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Geostatistical Analysis of Spatial and Temporal Variations of Groundwater Level

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Abstract Groundwater and water resources management plays a key role in conserving the sustainable conditions in arid and semi-arid regions. Applying management tools which can reveal the critical and hot conditions seems necessary due to some limitations such as labor and funding. In this study, spatial and temporal analysis of monthly groundwater level fluctuations of 39 piezometric wells monitored during 12 years was carried out. Geostatistics which has been introduced as a management and decision tool by many researchers has been applied to reveal the spatial and temporal structure of groundwater level fluctuation. Results showed that a strong spatial and temporal structure existed for groundwater level fluctuations due to very low nugget effects. Spatial analysis showed a strong structure of groundwater level drop across the study area and temporal analysis showed that groundwater level fluctuations have temporal structure. On average, the range of variograms for spatial and temporal analysis was about 9.7 km and 7.2 months, respectively. Ordinary and universal kriging methods with cross-validation were applied to assess the accuracy of the chosen variograms in estimation of the groundwater level drop and groundwater level fluctuations for spatial and temporal scales, respectively. Results of ordinary and universal krigings revealed that groundwater level drop and groundwater level fluctuations were underestimated by 3% and 6% for spatial and temporal analysis, respectively, which are very low and acceptable errors and support the unbiasedness hypothesis of kriging. Although, our results demonstrated that spatial structure was a little bit stronger than temporal structure, however, estimation of groundwater level drop and groundwater level fluctuations could be performed with low uncertainty in both space and time scales. Moreover, the results showed that kriging is a beneficial and capable tool for detecting those critical regions where need more attentions for sustainable use of groundwater. Regions in which were detected as critical areas need to be much more managed for using the current water resources efficiently. Conducting water harvesting systems especially in critical and hot areas in order to recharge the groundwater, and altering the current cropping pattern to another one that need less water requirement and applying modern irrigation techniques are highly recommended; otherwise, it is most likely that in a few years no more crop would be cultivated.

Keywords water resources management · groundwater level fluctuations · geostatistics · kriging · spatial analysis · temporal analysis

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1 Introduction

Groundwater is the main source of irrigation in arid and semi-arid regions across the world. Growing population causes more use of fresh water resources for more crop production. Crop production in the arid zone consumes large quantities of water. While the production of 1 kg of grain in the temperate zone takes less than 0.5 m^3 of water, 1.5–2.5 m^3 is normal in the arid zone. Irrigated crop production in the arid zone therefore exerts a heavy toll on the available scarce fresh water resources (Smedema & Shiati, 2002).

Groundwater is, however, the main and more reliable resource of irrigation. Both over-exploitation from aquifers to address the irrigation needs, and drought events have caused severe water table level drop in many areas. Where groundwater is used for irrigation, aquifers are also being depleted at an alarming rate. In Iran, the current groundwater abstraction exceeds the safe yields by some 15%–20% and water tables in some irrigated areas are falling at 0.5–1.0 m per year (Shiati, 1999). The situation is equally alarming in some parts of the Indo-Gangetic plains in India, the North China Plain and in the south-west of the USA (Smedema & Shiati, 2002).

Iran is located in an arid to semi-arid region of the world and about 95% of fresh water is allocated for agriculture, out of which 80% is supplied through groundwater. So, it is clearly concluded that groundwater is the vital component for sustainable agriculture. In recent years, many fertile and agricultural plains suffered from 0.5 to 15 m water table level drop, in which many wells are now out of use. Serious restrictions and regulations about increasing the number of agricultural wells in problematic areas are established by the government.

Monitoring of groundwater level of observation wells is the principal source of information on the effects of hydrologic stresses on groundwater systems. Water level data collected over periods of days to months are useful for such purposes; however, data collected over years to decades are required to address the long term effects of aquifer development and to compile a hydrologic record that defines water level fluctuations. A long term record of groundwater level measurements should encompass the period between the natural and the developed state of aquifer systems. Such records are invaluable in understanding and correcting problems that have developed in response to local and regional patterns of groundwater withdrawal and changes in land use (Alley & Taylor, 2001). Understanding the behavior of the groundwater body and its long term trends are essential for making any management decision in a given watershed (Reghunath, Sreedhara Murthy, & Raghavan, 2005). Therefore, having a deep knowledge and insight on the groundwater system seems necessary for optimum exploitation of the water.

Since groundwater is one of the main water resources in arid regions, it needs to be managed much more efficiently than other climates. The recently large variations of groundwater levels over years in many parts of Iran, suggest a precise and detailed study to be undertaken to elucidate the behavior of groundwater level fluctuations in both, spatial and temporal scales. A very useful tool for analyzing such processes is geostatistics (Rouhani & Wackernagel, 1990). Reghunath et al. (2005) and Kumar, Sondhi, and Phogat (2005) have emphasized the use of geostatistics for the better management and conservation of water resources and sustainable development of any area. They have reported that geostatistical methods are good tools for water resources management and can effectively be used to derive the long term trends of the groundwater (Reghunath et al., 2005). Nevertheless, several studies have been conducted to investigate the spatial variations of groundwater level, but less attention has been paid to the analysis of temporal variations of groundwater level due to lack of enough, frequent and regular data measurement in consecutive years since funding may be limited and groundwater level monitoring is a time- and labor-consuming process.

Theodossiou and Latinopoulos (2006) worked on spatial analysis of groundwater level of 31 wells using kriging, but they did not do any temporal analysis. However, they reported some simple statistical analysis such as maximum and minimum value, mean, median, and standard deviation on their data obtained from two year groundwater level observation.

Li and Revesz (2004) applied several interpolation methods to investigate the spatial-temporal variation of regionalized variables. They enriched their existing dataset with those of measured in different time periods. They used either the reduction method that treats time independent from the spatial dimensions or the extension method that introduces time as another spatial dimension.

Desbarats, Logan, Hinton, and Sharpe (2002) used the collateral information from a digital elevation model to estimate water table elevation in aquifer systems. They assumed that water table elevation is affected by earth topography and they are interrelated.

Olea and Davis (1999a) in a comprehensive study applied the kriging to estimate the water level at each observation well using the cross-validation method. Furthermore, they proposed some new observation wells based on kriging standard deviation. High standard deviation in kriged points revealed low network density areas (Olea & Davis, 1999b). In another application of kriging, Triantafilis, Odeh, Warr, and Ahmed (2004) used the non-linear kriging method for mapping the salinity risk of farmlands using saline groundwater as the source of irrigation. Their results proved the potential of geostatistics methods to simulate the critical conditions of salinization.

