshold values. The prepared spatial variability and probability maps will assist for proper management of groundwater resources for agricultural and drinking purposes and minimizing the pollution hazard in the study area.

Keywords: Groundwater level; Water quality parameters; Spatial distribution; Geostatistics; Drinking water standard

1. Introduction

Groundwater is one of the major sources of water in many parts of Iran especially in the arid and semi-arid regions. The importance of groundwater resources in Iran can be understood by the actuality that groundwater comprises about 50% of the total irrigation potential [1]. Groundwater quality varies from location to location and aquifer to aquifer. In some cases, groundwater is almost pure enough to be drinkable with only minimal treatment from pollution. Protection of groundwater quality is important because it can be very difficult to rehabilitate, if it becomes polluted. Hence, management of this resource is very important to assemble the increasing demand of water for drinking, agricultural. and industrial uses. For the best management, it is important to know the spatial and temporal behavior of groundwater. The harmful effects of agricultural, industrial activities and urban development on neighboring groundwater make us to investigate the quality of these sources. The quality of groundwater affected through domestic, agricultural, and industrial pollution and the nitrate (NO_3) pollution in each area is very important and must be evaluated. The NO_3 concentration in groundwater is usually low and can reach very high levels as a result of leaching from agricultural land with contamination from human or animal waste [2]. It is estimated that at least 30% of the groundwater reserves are affected by these unfavorable natural chemical conditions and among the factors contributing to the widespread deterioration, nitrates are a significant problem [3]. In many cases, the high NO_3 in groundwater is one of the most important human concerns [4]. It was reported in addition that excessive NO_3 in the groundwater could cause child methemoglobinemia and possibly human gastric cancer [5,6]. In some researches, various NO_3 contaminations in groundwater have been reported [7–15]. The relationship between land use and nitrate pollution has been confirmed many times [16,17]. It is well recognized that environmental pollution depends mainly on human activities [18]. In Asian countries especially in developing countries where intensive farming systems have developed in recent decades, water for drinking and other domestic uses for many of the rural poor originate from polluted sources [19]. The NO_3-N concentrations in groundwater have been increased with 1–3 mg l^{-1} annually during the last 20 years in the world [20]. Water-related diseases are responsible for 80% of all illnesses or deaths in developing countries, and kill more than five million people every year [21]. The measurement of pollutant concentration at each location is not always possible because of the data collection, whereas the time and the cost are involved. Hence, prediction of values at other locations based on selectively measured values could be one of the choices. In this research, the geostatistical methods were used to predict the concentration of pollutants at unmeasured locations. These geostatistical methods were developed to create mathematical models of spatial correlation structures with a variogram as the quantitative measure of spatial correlation [22–30] and are very common and widely accepted in soil science, hydrology, and environmental sciences [31–44].

The main objective of the present research was to make a groundwater quality assessment using geostatical methods. This study was undertaken to provide spatial distribution of different groundwater quality parameters and to generate the probability maps depicting the cutoff values and describing the affected areas in the Ardabil plain, Iran, where overexploitation of groundwater has resulted in progressive lowering of water table and seriously deteriorating the quality of the groundwater for drinking, irrigation, and other consumes.

2. Material and methods

2.1. Study area

The study area is Ardabil plain that is located in the central part of Ardabil province (48˚9′53′′–48˚37′6′′ E, 38˚4′38′′–38˚24′33′′ N) in the northwest of Iran (Fig. 1). The major city of the province is Ardabil with a population more than 420,000 inhabitants. The climate in the region is cold semiarid. The annual precipitation is 318.4 mm, most of which falls between August and April. The mean annual temperature is 11.1˚C and the total area of Ardabil plain is approximately 820 km^2. About 89% of total water demand in the area is supplied by groundwater and the remaining 11% is obtained from surface water. The most important rivers in the study area are Balighlu and Gharasu. Balighlu River passes through the city of Ardabil and in the north discharges its waters into the Gharasu river.

2.1.1. Geology and hydrogeology

Ardabil plain is a closed basin and surrounded on all sides by mountains that are parts of the Alborz Mountains. In the eastern and central parts of Alborz Mountains, green tuff facies of Eocene age are associated with volcanic rocks, while in the Ardabil area, volcanic rocks are dominant and green tuff is less. The base of the study area is formed by river and alluvial sedimentation mainly in the South. In the alluvial fan, foothill and in central part of the study area, grain size, and particle diameter is reduced. In the study area, Cenozoic formations have been folded, and older formations just in the north of the region may be found.

The aquifer in the plain having different ratios of clay, sand, and gravel is divided into two aquifers. The upper aquifer is multilayered and unconfined, while it is confined in the central part of the plain. Separation of the confined and unconfined parts of the aquifer is not appropriate because of lateral hydraulic interconnections of high permeable layers of the aquifer. Most of the extraction wells have been drilled in the upper aquifer, whereas few of them have penetrated the lower aquifer (occurs at a depth of 110–130 to 220 m). Generally, the thickness of the alluvium is increased eastward across the plain. In fact, thick coarse-grained alluvium and saturated zone is suited in the east and southeast parts [45]. Alluvium thickness, water level, and transmissivity of the region vary between 75 and 200 m, 5–40 m, and 50–2,200, respectively. Also, storage coefficient of the study area is 6%.

