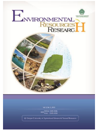

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Assessment of Geostatistical Methods for Determining Distribution Patterns of Groundwater Resources in Sari-Neka Coastal Plain, Northern Iran

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Abstract

This study aimed to evaluate the temporal change and accuracy of interpolation techniques used for spatial zonation of two groundwater quantity parameters including water table and depth to water table over 11 years. The study was conducted based on the data collected from piezometric wells of Sari-Neka Plain in Mazandaran Province, Iran. The investigated methods included a set of geostatistical approaches involving simple Kriging, ordinary Kriging, Radial Basis Function (RBF), and a deterministic interpolation method called Inverse Distance Weighting (IDW) with powers of 1 and 5. Subsequent to quality control and data normalization, the most appropriate variogram was chosen based on low RSS and high r^2 while the most suitable interpolation technique was determined regarding the cross validation, Mean Absolute Error (MAE), and Mean Bias Error (MBE). The results demonstrated that Simple Kriging was the most suitable method for zoning the depth to groundwater over the years 2001, 2006, and 2012. Meanwhile, the most suitable methods for zoning the water table included IDW with a power of 1for the year 2001, RBF for the year 2006, and IDW with a power of 5 for the year 2012. The important finding was that the interpolation methods showed a lower error for estimating water table than estimating depth to groundwater. This study also revealed a drop in water table in the study area over the 11 years' period. Meanwhile, new water table classes have been added and extended between the years 2006 and 2012 that had not existed five years earlier. The highest water table losses were observed in three points at 13m depth to water table in the middle and northern parts of the study area.

Keywords: Interpolation Methods, Variogram, Geostatistics, Groundwater, MAE, MBE

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Introduction

Gaining insight into spatial distribution of water resources is an important means to establish comprehensive planning and optimal use of available water resources. Supplying water for drinking, agriculture and industry needs is of great importance due to rapid population growth and increase in human demands. Because of the lack of consistency in the distribution of agricultural and industrial needs, the need for control and efficient use of water resources is greater than ever. Groundwater is the largest source of fresh water in the world. Groundwater provides a valuable source for water supply in shortage of surface water resources in arid lands (Shamsaei, 2010). The long-term climate records of Iran show that the annual mean precipitation (240 mm) is lower than one third of the world's annual mean precipitation (860 mm) emphasizing the country's arid climate (Khosravi *et al.,* 2012). According to a research completed by UN, Iran's water resources would likely range from 726 to 860 m^3 per capita in the year 2025 while it was estimated at 2200 m^3 per capita in the year 1990, indicating a big water shortage in the year 2025 (Abdi and Amini, 2002). Moreover, according to Kalyrad et al. (2012), aquifers of Iran are experiencing 5.5 billion cubic meters of shortages each year revealing their high sensitivity to over-exploitation (Alizadeh, 2003). The consequence of over-exploitation has been seen in a number of aquifers in the form of water table drop, shrinkage of reservoir, land subsidence, and even salt water intrusion contaminating drinking water (Data *et al.,* 1997). The situation of aquifers has forced authorities to prohibit further exploitation of groundwater resources in some parts of Iran. However, groundwater resources have mainly been used to supply agricultural and industrial needs in Sari-Neka region at Mazandaran Province. Using geostatistical techniques to investigate the changes in depth to groundwater and water table provides a means to spatial zonation of such parameters in order to assess the exploitation regime in the study area.

Several researches have been conducted to compare various interpolation techniques in different situations based on applying GIS as a tool in analysis of groundwater characteristics (e.g. Hutchinson, 1995., Collins, 1996., Feng *et al.,* 2004., Fang *et al.,* 2005., Li *et al.,* 2005, Kenneth, 1996., Wang *et al.,* 2004., Wei *et al.,* 2003; Xu and Cai, 2005). Dick and Gerard (2006) studied the optimization of sampling patterns of environmental variables using ordinary kriging in the Netherlands based on the average of maximum water table. They reported less variance for ordinary kriging than the ordinary cokriging as follows: 19% for 25 samples, 7% for 100 samples, 3% for 50 samples. Ghomshioun (2010) delineated the spatial zonation of groundwater depth using geostatistical techniques including kriging, cokriging, and the inverse distance method with a power of 1 to 5 in Semnan Province, Iran. He showed that the simple kriging method enhances the accuracy in estimating the depth to groundwater. Vijay and Remadevi (2006) displayed that kriging method provided higher accuracy than the inverse distance method in estimating groundwater level. Sun et al. (2009) reported that the kriging method provided more accurate results than the inverse distance and radial basic function methods for determining the temporal and spatial changes of depth to water table in China. They also showed a 10 m drop in water-table depth between 1981 and 2003. Kelinhu et al. (2005) revealed a six meters drop in depth to water-table since 1990 in North China Plain. Furthermore, they showed the effective ranges in groundwater level at 93.2, 19.2 and 55.3 km based on exponential, linear, and circular variograms.