Christakos (2000) performed the geostatistical analysis on water table elevation of about 70 wells in Kansas. The measurements of water table elevation were made frequently during the observation period. Due to some uncertainty and error in reading the water elevations, he applied the geostatistics to simulate those unreliable values. He also mapped the simulated water table elevation year by year and determined the direction of groundwater level drop. Standard deviation maps helped him to propose some new observation wells in regions having high standard deviations.

Sophocleous, Paschetto, and Olea (1982) conducted geostatistical analysis on water table elevation of approximately uniformly spaced observation wells along profiles in different geographical directions, northwest Kansas. They found a relatively strong spatial relationship between the water table elevations of the wells; and presented the kriged map of water table elevation. Furthermore, based on the error map (standard deviation of estimations) they suggested a network for groundwater management. Similar study has been reported by Pucci and Murashige (1987). They used kriging for optimizing data collection and utility in a regional ground water investigation in central New Jersey and showed that kriging is a useful tool to elucidate those areas lacking enough data for developing a water table management network. Similarly, Prakash and Singh (2000) used the kriging technique and determined optimum number of observation wells that can be added to the existing network of the study area for monitoring spatial distribution of groundwater level. However, the other researches citing the applicability of geostatistics on groundwater level are Ma, Sophocleous, and Yu (1999), Nunes, Cunha, and Ribeiro (2004), Rouhani and Wackernagel (1990) and Tonkin and Larson (2001).

Among the studies that have focused on temporal analysis of groundwater, Tuckfield (1994) used the appropriate sampling frequency for monitoring groundwater well contamination. He used temporal variogram to find the suitable sampling interval. In a similar study Cameron and Hunter (2002) applied spatial and temporal analysis to find the most suitable sampling network and sampling frequency of groundwater contaminants. Kumar and Ahmed (2003) monitored the groundwater level during 12 months of the year and used the kriging method to estimate groundwater level for unmeasured points and wells for each month.

In this study, we applied the geostatistics as a management and decision support system tool for analyzing spatial and temporal variations of groundwater level fluctuations so that we can achieve a better picture of the behavior of aquifer system over a long period (temporal) and large area (spatial) scale. In this way, based on the findings of the study management on the current water resource can be applied efficiently.

2 Materials and Methods

The theoretical basis of geostatistics has been fully described by several authors (Goovaerts, 1997; Isaaks & Srivastava, 1989; Kitanidis, 1997). The main tool in geostatistics is the variogram which expresses the spatial dependence between neighboring observations. The variogram, $\gamma(h)$, can be defined as one-half the variance of the difference between the attribute values at all points separated by h as follows:

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

where $Z(x)$ indicates the magnitude of variable, and $N(h)$ is the total number of pairs of attributes that are separated by a distance h.

Prior to the geostatistical estimation, we require a model that enables us to compute a variogram value for any possible sampling interval. The most commonly used models are spherical, exponential, Gaussian, and pure nugget effect (Isaaks & Srivastava, 1989). The adequacy and validity of the developed variogram model was tested satisfactorily by a technique called cross-validation. The idea of cross-validation consists of removing a datum at a time from the data set and re-estimating this value from remaining data using different variogram models. Interpolated and actual values are compared, and the model that yields the most accurate predictions is retained (Goovaerts, 1997; Isaaks & Srivastava, 1989; Leuangthong, McLennan, & Deutsch, 2004). Crossing plot of the estimate vs the true value shows the correlation coefficient (R^2). The most appropriate variogram was chosen based on the highest correlation coefficient by trial and error procedure.

Kriging technique is an exact interpolation estimator used to find the best linear unbiased estimate. The best linear unbiased estimator must have minimum variance of estimation error. Among the different kriging methods, we used ordinary and universal kriging for spatial and temporal analysis, respectively. Ordinary and universal kriging methods are mainly applied for datasets without and with a trend, respectively. Detailed discussions of kriging methods and their descriptions can be found in Goovaerts (1997). The general equation of linear kriging estimator is:

$$Z^*(x_p) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{2}$$

In order to achieve unbiased estimations in ordinary kriging the following set of equations should be solved simultaneously.

$$\begin{cases} \sum\limits_{i=1}^{n} \lambda_i \gamma(x_i, x_j) - \mu = \gamma(x_i, x) \\ \sum\limits_{i=1}^{n} \lambda_i = 1 \end{cases} \tag{3}$$

where $Z^*(x_p)$ is the kriged value at location x_p, $Z^*(x_i)$ is the known value at location x_i, λ_i is the weight associated with the data, μ is the Lagrange multiplier, and $\gamma(x_i, x_j)$ is the value of variogram corresponding to a vector with origin in x_i and extremity in x_j.

The general equations of unbiased universal kriging which must be solved simultaneously are as follows.

$$\begin{cases} \sum\limits_{i=1}^{n} \lambda_i \gamma(x_i, x_j) - \sum\limits_{i=1}^{n} \mu f(x_i) = \gamma(x_i, x) \\ \sum\limits_{i=1}^{n} \lambda_i = 1 \\ \sum\limits_{i=1}^{n} \lambda_i f(x_j) = f(x) \end{cases} \tag{4}$$

where $f(x)$ is the type of function used to model the trend and is directly suggested by the physics of the problem (Goovaerts, 1997). The GS$^+$ software (version 5.1.1) was used for geostatistical analysis in this study (Gamma Design Software, 2001).

Available monthly groundwater level (depth to water table) of 39 piezometric wells monitored continually from 1993 to 2004 has been used. These wells are distributed across the study area to represent the fluctuations of groundwater level of the whole area of plain. The data recorded for each well consisted of average monthly water table level, totally 144 measurements for each well for 12 years (Fars Regional Water Organization, 2005). Handling the data set, we omitted a few values from the data set of some wells as being considered completely erroneous values; consequently, there exist less than 144 values in the data set of few wells. Nevertheless, there exist some outliers or extreme values which were not removed from the data set since according to Goovaerts (1997) in environmental applications large values may indicate potentially critical points so they should be removed only if they are clearly wrong.