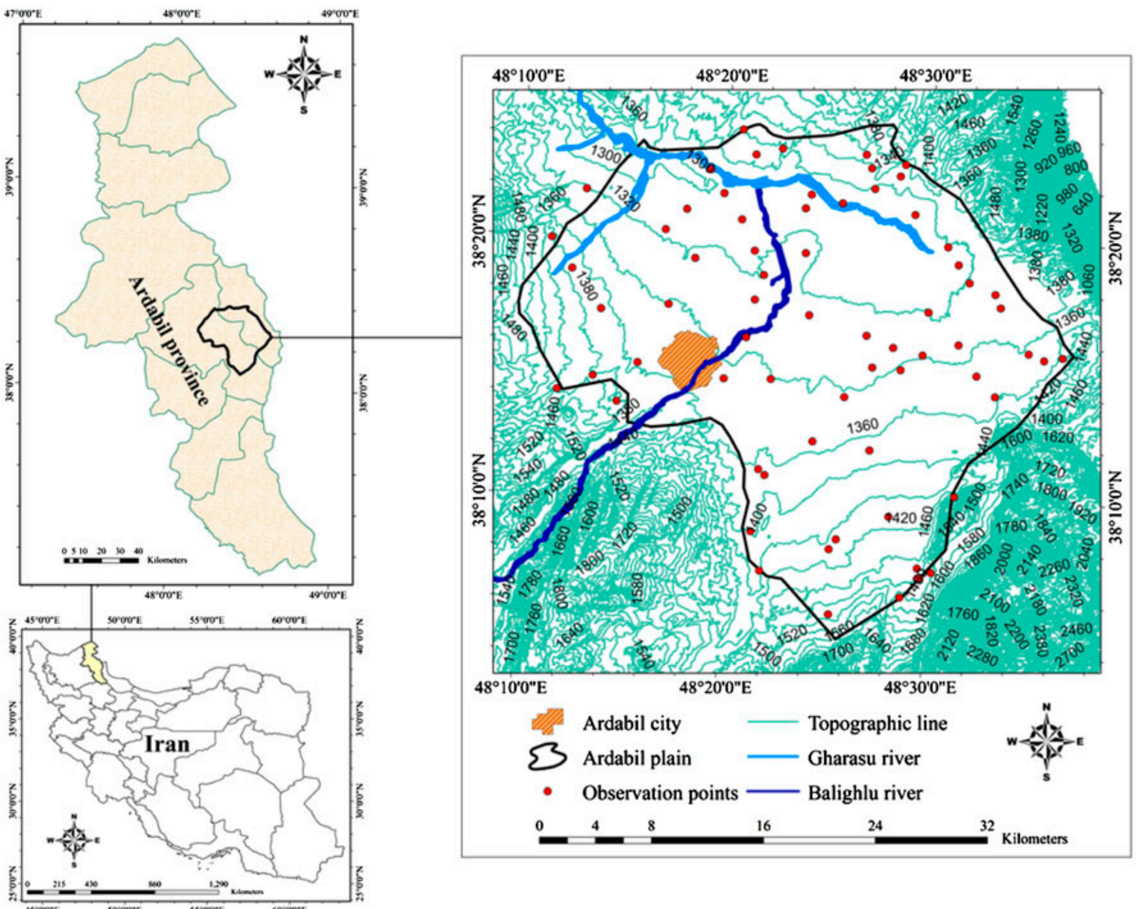

Fig. 1. Location of Ardabil plain with sampling distribution patterns.

2.1.2. Groundwater sampling and measurements

All of 69 groundwater samples were taken from underground wells in the study area in October 2008. Out of these 69 samples, 60 were from deep wells, 6 from springs, 2 from shallow wells, and 1 from aqueduct. The groundwater samples were processed and analyzed for water depth in meter, electrical conductivity (EC) in $dS\,m^{-1}$, pH, sodium (Na^+) in $mg\,l^{-1}$, magnesium (Mg^{2+}) in $mg\,l^{-1}$, calcium (Ca^{2+}) in $mg\,l^{-1}$, bicarbonates (HCO_3^-) in $mg\,l^{-1}$, sulfates (SO_4^{2-}) in $mg\,l^{-1}$, chlorides (Cl^-) in $mg\,l^{-1}$, total dissolved solids (TDS) in $mg\,l^{-1}$, total hardness (TH) and nitrate (NO_3^-) in $mg\,l^{-1}$. The locations of groundwater sampling points are shown in Fig. 1. The samples were gathered from Ardabil Water District Organization.