Some researchers studied interpolation methods for the estimation of groundwater contamination (Mirzaei and Sakizadeh, 2016), for spatial distribution of heavy metals in groundwater (Arslan and Ayyildiz Turan, 2015), for groundwater depth and elevation (Nikroo *et al.,* 2010), for spatial representation of groundwater monitoring data (Fahid *et al.,* 2011) for groundwater level in Morocco (Khazaz *et al.,* 2015) and for groundwater level in arid land (Yaho *et al.,* 2014).

The main objective of this research is to assess the accuracy of various spatial interpolation methods including the ordinary and simple Kriging, the Radial Basic Function (RBF), and the Inverse Distance Weighting (IDW) with powers of 1 and 5. Moreover, this study aims to determine the best interpolation method for zoning of spatial-temporal changes in quantitative parameters involving water table and depth to groundwater, and distribution of groundwater resources over the years 2001, 2006 and 2012 in the study area.

Materials and Methods

The study area

The Sari-Neka Plain is an area of 1607 km^2 located at Mazandaran Province, Iran, between latitudes 36°28'N to 36°39'N and longitudes 52°43'E to 52°52'E. The study area is situated between the south coast of the Caspian Sea, the north of the Alborz Mountains, the east of Siahroud Basin, and the west of Shouresh Basin in Rostamkolah (Figure 1) with elevation ranging from -26 m (in the northern lowland plains connected to the Caspian Sea) to 95 m (in the southern parts). This area was chosen due to the following reasons: 1) connection to the sea, 2) high water consumption due to extensive agricultural practices such as existing numerous citrus orchards, 3) existing of a large number of distributed wells that enhances the accuracy of interpolation results knowing that the number and the spatial proximity of samples influence the outcomes of interpolation techniques (Sun *et al.,* 2009).