Because of considerable and drastic water table drop, the Darab plain is recognized as a critical plain and augmenting more agricultural wells is strictly prohibited by the government. The aquifer under study is continuous, unconfined, sedimentary and nonhomogenous and is composed of sedimentary layers. Due to large variations of the diameters of sediment particles, the transmissivity of the aquifer ranges between 8 and 4500 m^2/day for different parts of the aquifer, and the average storage coefficient is reported 0.07 (Fars Regional Water Organization, 2005).

The number of existing legally and illegally agricultural wells are reported about 4,403 with an average annual discharge of 635×10^6 m^3, and 767 with an average annual discharge of 110×10^6 m^3, respectively. Due to severe droughts in recent years, no groundwater is present in about 500 agricultural wells. Out of 277 mm of rainfall, 65% is used for evapotranspiration, 23% infiltrates into soil, and 12% is converted to runoff. Annually, 380×10^6 m^3 is recharged into the aquifer. Based on the data of 16 years (1990–2005), the water balance of the plain was about -350×10^6 m^3 (Fars Regional Water Organization, 2005). It means that annual water demands are nearly two times greater than the corresponding recharge, resulting in a significant decrease in the non-renewable groundwater reserves. However, more valuable data e.g., reliable seasonal discharges from numerous agricultural wells for different months of the year throughout the study area, groundwater flow direction(s), and geological structure of the study area that can be used in conclusion of the result of our study were not available through the Fars Regional Water Organization (2005) or other relevant organizations due to lack of financial supports for data collection in last years. Obviously, such preliminary data are required for better conclusion of aquifer systems behavior.

3 Study Area

The study area is the Darab plain which is located in south-east of Fars province, south of Iran; between 28° 35′–28° 44′ northing and 54° 13′–54° 44′ easting, with an elevation about 1,110 m above sea level. Figure 1 shows the study area. Average rainfall, from 1993 to 2004 is 277 mm and the average temperature varies from 3 °C in January to 42 °C in July. Its climate is warm and dry. Wheat, barely, corn, cotton and citrus trees are extensively cultivated in this area. Due to both severe droughts in recent years and overexploitation of groundwater for irrigation purposes, the groundwater level has declined, on average, about 12.6 m in 12 years (1993–2004) (Fars Regional Water Organization, 2005).

Figure 2 shows the geographical location of piezometric wells. The coordinates system used in Figure 2 is Universal Transverse Mercator (UTM). The datum of this system is World Geodetic System of 1984 (WGS 1984) upon which Global Positioning

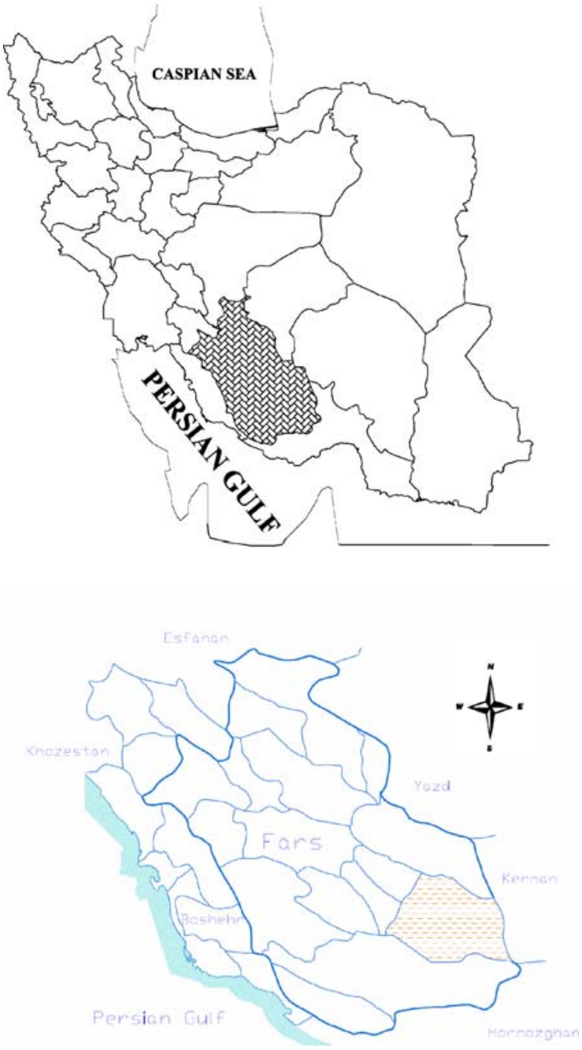


Figure 1 The location of the study area (hatched area includes the study area).