2.2. Geostatical analysis

Geostatistics provides quantitative descriptions of natural variables distributed in time and space [46,47]. The main tool in geostatistics is the semivariogram, which declares the spatial dependence between neighboring observations. The semivariogram describes the spatial autocorrelation of the measured sample points. It is the usually the half mean squared difference of values separated by a given distance h. This technique is based on the regionalized variable hypothesis, which states that variables in an area demonstrate both random and spatially structured properties. The spatial structure is quantified using semivariogram model [48]. The experimental semivariogram is a graphical exhibit of the mean square variability and can be defined as one-half of the variance of the difference between two neighboring points of distance h as shown in the following equation:

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

where $\gamma(h)$ is the estimated value of the semivariance for lag h; $N(h)$ is the number of experimental pairs divided by vector h; $z(x_i)$ and $z(x_i + h)$ are the values of variable z at x_i and $x_i + h$, respectively; x_i and $x_i + h$ are positions in two dimensions. The experimental semivariogram, $\gamma(h)$ is fitted to a theoretical model such as spherical and Gaussian to define three parameters of the nugget (c_0), the sill (c) and the range (A_0).

These theoretical models are defined as follows [47]:

Spherical model:

$$\gamma(h) = c_0 + \left[1.5\left(\frac{h}{A_0}\right) - 0.5\left(\frac{h}{A_0}\right)^3\right] \qquad h \leqslant A_0 \tag{2}$$

$$\gamma(h) = c_0 + c \qquad h \succ A_0$$

Gaussian model:

$$\gamma(h) = c_0 + c\left[1 - \exp\left[-\left(3\frac{h}{A_0}\right)^2\right]\right] \tag{3}$$

2.2.1. Kriging

In this investigation, the ordinary kriging method was used to estimate the unobserved points and to prepare the map of the observed variables as shown in Journel and Huijbregts [46]. The method is based on two suppositions. The mean of the process is constant and is invariant within the spatial area. This is declared as:

$$z(x) = \mu + \varepsilon(x) \tag{4}$$

where μ is an unknown constant and ordinarily considered as mean of the characteristic values; and $z(x)$ is the attribute value at any location x with stochastic residual $\varepsilon(x)$ with zero mean.

The indicator kriging (IK) method was also used to assess the risk of NO_3 and EC contaminations. The IK method usually uses nonparametric approach of geostatistical analysis. In IK technique, an observation $z(x)$ is allocated to a known value and that known value is transformed into binary indicator coding 1 or 0. Likewise, if values are above the threshold, they become as 1, and if they are below the threshold, they become as 0. The binary indicator codes also have no uncertainty and are consequently called hard indicator data [22]. Additionally, the 0–1 indicator transformation of data makes the predictor robust to outliers [49]. The Indicator function of the observation $z(x)$ at location x associated with the threshold or cutoff value z as follows [50]:

$$i(x;z) = \begin{cases} 1 & \text{if } z(x) \leqslant z \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

The accurate ratio of grades $z(x)$ below the threshold z with any area A is written as:

$$\varphi(A;z) = \frac{1}{A}\int_A I(x;z)dx \in [0,1] \tag{6}$$

where $\varphi(A;z)$ is the bivariate function on $z(x)$ and z, namely the average of all the indicator values $i(x;z)$ with $z(x) \leqslant z(x \in A)$. The estimator of $\varphi(A;z_{IK})$ can be written as:

$$\varphi^*(A;z_{IK}) = \sum_{\alpha=1}^{n} \lambda_\alpha(z_{IK}) \cdot i(x_\alpha;z_{IK}) \tag{7}$$

The weights $\lambda_\alpha(z_{IK})(\alpha = 1,2,\ldots,n)$ are associated with $i(x_\alpha;z_{IK})$ and can be calculated as same as the ordinary kriging (OK) procedure.

The indicator $i(x_\alpha;z)$ can be explained as:

$$i(x_\alpha;z) = \text{Prob}\ \{z(x_\alpha) \leqslant z | z(x_\alpha) = z_\alpha\} \tag{8}$$

Therefore, the estimator $i^*(x;z)$ appears as an estimate of the unknown conditional probability:

$$i^*(x;z) = \text{Prob}\ \{z(x) \leqslant z | \text{surrounding data}\} \tag{9}$$

The estimator $\varphi^*(A;z)$ of $\varphi(A;z)$ in the unknown region A can be written as:

$$\varphi^*(A;z) = \frac{1}{A}\int_A \text{Prob}\ \{z(x) \leqslant z | \text{surrounding data}\}dx \tag{10}$$

And ultimately, the average estimator $[z(x)]^*$ of the unknown region A is given as follows:

$$[z(x)] = \sum_{l=1}^{L} [I_{IK}(x)]^* [z(x) | x \in z_{IK}]^* \tag{11}$$

In continuance, experimental semivariogram parameters were calculated for EC, TDS, NO_3^-, and groundwater depth in the Ardabil plain.