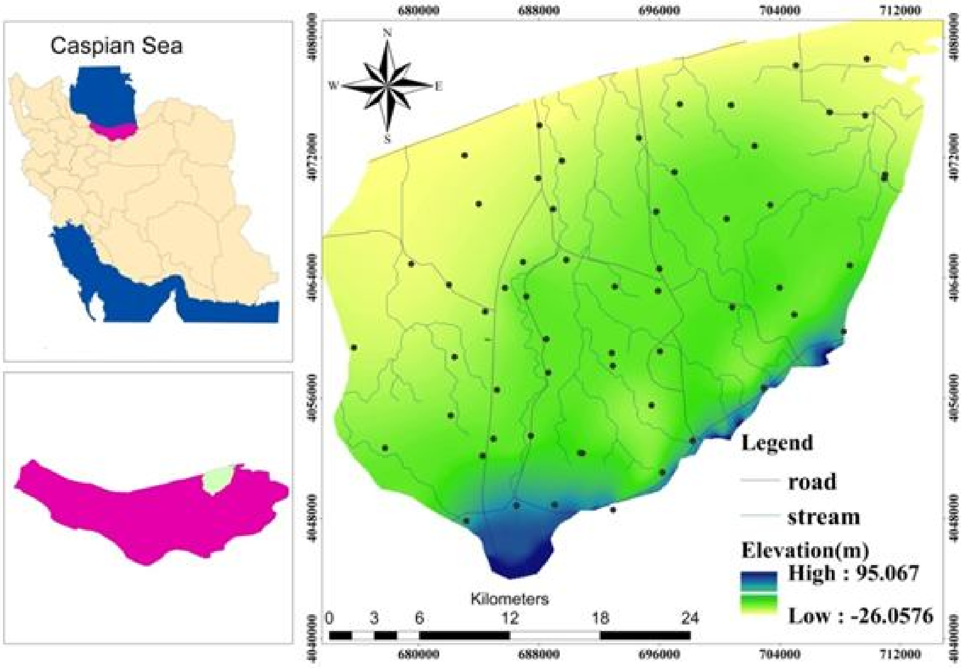

Figure 1. The location of the study area

Methods

In order to quantitatively predict the spatial distribution of groundwater, the data for groundwater depth and the absolute height of 55 wells in the study area were obtained from the Regional Water Company of Mazandaran Province. The obtained data were then screened to remove biased data from analysis. A common baseline time was selected for the study. On account of dependency of accuracy to data homogeneity or heterogeneity, even with good records in a station (Mahdavi, 2005), the 11 years of groundwater data were evaluated for accuracy and homogeneity based on sequence test (Kalyrad *et al.,* 2013). The test did not show heterogeneity in the data. Statistical errors were then determined by the multivariate correlation coefficient method. Meanwhile, the test of normality by Kolmogorov-Smirnov test did not show a normal distribution. The non-normal data were then transformed to normally distributed data using the Log-Normal Transformation method in GS+ software. The data were finally transformed back to the initial state using the Weighted Back Transformation method (Owsati *et al.,* 2012; Moradi *et al.,* 2011). The exact location of wells was determined in ArcGIS environment. After determining the depth to groundwater in each well, the level of water in the wells (absolute height) was calculated according to absolute height in marked-point. We needed to conduct a structural analysis or variography in order to fit the variogram model to spatial structure of data and determine the associated parameters including impact range, threshold, and partial impact. The best variogram was selected based on the low Root Mean Square Error (RMSE) provided by GS+ software. The spatial and temporal changes in quantitative parameters of groundwater including depth to water and water level were examined using a set of geostatistical approaches including simple Kriging, ordinary Kriging, Radial Basic Function (RBF), and Inverse Distance Weighting (IDW) with powers of 1 and 5. The evaluation of interpolation techniques and selection of the best one was completed using Cross Validation (CV) technique and the Mean Absolute Error (MAE) method representing the deviation of the estimation from observation such that the lower value is preferred.

Variogram Calculation

The semi-variogram is defined according to the measured points as follows:

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

where *N(h)* denotes number of pairs of samples used in the calculation for each distance *h*, *Z(x)* is the observed variable, and *Z(x+h)* is the observed variable situated in the distance *h* from *Z(x)* (Xie *et al.,* 2011). $\gamma(h)$ is variogram, which is also referred to as semi-variogram in some literature. This measure is used as variance in classic statistics while it is around the mean. The variogram measures the difference between two samples.

Variogram

The main purpose of calculating the variogram is to evaluate inconsistency of variables to spatial and temporal changes. In order to calculate a variogram, it is necessary to first calculate the average squared difference of points situated by a distance *h* and then plot it against *h* (Hassani pak, 2010).

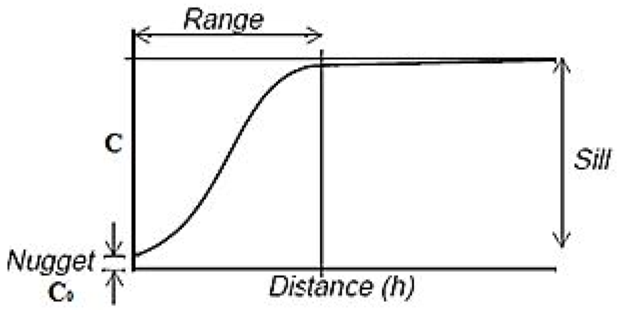

Figure 2. Components of a variogram

Interpolation methods

Kriging

Kriging is an unbiased estimator providing the minimum variance of estimation. The unbiasedness of kriging is very important due to removal of systematic errors in such a system (Kalyrad *et al.,* 2013). Kriging is based on the notion that the parameter