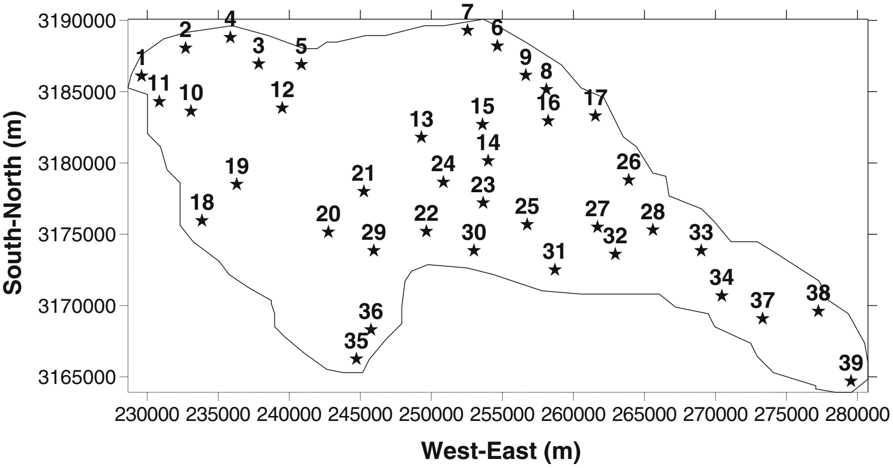
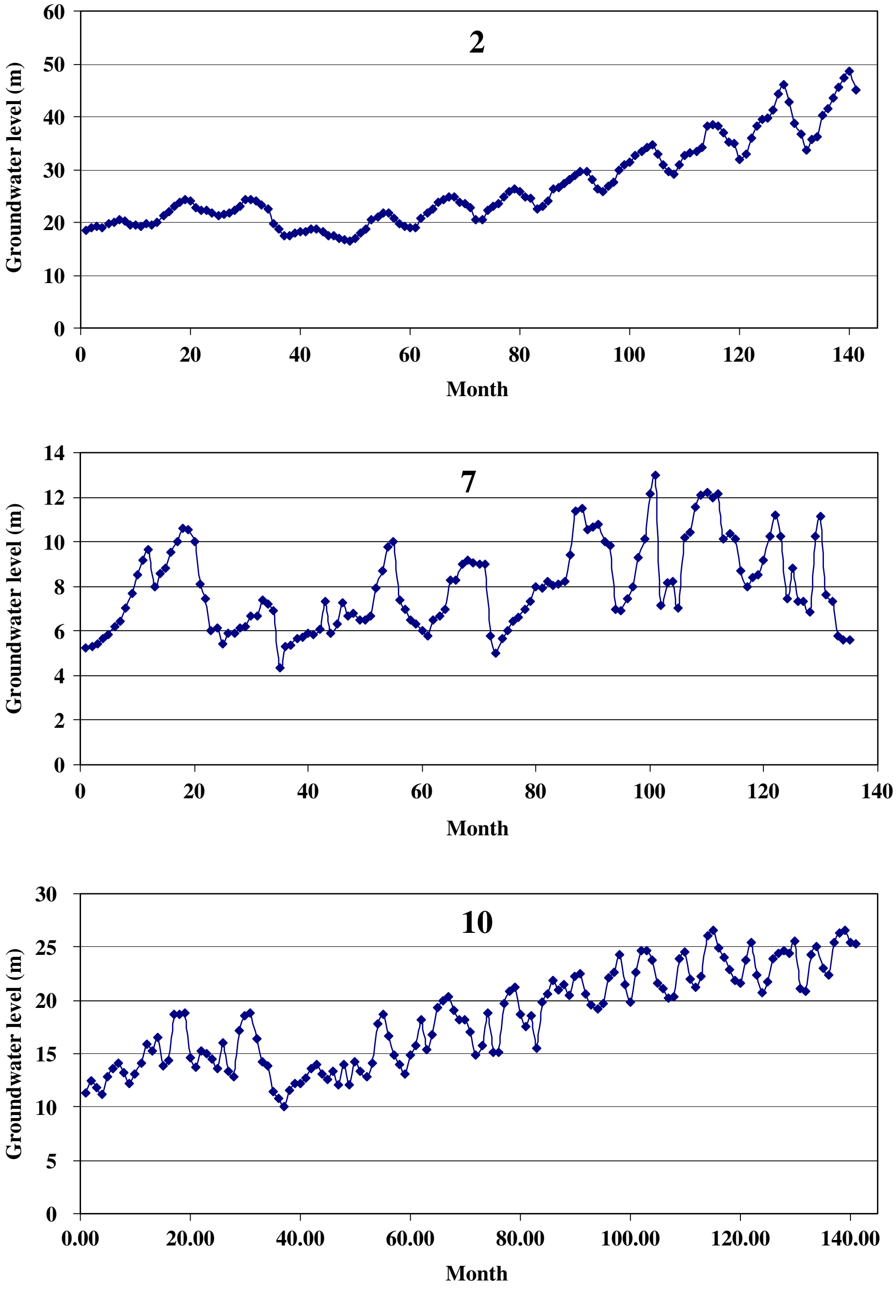


Figure 2 Geographical locations of the piezometric wells.

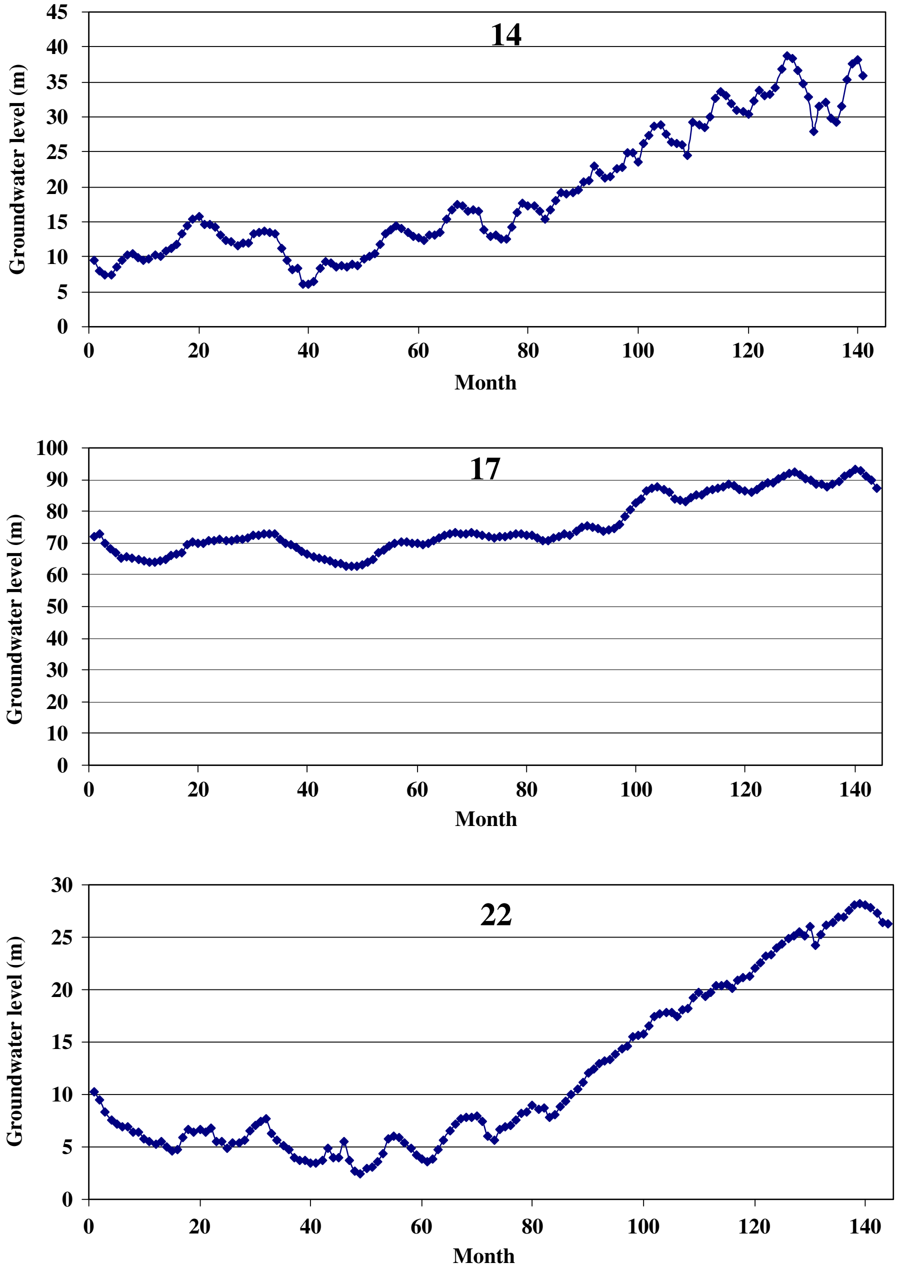
Figure 3 Hydrographs (water level vs time) of some piezometric wells in the study area. Numbers in the *top center* of the graphs show the identification number of the well.