2.2.2. *Theoretical model, semivariogram parameters and cross validation*

Groundwater depth and quality data were analyzed to get the explanatory statistics of each groundwater depth and quality parameters. Additionally to ensure a normal distribution, different transformations such as lognormal, box-cox (also known as power transformations), and square root were performed. Afterwards, for each theoretical model (such as spherical, Gaussian, etc.) semivariogram parameters were created. Model selection for semivariogram was done with considering maximum of the coefficient of determination (r^2) and minimum residual sums of squares (RSS). The predictive performances of the fitted models were tested on the basis of cross-validation tests. The values of mean error (ME), root mean square error (RMSE), mean standardized error (MSE), and root mean square standardized error (RMSSE) were estimated to prove the performance of the best-fitted theoretical models. The aim should be to have $ME \cong 0$, $RMSE \cong$ minimum, $MSE \cong 0$, and $RMSSE \cong 1$. If the RMSSE is greater than 1, then predicted model underestimates the variability of the data-set and if it is less than 1, predicted model overestimates the variability of the data-set [41].

After selecting the suitable theoretical model and semivariogram parameters by using ordinary kriging, spatial variability maps were created for groundwater depth and quality parameters. In the GS+ software, the ordinary kriging method with the point kriging option was used. Furthermore, IK was applied to create the probability of exceedance maps for the EC and nitrate based on threshold values of the pollutants in drinking water. Threshold limits of the groundwater quality parameters for IK were determined according to drinking water standards of World Health Organization [51], and exceedance of these values would cause human health risk. Threshold values as desirable limits for groundwater quality parameters are shown in Table 1.

Table 1
Maximum threshold values of drinking water quality according to WHO

Parameters	WHO desirable limit
Electrical conductivity, mg l^{-1}	2.5*
Total dissolved solids, mg l^{-1}	600
Nitrate, mg l^{-1}	50*
Chloride, mg l^{-1}	250*
pH	Not specified
Sulfate, mg l^{-1}	250
Bicarbonate, mg l^{-1}	Not specified
Calcium, mg l^{-1}	300
Sodium, mg l^{-1}	200
Magnesium, mg l^{-1}	300
Total hardness, mg l^{-1}	500

*The started threshold values are a guideline values assigned by WHO for the electrical conductivity (EC), nitrate (NO_3^-), and chloride (Cl) since they might inflict potential health risk.

3. Results and discussion

3.1. *Spatial pattern of the groundwater parameters*

In the Ardabil plain, groundwater level varied from a minimum of 0.31 m to a maximum of 70.38 m during the fall season in the year 2008. Ardabil's groundwater level has gone down approximately by 2.6 m in the last 10 years at the rate of about 0.26 m/year. This is related to the overuse of the groundwater resources to meet the needs of the growing population as well as decreased recharge due to the increased urbanization rate. The nitrate concentration in groundwater ranged from a minimum of 1 to a maximum of 143 mg l^{-1}, with eight wells having a concentration higher than the permissible one, i.e. 50 mg l^{-1} (Table 1). The TDS values in the groundwater ranged from 52 to 3,402 mg l^{-1}, with a mean value of 807.12 mg l^{-1}. There were 41 wells of 69 in which the TDS concentration exceeded the WHO standard (600 mg l^{-1}). The EC of water ranged from 0.29 to 4.86 dS m^{-1}, with a mean value of 1.16 dS m^{-1}. The EC values in eight out of 69 wells exceeded the drinking water standard value, i.e. 2.5 mg l^{-1} (Table 1). The other parameters of groundwater quality, i.e. chloride, pH, sulfate, bicarbonate, calcium, sodium, and magnesium in the study area had a good quality and their values were within the WHO limits (Table 1), except TH whose concentration exceeded the drinking water standard value in six measurement points. It was observed that the groundwater depth, EC, TDS, and nitrate concentrations were not normally distributed. Consequently, to fit the normal distribution different transformations were performed, which is a prerequisite for calibration of the theoretical model and creation of semivariogram parameters and kriged maps. Fig. 2 represent the graphs of the groundwater quality parameters whose concentrations are within the desirable limits suggested by WHO [51] with the exception of TH.

The details of descriptive statistics for groundwater depth and quality parameters are given in Table 2. The results in this table showed that the lognormal transformation would be able to convert all the data-sets to follow the trend of a normal distribution. A significant correlation existed between groundwater depth and EC and nitrate values, which indicated that higher EC and nitrate existed in shallow groundwater depth.

The significant relationship between groundwater depth and EC obtained in this study is in line with the findings of Hu et al. [50] and Dash et al. [52]. Moreover, a significant correlation between groundwater depth and nitrate was also found by Hu et al. [50].

3.2. Semivariogram analysis of the groundwater parameters

The nugget, sill, and range values of the best-fitted theoretical models (Fig. 3) for groundwater depth and some (NO_3, EC and TDS) quality parameters are given in Table 3. Nugget semivariance is the variance at zero distance. Sometimes, the nugget is different from zero due to measurement error. Sill is the lag distance between measurements at which one value for a variable data does not influence neighboring values. Range is the distance at which the variogram reaches the sill value.