under interpolation can be considered as a regionalized variable. Compared to Inverse Distance Weighting (IDW) method, the kriging estimator is known by a linear combination of the observed values and weights. A certain type of kriging defines the linear constraint on weights supplied by the unbiased condition. There are different types of kriging such as simple kriging, ordinary kriging, and universal kriging that considers stochastic properties of random fields. Ordinary kriging is the most commonly used one among the different types of kriging (Xie *et al.,* 2011). The weights are extracted from the equations of kriging by a semivariance function such that the parameters of the function and the nugget effect can be assessed using an empirical function of semivariance (Webster and Oliver, 2007).
The estimator of simple kriging can be expressed by the following equation:

$$Z^*(x_0) = m + \sum_{i=1}^{n} \lambda_i [Z(x_i) - m] \quad (2)$$

where $Z^*(x_0)$ is the estimate value at x_0, n denotes the number of values used for the estimation, m is the mean, $Z(x_i)$ is the measure value at $x_i; \lambda_i$ stands for the weight assigned to the residual $Z(x_i)$, and the summation is 1 (Li et al.2000; Zhang 2005).
In addition to simple kriging, the estimator of ordinary kriging can be defined as follows:

$$Z^*(x_i) = \sum_{i=1}^{n} \lambda_i Z(x_i) \quad (3)$$

where the variables are defined similar to the Eq. 2.
Radial Basis Function (RBF)
This method is an exact interpolator based on a basic equation that depends on the distance between the interpolated and sampling points (Aguilar et al., 2005). For this research, the multi-quadratic RBF was used as follows:

$$\phi(r) = \sqrt{(r^2 + c^2)} \quad (4)$$

where r is the distance from sample to prediction location and c is a smoothing factor.

Inverse Distance Weighting (IDW)
This method is based on the assumption that predictions are a linear combination of existing data. The following notation defines the method:

$$Z(x) = \frac{\sum_{i=1}^{n} \frac{w_i}{z_i}}{\sum_{i=1}^{n} w_i} \quad (5)$$

$$w_i = d_i^{-u} \quad (6)$$

where $Z(x)$ denotes the predicted value at an interpolated point, Zi located at a given point, n represents the total number of given points applied in interpolation, d_i stands for the distance between point i and the point of prediction, and w_i denotes the assigned weight to point i. The higher the distance, the higher is the assigned weight (Shepard, 1968). Lastly, u stands for the weighting power determining decrease of weight whenever the distance increases.

Validation

We used the Cross Validation (CV) method for assessing the accuracy of applied statistical models. In this method, a value for a known point was calculated based on the adjacent values. The actual amount was then returned to the previous location while the operation repeated for all grid points. Finally, according to the observed and estimated values, accuracy of each method was calculated regarding the statistical criteria. Moreover, two methods including Mean Absolute Error (MAE) and Mean Bias Error (MBE) were applied to evaluate the adopted methods. MAE represented the accuracy while MBE represented the deviation of model as follow:

$$MAE = \frac{\sum_{i=1}^{n} |Z^*(xi) - Z(xi)|}{n} \quad (7)$$

$$MBE = \frac{\sum_{i=1}^{n} (Z^*(xi) - Z(xi))}{n} \quad (8)$$

where $Z^*(xi)$ denotes the estimated value while $Z(xi)$ denotes the observed value.

Results and Discussion

The general trend of groundwater level

The spatial variation of water level over the years 2001 and 2012 are shown in Figures 3 and 4. Figure 3 illustrates a higher water level in the middle part than the eastern and western parts of the plain while forming a U shape from north to south. However, as depicted in Figure 4, groundwater level reduces from east to west and from south to north. It is worth mentioning that regarding DEM and Figure 4, ground water level follows the topography of the plain. The trend of groundwater level and the Z-axis values indicates the lack of rainfall, aquifer over-exploitation and distribution of spatial patterns of water.