System (GPS) measurements were made. Study area is located in zone 40R based on this system.

In order to help the reader to incarnate the severe drought in the area, the seasonal influence of irrigation pumping on water table elevation and the trend of drop in water table level during 12 years Figure 3 shows the hydrographs (water level versus time) for wells 2, 7, 10, 14, 17, 22, 28, 29, 33, and 37 as the representatives of other piezometric wells. Figures 4 and 5 show the areal contour map of the water table level in October 1993 and 2004, respectively. As it is obvious, the northern and eastern parts of the area have experienced more declines in water table level. However, as it is shown in Figure 4, the water table level in northern and eastern parts of the area is deeper than the other parts at the starting date of the study.

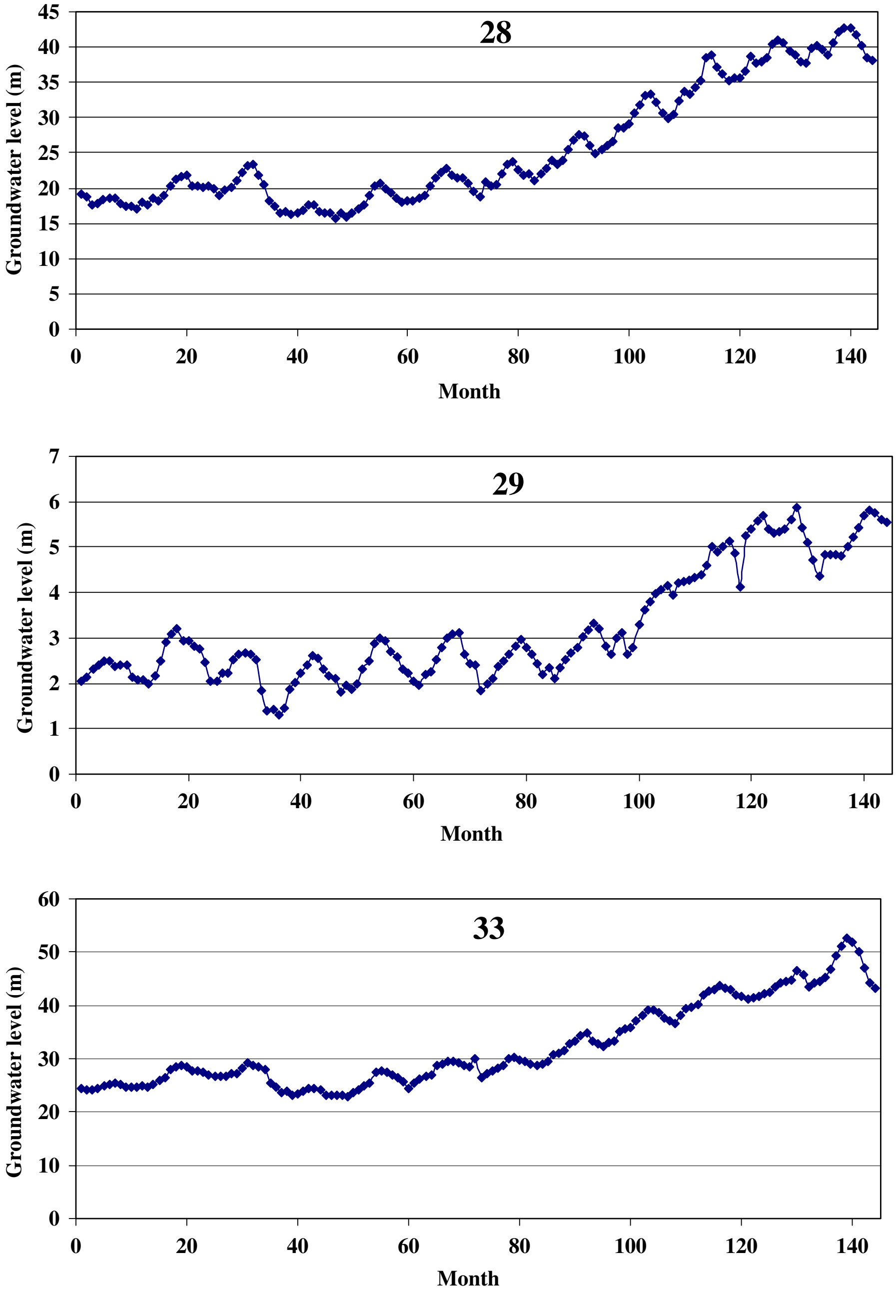
Figure 3 (continued)



4 Results and Discussions

Although Rouhani and Meyers (1990) have noted the likely problems in spatial and temporal kriging of data due to their correlation and dependency, many integrated spatial and temporal analysis have been reported even in recent years (Bogaert, 1996; Chiles & Delfiner, 1999; Christakos, 2000; Mardia & Goodall, 1993; Pokrajac, Hoskinson, & Obradoviæ, 2003; Stein Van Groenigen, Jeger, and Hoosbeek, 1998; Tuckfield, 1994; Wikle, Berliner, & Cressie, 1998). Among the published articles concerning the integrated spatial and temporal analysis, Bogaert (1996), Cameron and Hunter (2002), Gilleland and Nychka (2005), Pokrajac et al. (2003), Stein et al., (1998), and Tuckfield (1994) have reported the acceptable results obtained from integrated spatial and temporal analysis. However, in this study, applying one way ANOVA ($\alpha = 0.01$)

Figure 3 (continued)



revealed that the data could be assumed separable and independent and the spatial and temporal analysis are sufficiently valid (P-value < 0.0001).