The lowest and highest autocorrelation ranges among the selected samples were 8,950 and 24,800 m,

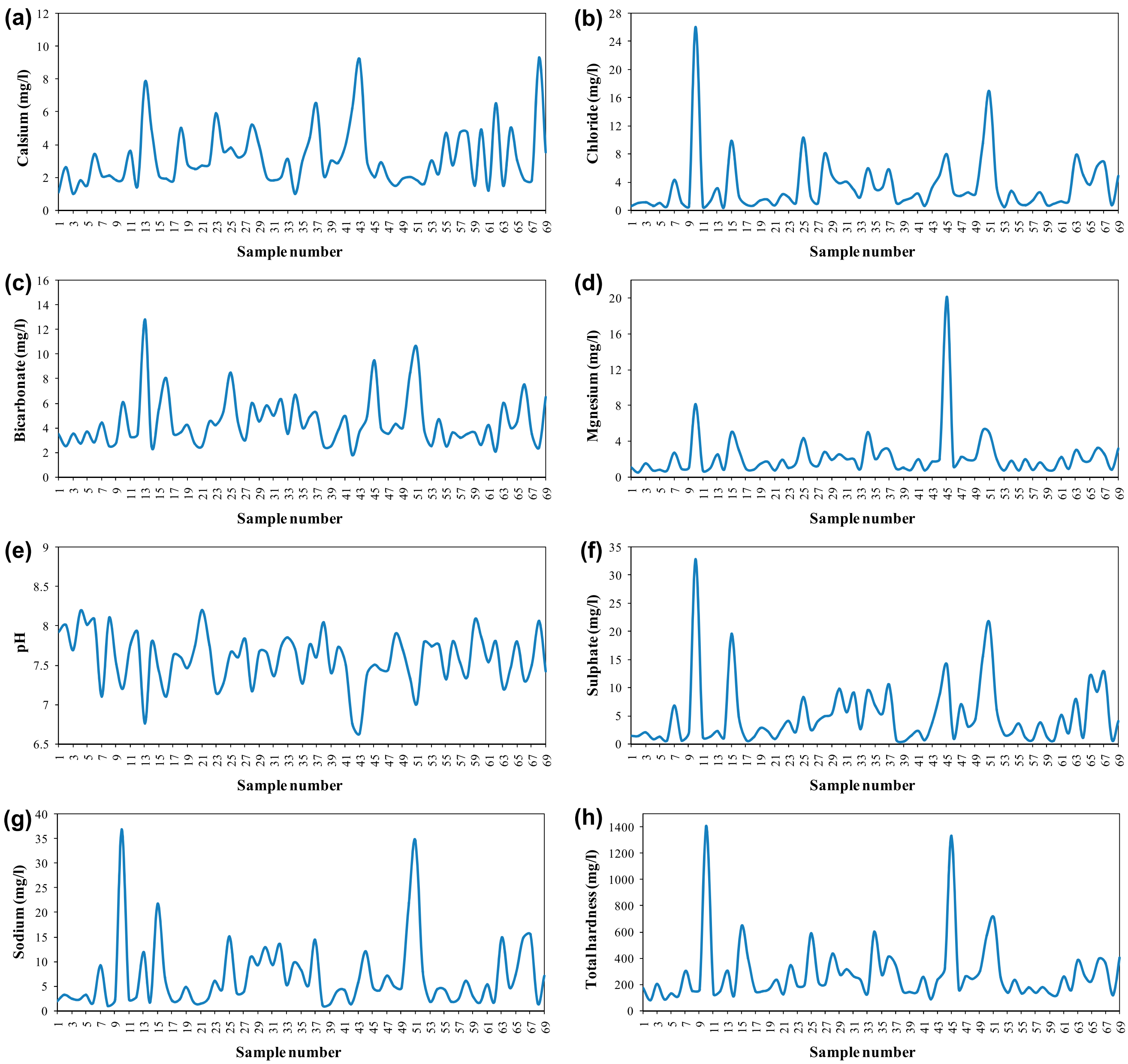

Fig. 2. Graph of the some groundwater quality parameters: (**a**) calcium concentration, (**b**) chloride concentration, (**c**) bicarbonate concentration, (**d**) magnesium concentration, (**e**) pH, (**f**) sulfate concentration, (**g**) sodium concentration, and (**h**) TH concentration.

Table 2
Descriptive statistics of groundwater depth and quality parameters measured in the study area

Parameters	Minimum	Maximum	Mean	Transformation
Groundwater depth, m	0.31	70.38	19.3	lognormal
Electrical conductivity, dS m^{-1}	0.29	4.86	1.16	lognormal
Total dissolved solids, mg l^{-1}	52	3,402	807.12	lognormal
Nitrate, mg l^{-1}	1	143	32.9	lognormal
Chloride, mg l^{-1}	0.4	16.8	2.92	–
pH	6.63	8.2	7.6	–
Sulfate, mg l^{-1}	0.3	21.48	4.52	–
Bicarbonate, mg l^{-1}	1.8	12.8	4.36	–
Calcium, mg l^{-1}	1	9.3	3.18	–
Sodium, mg l^{-1}	0.8	34.48	6.34	–
Magnesium, mg l^{-1}	0.5	20.1	2.04	–
Total hardness, mg l^{-1}	80	1,330	261.37	–