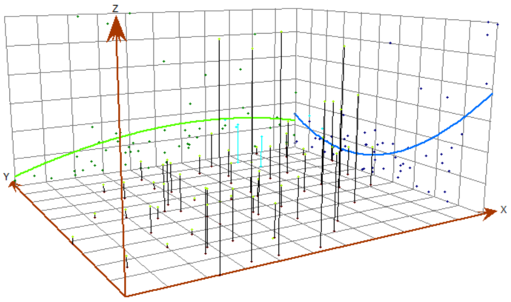

Figure 3. The spatial variations in groundwater table in 2002

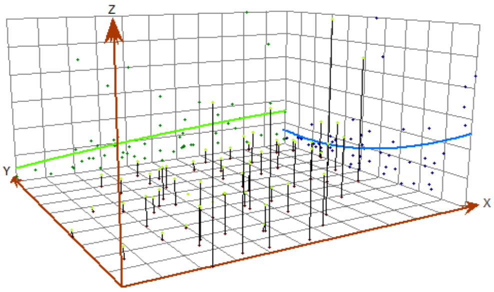

Figure 4. The spatial variations in groundwater table in 2012

The experimental variograms were plotted for different levels and depths using GS+ software. The best model and theory was then selected for fitting the variogram according to the values of RSS, r2, and the ratio of C/C_0+C (Table 1).

Table 1. Best-fitted variogram models of water table and depth for the years 2001, 2006 and 2012 and their parameters

Model	Year-Parameter	Nugget	Sill	Effective range(m)	C/C_0+C	r^2	RSS
Spherical	2001-Water table	0.24	0.69	24870	0.64	0.92	0.015
Spherical	2006-Water table	0.31	0.91	18430	0.65	0.94	0.017
Spherical	2012-Water table	0.24	0.7	22690	0.66	0.94	0.01
Linear	2001-Depth	0.47	0.47	30293	0	0.023	0.014
Linear	2006-Depth	0.47	0.47	30293	0	0.019	0.0149
Linear	2012-Depth	0.46	0.48	32158	0.045	0.024	0.018

Based on the water table and the depth to groundwater in Table 1, the spherical model was chosen as the best theoretical model while the linear model provided the best fit with data in all the three years of experiment. The ratio of nugget effect to sill (C/C_0+C) was used to assess the strength of a variable. The ratio ranges between 0 and 1 indicating the worst to best scale. The ratio also represents how much of the total variability may be explained by the nugget effect (Deutsch and Journel, 1998). If the value is less than 0.5, the variable has a weak spatial structure telling that geostatistical methods will not provide useful results (Hamidianpour et al., 2013). In this study, groundwater level showed a robust spatial structure in three time steps. Although, some other structures of water level indicated a higher value of the nugget effect to sill ratio in the spherical structure, the spherical model was chosen as the best model due to the higher r^2 and lower RSS in three time steps. In terms of water depth in the years 2001, 2006 and 2012, the linear model was preferred due to the higher r2 and lower RSS. However, according to the value 0 of the ratio C/C_0+C, applying the geostatistical methods did not provide a useful outcome.

Cross Validation

The cross validation technique was used to identify the best interpolation method (Tewolde et al., 2010). The procedure was accomplished through comparing different methods including simple kriging and ordinary kriging, RBF, and IDW with powers 1 and 5 for interpolating groundwater depth and water table in Sari-Neka Plain for the years 2001, 2006 and 2012 (Table 2).

Table 2. Determining the best method for interpolating the groundwater level and groundwater depth

Interpolation Method	Parameter	2001		2006		2012	
		MBE	MAE	MBE	MAE	MBE	MAE
Ordinary Kriging	Water table	-0.07	2.28	-0.109	2.50	-0.150	49/2
RBF	Water table	-0.14	2.29	-0.23	2.19	-0.124	2.43
Simple Kriging	Water table	-0.04	2.30	-0.130	2.64	-0.319	2.86
IDW (Power 1)	Water table	-0.276	1.63	-0.425	2.49	-0.467	2.42
IDW (Power 5)	Water table	0.14	2.81	-0.244	2.53	-0.242	2.499
Ordinary Kriging	Depth	-2.14	14.52	-2.14	14.52	-2.14	14.52
RBF	Depth	0.5	18.64	0.529	18.67	3.09	29.53
Simple Kriging	Depth	-2.29	14.71	-2.51	14.60	-2.51	14.60
IDW (Power 1)	Depth	0.4	19.09	0.32	18.38	0.32	18.38
IDW (Power 5)	Depth	0.92	20.48	-0.915	20.53	0.915	20.53