4.1 Spatial analysis

To investigate the spatial analysis of fluctuations of the groundwater level drop, the data of water table levels of October were used because there is no discharge from agricultural wells for irrigation in this month and the water table levels are recovered and in equilibrium. The difference of water table levels in October 1993 and October 2004 was used as an indication of the measure of groundwater level drop and is the representative of the total drop in 12 years. Theodossiou and Latinopoulos (2006) also used the measurements of October for their spatial analysis.

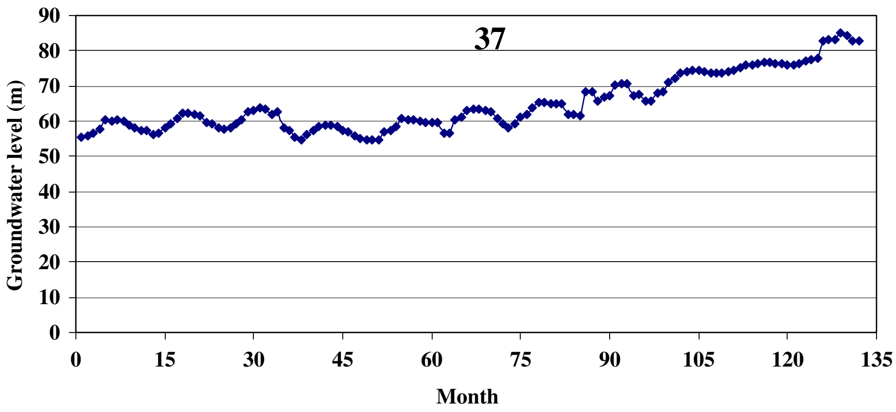


Figure 3 (continued)

Table I shows the values of water level drops in the piezometric wells.

In order to check the anisotropy in the groundwater level drop, the conventional approach is to compare variograms in several directions (Goovaerts, 1997). In this study major angles of 0°, 45°, 90°, and 135° with an angle tolerance of ±45° were used for detecting anisotropy. However, there were no distinct differences among the structures of the calculated variograms in the four directions. Therefore, the spatial variation of groundwater level drop is considered to be isotropic. Figure 6 shows the best fitted omnidirectional variogram of groundwater level drop obtained based on cross-validation. The accuracy of kriged values depends mostly on the variogram values at small lags (Isaaks & Srivastava, 1989) and Figure 6 clearly demonstrates that the first few points associated to small lags of the variogram carry more weights of spatial structure (Ma et al., 1999).

Ordinary kriging was applied for estimation of groundwater level drop across the study area. Figures 7 and 8 show the maps of kriged groundwater level drop and standard deviations (error) associated with the estimations, respectively. Figure 7 illustrates that northern parts of the study area are experiencing more groundwater level drop and it shows that more attention should be paid to these areas to prevent future problems. The outlet of the watershed is located in the southern part of the region, and perhaps much water is recharged into the aquifer in these parts of the study area because of longer opportunity time for infiltration. Furthermore, the agricultural wells are denser in northern parts of the area than southern parts which directly exert much push on groundwater level (personal communication with the staff of Fars Regional Water Organization, 2005). Therefore, the water table level in the regions next to the outlet is not as deep as the northern regions. It seems that

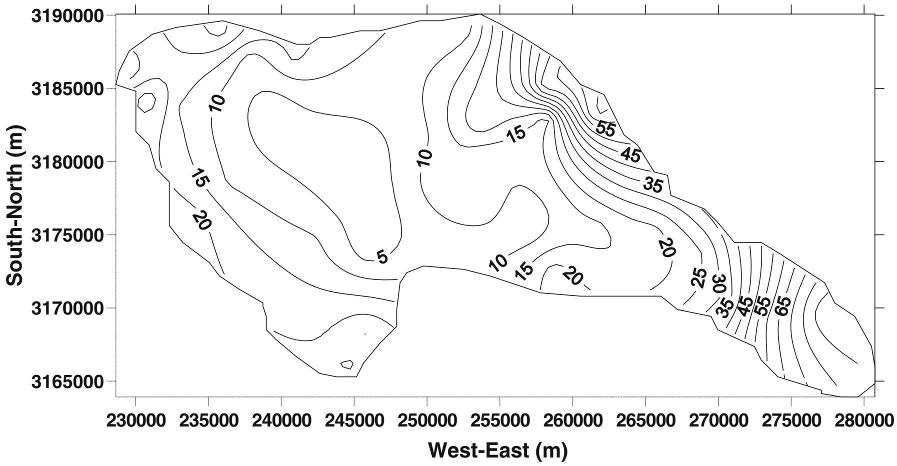


Figure 4 Areal water table level contour map of the study area in October 1993 (starting year of study).

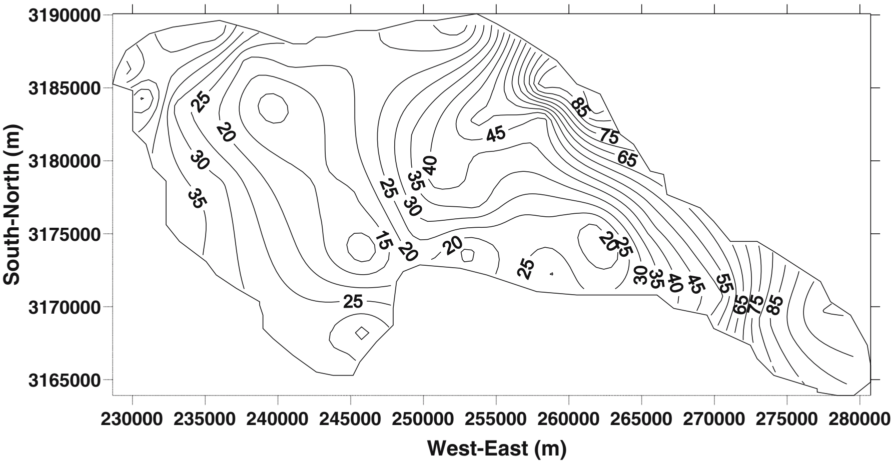


Figure 5 Areal water table level contour map of the study area in October 2004 (ending year of study).

practicing water harvesting systems might be a good strategy for recharging fresh water into the aquifer in the northern parts. However, the water managers and regarding water organizations should be more cautious about exploiting water from northern parts of the area without extra supervision. Changing the pattern of cultivation and growing those crops having low irrigation water requirement are highly suggested. It is believed that having a good insight in managing water resources, such critical aquifers can be revived.