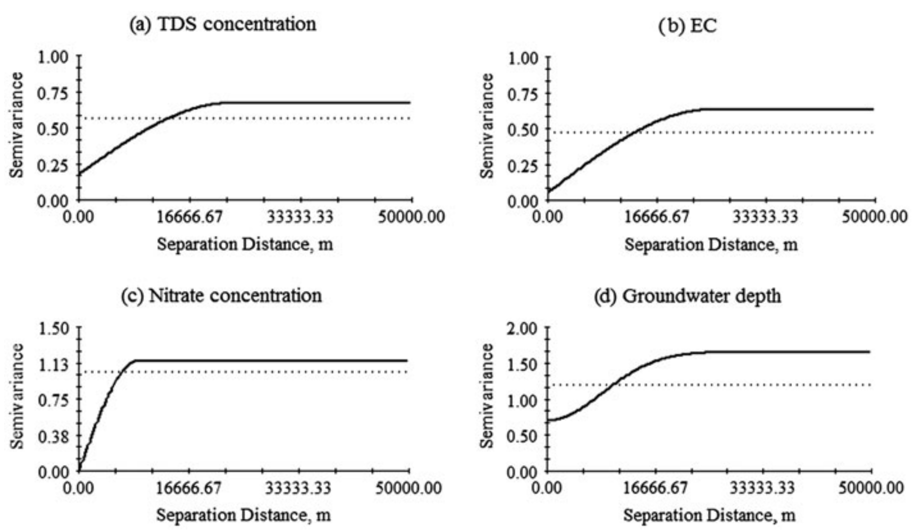

Fig. 3. Best-fitted semivariogram model of groundwater depth and quality parameters in the Ardabil plain (the dash line is the sample variance on the variogram graph): (a) TDS; (b) EC; (c) nitrate; and (d) groundwater depth.

respectively (Table 3). It is commented that the spatial correlation range (distance) of all groundwater quality parameters except nitrate was higher than that of groundwater depth. A larger range values indicates that observed values of the samples are influenced by other values of this property over greater distances [47]. The Gaussian semivariogram model (Fig. 3(d)) was observed to be the best-fit model for groundwater depth, which accorded the results reported by Taany et al. [53]. For all of the quality parameters, the spherical model fits well.

Furthermore, to determine the predictability of the theoretical model, prediction error statistics were calculated for all models (Table 4). It was shown that the error terms ME, and MSE were close to zero, whereas the RMSE values for all the parameters were high. R^2 and RMSSE were close to 1 and ranged from 0.727 to 0.97 and 0.747 to 1, respectively. Subsequently, with implementing these best-fit theoretical models and corresponding semivariogram parameters, spatial variability maps of groundwater depth, and quality parameters were created using the ordinary kriging.

3.3. Map-based spatial analysis of the groundwater parameters

The spatial variability map of groundwater depth is shown in Fig. 4(d), with three classes, representing the regions having a groundwater table within 20 m, between 20 and 40 m, and more than 40 m from the

Table 3
Summary of the best-fitted models for different groundwater depth and quality parameters

Groundwater parameters	Best-fitted model	Nugget (C_0)	Sill (C_0 + C)	Range (A_0)	R^2	RSS
Total dissolved solids	Spherical	0.178	0.668	22,490	0.929	0.011
Electrical conductivity	Spherical	0.053	0.631	24,800	0.97	0.008
Nitrate	Spherical	0.001	1.146	8,950	0.727	0.416
Groundwater depth	Gaussian	0.699	1.655	20,510	0.832	0.093

Table 4
Prediction statistics of semivariogram model generated parameters of groundwater depth and quality using kriging techniques

Groundwater parameters	ME	RMSE	MSE	RMSSE
Total dissolved solids	−0.011	486.3	0.032	0.747
Electrical conductivity	−0.383	0.825	−0.034	1
Nitrate	−3.664	28.73	−0.152	0.847
Groundwater depth	−0.301	12.34	−0.044	0.969