Interpolation accuracy is a relative concept depending on criteria and interpolation objectives. According to Table 7, ordinary kriging was selected as the best method for interpolating depth to groundwater in all the three time steps 2001, 2006 and 2012. Moreover, the value of MAE was calculated 14.52 in all time steps. Therefore, the models of depth to groundwater were used to determine the spatial and temporal distribution patterns of water during the years 2001 to 2012 due to the lack of strong spatial structure of the water table. The best methods to interpolate water table in different years were chosen as follows: for 2001, the IDW method with power 1 and the least value of MAE (1.63); for 2006, the RBF method with the least value of MAE (2.19), and for 2012, the IDW method with power 1 and MAE value of 2.46. The obtained results in Table 7 reveal that the greater the power of the IDW method, the lower is the accuracy of the results. The outcomes are in line with findings of Xie et al (2011) expressing that increase in the power of IDW method enhances the value of RMSE. The IDW and RBF interpolators predicted exactly similar values to the measured values (Xie *et al.,* 2011). The RBF approach may predict the values higher than the maximum and less than the minimum measured values while the predicted minimum and maximum values of the IDW method exactly follows that of the measured sample. However, the IDW method is highly sensitive to the value of power in which increase in the weighting power causes the prediction value to approach the value of the nearest sample (Xie et al. 2011). There were three main purposes in this research in order to generate interpolated maps of groundwater table for the coastal plain: (i) determining the spatial distribution, (ii) determining the temporal distribution, and (iii) determining the alternations in groundwater table in accordance with over-exploitation of groundwater resources.

Determining the distribution patterns, and spatial and temporal changes of groundwater resources

Figures 5, 6, and 7 show the spatial and temporal distribution of water table in Sari-Neka Plain for the years 2001, 2006, and 2012. Table 3 provides the lower mean and median water table in the years 2006 and 2012 than the year 2001 showing a declining trend. The water table was declined 0.93 meters over 11 years' period between 2001 and 2012 with an average loss of 0.087 m per year. However, due to over-exploitation of groundwater resources in the area (depth to groundwater is about 13 m) further research is required to find out the accuracy of the assessed loss in water table taking into account replacement of fresh groundwater with sea water.

Table 3. Statistical results of water table for 58 observation wells.

Year	Mean Water Table(m)	Minimum Water Table(m)	Median Water Table(m)	Maximum Water Table(m)	Decline Rate(m a-1)	Mean Decline Rate(m a-1)
2001	4.63	1.4	3.45	17.3		
2006	4.03	0.25	3.16	17.88	0.12	0.087
2012	3.70	0.61	2.64	21.62	0.055	