However, as groundwater level becomes deeper, more electrical and fossil energy is needed for pumping water and higher capacity motors must be used for lifting water to compensate the water level drop which imposes higher costs to the farmer. Moreover, deep and narrow fractures have been appeared at some locations of the study area in recent years which are indicative of elastic deformation of the water bearing strata due to excessive pumping from the aquifer. Furthermore, the quality of water has decreased and the electrical conductivity has increased (Fars Regional Water Organization, 2005) which this problem may dictate changing the cropping pattern and continuous use of saline water may affect the quality the soil of irrigated lands. Hence, managing efforts on the appropriate use of groundwater in such areas are very important for sustainable agriculture. Appropriate awareness and extension programs should be carried out to convince the farmers to apply other methods of irrigation such as sprinkler irrigation, drip irrigation and alternate furrow irrigation as the water saving strategies to cope with more

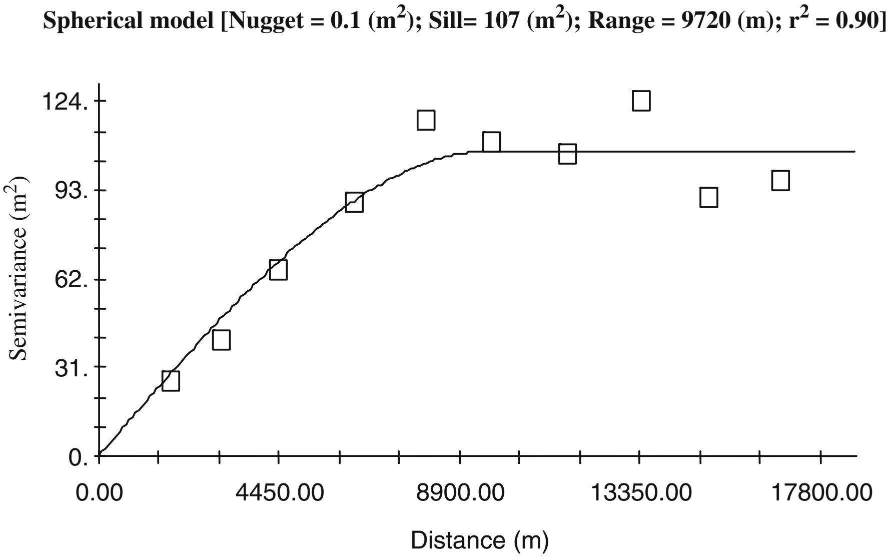


Figure 6 Fitted variogram for the spatial analysis of the drop in the groundwater level of 39 wells.

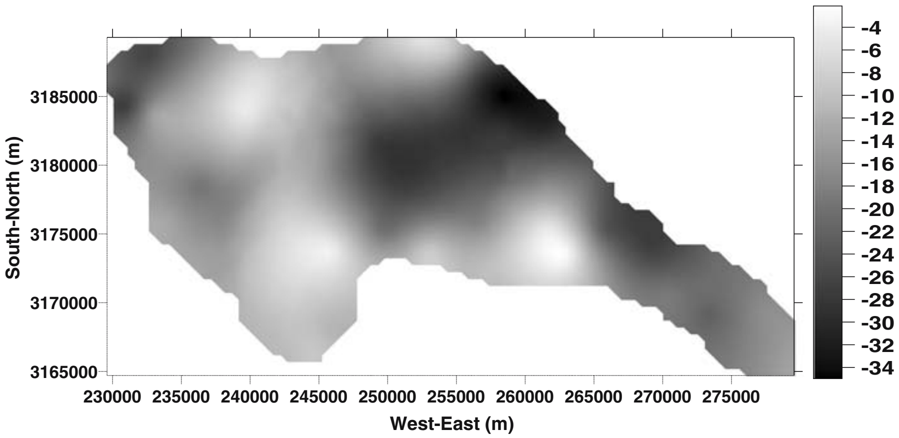
Table I Geographical locations of piezometric wells and the difference between groundwater levels measured in October 2004 and 1993

Ground water level drop (m)	*Y* (m)	*X* (m)	Well no.
−20.35	3,186,100	229,600	1
−26.99	3,188,050	232,700	2
−11.44	3,186,950	237,850	3
−20.27	3,188,800	235,850	4
−6.94	3,186,900	240,850	5
−9.12	3,188,200	254,650	6
−4.74	3,189,300	252,550	7
−35.83	3,185,150	258,100	8
−28.57	3,186,150	256,650	9
−12.45	3,183,625	233,075	10
−29.22	3,184,300	230,850	11
−4.13	3,183,850	239,500	12
−28.12	3,181,800	249,300	13
−27.42	3,180,150	254,000	14
−27.77	3,182,700	253,600	15
−28.91	3,182,950	258,225	16
−32.46	3,183,300	261,550	17
−12.84	3,175,950	233,850	18
−20.33	3,178,500	236,300	19
−6.61	3,175,150	242,750	20
−13.57	3,178,000	245,250	21
−21.37	3,175,200	249,650	22
−22.57	3,177,200	253,650	23
−28.12	3,178,650	250,850	24
−17.95	3,175,675	256,750	25
−19.32	3,178,800	263,900	26
−4.52	3,175,500	261,700	27
−24.22	3,175,300	265,600	28
−3.07	3,173,850	245,950	29
−7.86	3,173,850	253,000	30
−8.63	3,172,500	258,700	31
−1.44	3,173,600	262,950	32
−27.21	3,173,850	269,000	33
−18.74	3,170,675	270,450	34
−8.58	3,166,250	244,725	35
−11.8	3,168,300	245,750	36
−22.9	3,169,075	273,325	37
−16.37	3,169,600	277,250	38
−13.17	3,164,700	279,550	39

and more drops in water table level. Future sustainable agriculture of this area depends highly on the present management of the renewable and nonrenewable resources. Therefore, it is believed that applying the kriging method is so helpful in detecting the problematic areas and a good tool for water resources management.

Regions illustrating high standard deviation values (Figure 8) indicate the need for expansion of the current monitoring network by augmenting new piezometric wells. However, predefined limit for the standard deviation controls the number of wells that should be augmented in future. The smaller the predefined value is, the larger the number of new wells is. While the areas of higher uncertainty needs to become much denser by including more piezometric wells, and more water table level measurements, areas of lower uncertainty can experience periodically measurement of water table level. Piezometric wells in areas of lower uncertainty, however, can be trans-

Figure 7 The kriged map of the drop in the groundwater level of the study area.