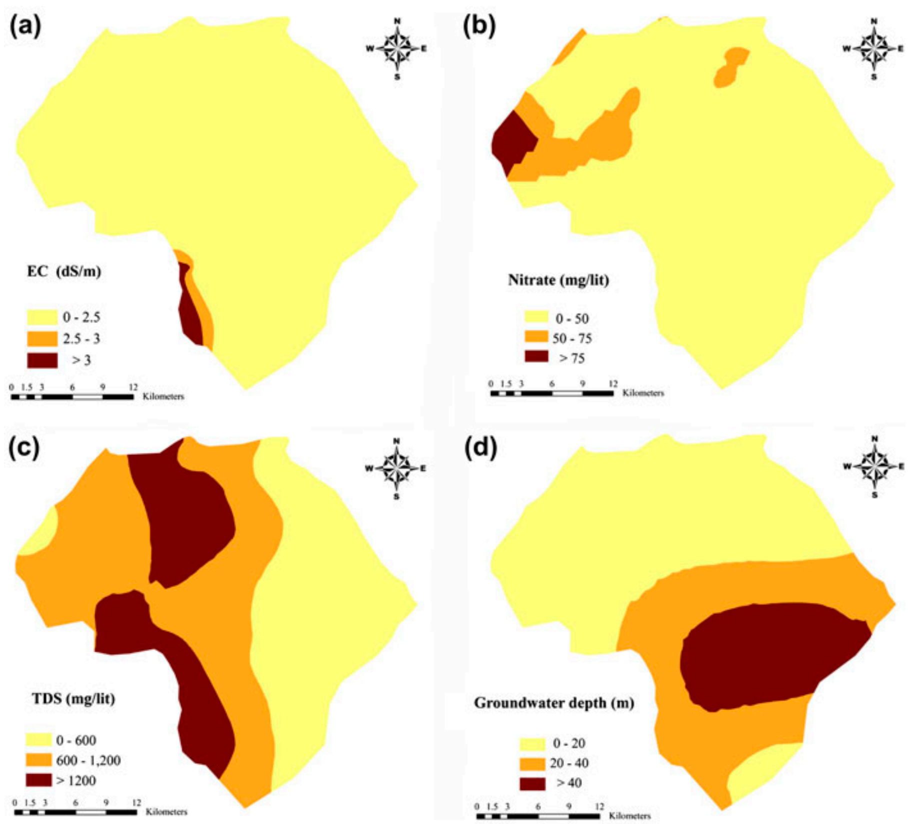

Fig. 4. Spatial variability maps of groundwater depth and quality parameters in the Ardabil plain: (a) EC; (b) nitrate; (c) TDS; and (d) groundwater depth.

ground surface. The groundwater depth variability map exhibited that about 53% of the study area had a groundwater depth occurring within 20 m, about 29% in 20–40 m, and 18% had a groundwater depth more than 40 m from the ground surface. The groundwater depth in the southeastern region exceeded 40 m and

Table 5
Delineated areas with different concentration limits and depth ranges of groundwater quantity and quality parameters in the study area

Total dissolved solids		Electrical conductivity		Nitrate		Groundwater depth	
Conc. limits mg l^{-1}	Area (%)	Conc. limits dS mg l^{-1}	Area (%)	Conc. limits mg l^{-1}	Area (%)	Range (m)	Area (%)
0–600	36	0–2.5	98	0–50	92	0–20	53
600–1,200	42	2.5–3	1	50–75	6	20–40	29
>1,200	22	>3	1	>75	2	>40	18

in the north region was 3.4–15.5 m, but in the south region was the lowest (0.31 m). In the study area, the groundwater depth increased from all sides toward the southeastern. The reason for this might be attributable to the increase in the overexploitation from the aquifer and hence groundwater table drawdown. Groundwater depletion as a result of overexploitation was reported in the Ardabil plain [54] and other parts of Iran [55]. This depletion of aquifers which was observed in many developing countries [56–59] has many negative consequences such as drying up of springs and ghanats, reduction of surface water supplies, deterioration of water quality and land subsidence.

The spatial variability maps of the quality parameters were classified in accordance with the WHO specification. The variability map of EC (Fig. 4(a)) shows that the EC values were higher toward the southwestern parts of the Ardabil plain. The high concentration of EC values in the southwestern part of the plain can be related to gypsum and salt formations in this part. From hydrochemical points of view, ion exchange process in the Miocene formations led to increase of the water salinity in the north–south direction. Generally, about 18.9 km^2 (2.3%) of the area has salinity values higher than the threshold value, restricting its use for drinking purpose. The spatial variability map of nitrate concentrations indicated that the majority of the nitrate load was located in the northwestern part of the study area (Fig. 4(b)). Table 5 shows that about 65.5 km^2 (8%) of the area had a nitrate concentration of more than 50 mg l^{-1} and unsafe limit for use. This higher nitrate concentration might be attributed to the combined effect of contamination from runoff from fertilized fields, domestic sewage, livestock rearing, industrial wastewater, and cattle sheds. Generally, the shallow portion of the aquifer is more contaminated by nitrate than the deeper portion primarily due to the shorter pathway for nitrate transport. Lower concentrations of nitrate in deep groundwater may occur due to low vertical gradients and the possibility of denitrification [60]. The variability map of TDS shows that the TDS values increased from the center part of the study area toward the west side (Fig. 4(c)). The southwestern and northern areas of the plain which showed the high concentrations of TDS are in conformity with Miocene formations. It was found that about 524.8 km^2 (64%) of the area had a TDS concentration of more than 600 mg l^{-1}. The eastern area of the plain corresponds to the principle recharge zone for the aquifer where TDS concentrations are low. The study area shows an increase of TDS concentrations from east to west along with the direction of groundwater flow. Generally, the distribution of TDS can represent groundwater flow direction to a certain context as its concentration increases along groundwater direction [61]. In addition, the fine-grained lithology in the northwest and west regions has high TDS concentration due, primarily, to longer residence time that increases the dissolution of minerals (primarily salts).