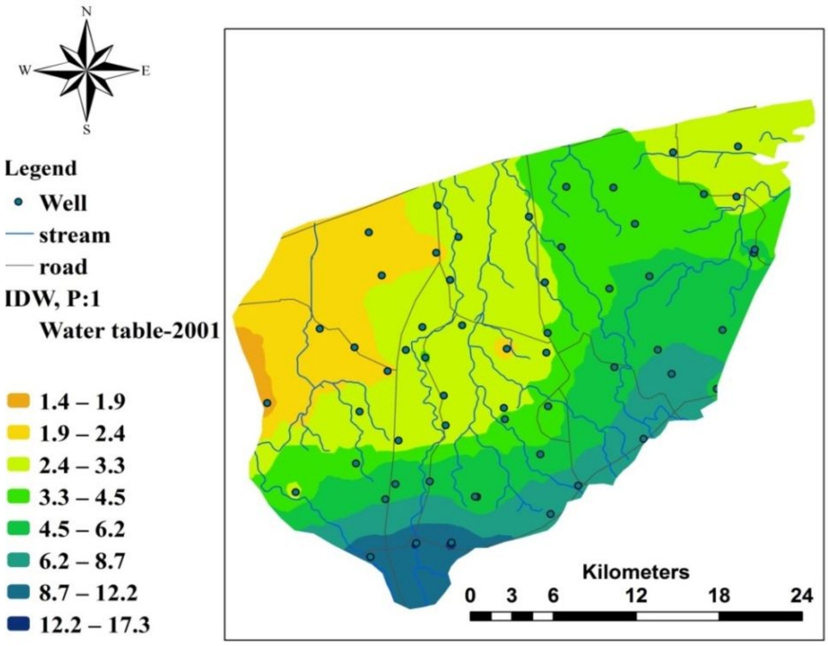

Figure 5. The IDW method with power of 1 for water table in 2002

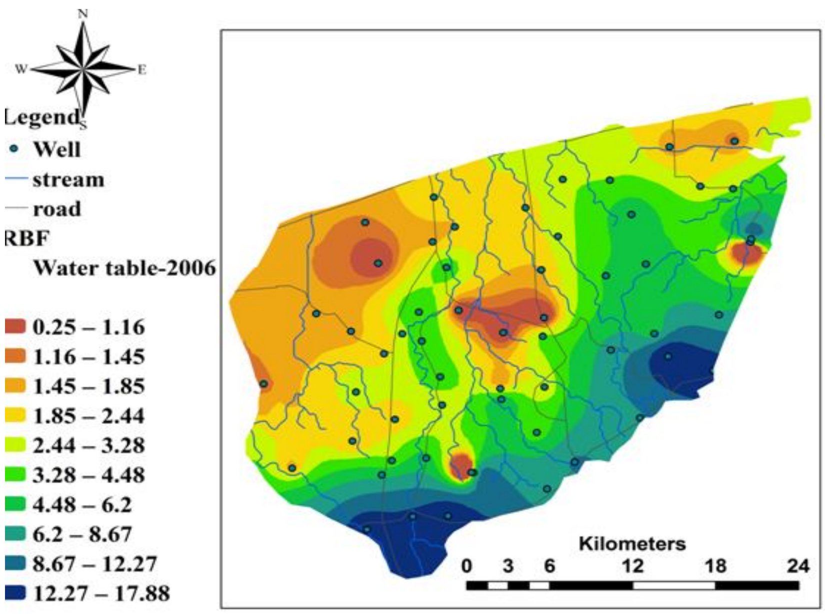

Figure 6. The RBF method for water table in 2006

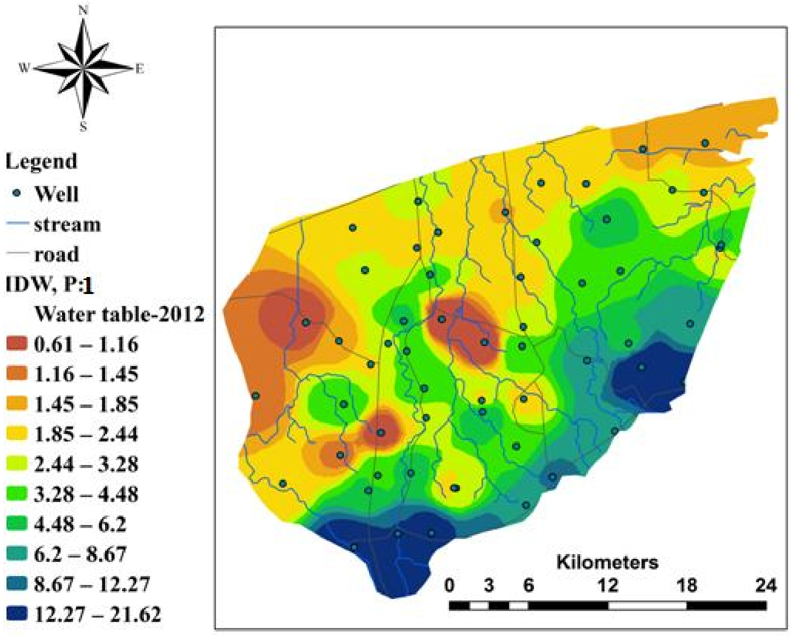

Fig. 7 The IDW method with power of 1 for water table in 2012

Table 4. Area and percentage for different classes of water table

Classes	Area of water table in 2001	Percentage	Area of water table in 2006	Percentage	Area of water table in 2012	Percentage
0.25-1.16	0	0	26.41	1.64	41.5	2.58
1.16-1.45	0	0	37.46	2.33	66.52	4.13
1.45-1.85	15.78	0.98	233.37	14.52	114.44	7.12
1.85-2.44	264.86	15.36	328.51	20.44	412.10	25.64
2.44-3.28	402.54	25.04	243.36	15.14	185.9	11.56
3.28-4.48	238.68	14.85	166.11	10.33	180.4	11.22
4.48-6.20	240.52	14.96	168.7	10.49	87.4	5.43
6.20-8.67	367.98	22.89	169.3	10.53	194.4	12.05
8.67-12.22	94.78	5.89	126.7	7.88	159.1	9.9
12.22-21.62	0.67	0.04	107.80	6.70	166.8	10.37

Note: The first and last classes were considered the same in order to unify the three periods.