After creation of the spatial distribution maps, the best-fitted theoretical model and the semivariogram parameters were used to create the probability maps, showing the probability of exceedance of the threshold values in groundwater. The probability map of nitrate concentrations shows that high nitrate concentrations were found in the shallow groundwater in the north and northwest of the study region (Fig. 5(a)), indicating that shallow groundwater is prone to nitrate contamination. The probability of exceedance of the threshold value and their corresponding area are given in Table 6. It also found that for about 3% of the Ardabil plain, the probability of exceedance of the threshold value of nitrate concentration was the maximum, i.e. from 0.8 to 1.0. Similarly, the probability map of EC was created as shown in Fig. 5(b). It is observed from the probability map of EC and Table 6 that there is no higher probability of exceedance of the threshold value for EC in the Ardabil plain.

In general, it was seen that the ordinary kriging technique resulted in smoothing the effects of the lower and higher concentration model of pollutants in the data and resulting in poor exhibition of these values in the spatial variability maps. In contrast, the IK

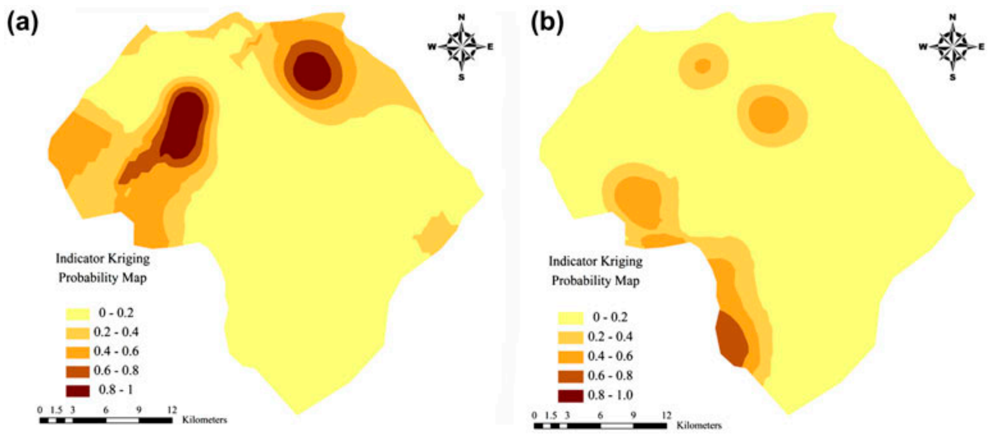

Fig. 5. Probability maps of (a) nitrate and (b) EC based on threshold values in the Ardabil plain.

Table 6
Delineated areas with different probability range and concentration thresholds of groundwater quality parameters in the study area

Probability range	Area (%)	
	Electrical conductivity	Nitrate
0.0–0.2	82	67
0.2–0.4	10	15
0.4–0.6	6	11
0.6–0.8	1	4
0.8–1.0	0	3

technique could characterize correctly the potential of different pollutant concentrations [62]. It provided information on the probability of pollution by different pollutants when there are the highest values in the data-set. Hence, the IK technique could be useful for evaluation of the risk presented by several pollutants that exceed the desirable value in drinking water and for the development of scientific groundwater management strategies for a region.

4. Conclusions

This study investigated the spatial distribution of groundwater depth and quality parameters in the northwest of Iran. The groundwater depth and quality parameters (NO_3, TDS, and EC) were lognormally transformed to ensure normality of the data trend. The spatial variability maps created using the ordinary kriging technique exhibited that the depth of groundwater levels tended to increase from the south and southeast of the Ardabil plain to the north. In particular, the groundwater level decreased an average of 2.6 m compared to the level measured a decade before, during 1999. The regions with high levels of salinity were found in the southwest part of the area. Thus, the use of groundwater for agriculture in these regions should ordinarily be avoided to prevent the damage to crops, causing in a poor yield. Furthermore, use of good-quality water, use of saline-resistant crop varieties, leaching with additional irrigation water for reduced salts of the root zone, and installation of a subsurface drainage system should be adopted as effective measures to prevent soil salinization and produce a conductive environment for correct growth of crops. A nitrate concentration exceeding the standard drinking level was found in the northwest part of the study area. In addition, a TDS concentration exceeding the standard drinking level in the groundwater was observed in the central part of the Ardabil plain toward the west side. The other parameters of groundwater quality, i.e. chloride, pH, sulfate, bicarbonate, calcium, sodium, magnesium, and TH had good quality and their values were lower than maximum threshold values suggested by WHO.

It is obvious that, if the appropriate management procedures are not implemented for the use of groundwater resources in the Ardabil plain, someday water resource quality in this region will be critical. Hence, prevention is better than cure. Therefore, attending the aim of the research, the spatial variability and probability of exceedance of groundwater depth and quality parameters were investigated and affected areas were identified. The maps and information created will help water resource managers in devising policy guidelines for efficient management of resources (surface and groundwater) for improving groundwater recharge and minimizing pollution levels for its sensible use for drinking.

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