Table 5. Mean annual precipitation of Sari-Neka Plain

Year	Mean annual precipitation(mm)
2001	585.25
2006	723.07
2012	831.38

Results in Table 4 show no water table classes 1.16, 0.25, 1.45, and 1.16 m in the study area in the year 2001. However, these classes were present in the years 2006 and 2012 indicating a drop in water table. Moreover, the area of aforementioned classes doubled between 2006 and 2012 showing an ongoing utilization of groundwater resources. Meanwhile, as shown in Table 5, the loss of groundwater table accelerated from 2006 to 2012 even though the precipitation increased almost 110 mm over the same period. In 2002, the class 2.44-3.28 m of the water table covered the largest area (402.54 km^2) occupying almost a quarter of the size of the aquifer. In 2006, the class 1.85-2.44 m of the water table occupied the largest area (328.51 km^2) covering 20.44% of the aquifer. In 2012, the same class in 2006 covered the biggest area (412.10 km^2) occupying 25.61% of the aquifer. Figures 5, 6, 7 and Table 4 reveal that the upper-middle classes declined while the lower classes replaced them indicating the decline of the aquifer during the study period. Meanwhile, the groundwater level increased from the area close to Caspian Sea coast in the north (-26 m) to the area close to Alborz Mountains in the south, implying that groundwater level follows surface topography. Furthermore, the citrus orchards and agricultural activities are highly reduced in the southern parts of the study area due to proximity to highlands that cause reduction in water utilization in the area. It is anticipated that increase in rainfall would expand the classes of water table, which are close to the highlands (see two last rows of Table 4), and even causing a rise in water table. The important issue in utilization of groundwater in this area is replacement of fresh water with salt water due to connection to the sea and having a sandy textured soil with a high hydraulic conductivity. The highest loss in water table between 2001 and 2012 has been occurred in the middle and northern parts of the study area in three points at 13 m depth to water table. It is recommended that quality of water for drinking and agricultural purposes be examined due to the possibility of salt water contamination and chemical pesticides pollution.

Summary and Conclusions

Analysis of semi-variogram and evaluating various methods of interpolation revealed that the semi-variogram of water table and depth to groundwater in Sari-Neka Plain follows a spherical and linear model, respectively. Analysis of interpolation methods revealed that water table has generally changed according to the area's gradient of topography such that the higher the slope, the higher is water table considering the distance from sea to highlands. Analysis of water table by MAE and MBE demonstrated a very strong spatial structure over the study period. The value of nugget effect to sill ratio (C/C_0+C) for depth to groundwater was calculated zero over the study period indicating a weak spatial structure of the linear model. This suggests that implementing geostatistical methods for analyzing depth to groundwater in the study area could not provide reliable outcomes. In terms of water table zoning, the most suitable methods included IDW with a power of 1 for the year 2001, RBF for the year 2006, and IDW with a power of 5 for the year 2012. Generally, the interpolation methods showed less error for water table than depth to groundwater. In IDW method, increase in the power from 1 to 5 increased the amount of error. This study revealed that the water table has declined over 12 years due to high utilization of fresh groundwater (8.7 cm per year). The highest water table loss was observed at 13 m depth to water table and water table class 0.6-1.16 m in three points of the middle and northern parts of the study area. In the year 2002, the water table class 2.44-3.28 m, and in the years 2006 and 2012, the water table class 1.85-2.44 m were largest in area, covering 25.04%, 20.44%, and 25.61% of the aquifer, respectively. There were no water table classes 0.25-1.16 m and 1.16-1.45 in the study area in the year 2001. However, those classes have been added to aquifer in 2006 and 2012 with an accelerating trend.

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