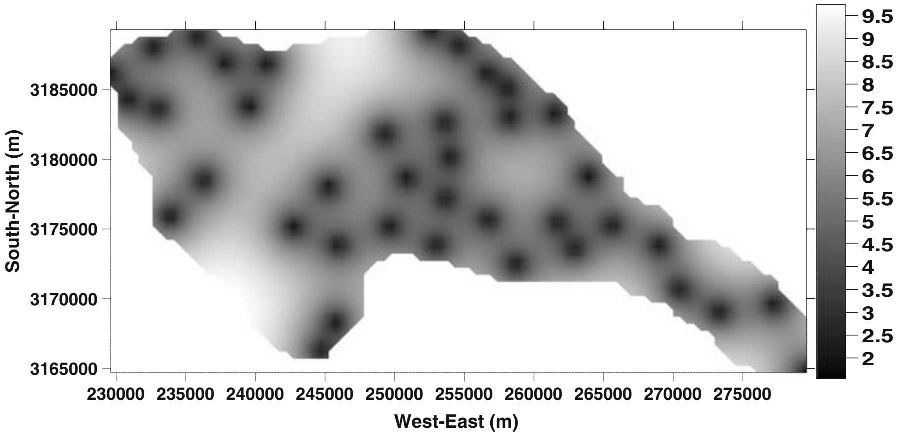
ferred to a secondary network where measurements are not as often as those of the primary network located in high uncertainty areas.

Low nugget effect in Figure 7 reflects this fact that the fluctuation of groundwater level drop is highly spatially structured. However, nugget effect may be caused by wrong measurements, variability smaller than minimum distances between measurements (short range variability), random, and inherent variability (Goovaerts, 1997; Liu et al., 2006; Theodossiou & Latinopoulos, 2006). Very low nugget effect shows that variability of water table level drop in shorter distances of range value does not exist and it is concluded that the fitted variogram represents the spatial structure of fluctuation of groundwater level drop well. In general, the nugget-to-sill ratio can be used to classify the spatial dependence (Cambardella et al., 1994). A variable is considered to have strong spatial dependence if the ratio is less than 0.25, and has a moderate spatial dependence if the ratio is between 0.25 and 0.75; otherwise the variable has a weak spatial dependence (Liu et al., 2006). Therefore, it is understood that groundwater level drop have strong spatial dependence in our study.

In order to check the accuracy of fitted variogram, we estimated the decline in water table elevations of the known points by kriging with cross-validation. Results showed that the variogram can reasonably present the spatial structure of groundwater level drop. Figure 9 shows the regression line between observed and estimated values groundwater level drop. Very high $R^2 = 1$ shows that the kriging estimations are so reliable and exact. Figure 10 shows the correlation between the estimated values and the estimation error (the difference between measured and estimated values). It can be easily observed that values are distributed around a horizontal line ($Y = 0$), demonstrating that the mean estimation error is zero satisfying the unbiasedness constraint of kriging (Goovaerts, 1997). The majority of values vary between ±0.5 m.

The slope and intercept of Figure 9 show, however, a too little bias. *F* test (Snedecor & Cochran, 1967) was

Figure 8 The standard deviation (error) map associated with the kriged drop in the groundwater level of the study area.



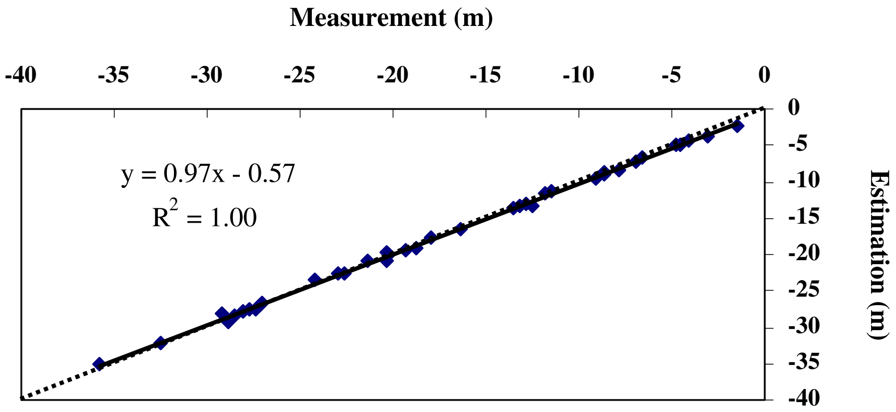


Figure 9 The best fitted line (*solid line*) between the measured and estimated drop in the groundwater level and 1:1 line (*dashed line*).

performed to determine the difference between regression (solid) and 1:1 (dashed) lines ($\alpha = 0.01$). Results revealed a non-significant difference between the intercept of the regression line and 1:1 lines, which meant that the intercept could be considered zero, but significant difference between slopes (Ahmadi & Niazi Ardekani, 2006; Sepaskhah, Ahmadi, & Nikbakht Shahbazi, 2005). So, we could present the regression line as $Y = 0.97X$ (Ahmadi & Niazi Ardekani, 2006; Sepaskhah et al., 2005). Hence, on average, kriging underestimates groundwater level by 3% which is so reliable enough and applicable for those regions having no data of groundwater level. Through using this technique much money and funding can be saved so that more groundwater networks can be setup in other parts of a region for monitoring and assessing the groundwater level.

4.2 Temporal analysis

Figure 11 shows the statistical analysis (box-plot) of the measured groundwater level emphasizing on the extreme values such as, mean, median, 25th and 75th percentiles (boundaries of the box), whiskers or error bars (10th/90th percentiles), and outliers. However, as noted in the preceding sections, these outliers are not considered the wrong data and are of high importance since they represent the reaction of the aquifer to the environmental effects. Nevertheless, a few isolated very small or very large values that seemed suspicious were removed from the data series prior to analysis.

Temporal analysis using geostatistics was performed on the data set of each well independently from the other wells. Similar studies on ground water are published by Tuckfield (1994) and Cameron and Hunter (2002). Table II summarizes the properties of the best fitted variograms calculated based on cross-validation. Considering Table II, it is observed that the time series of groundwater levels of each well has strong temporal structure, in addition to the spatial structure revealed in the preceding section. Very low nugget effects show that the groundwater level fluctuation is severely time-correlated and depicts a strong temporal structure.

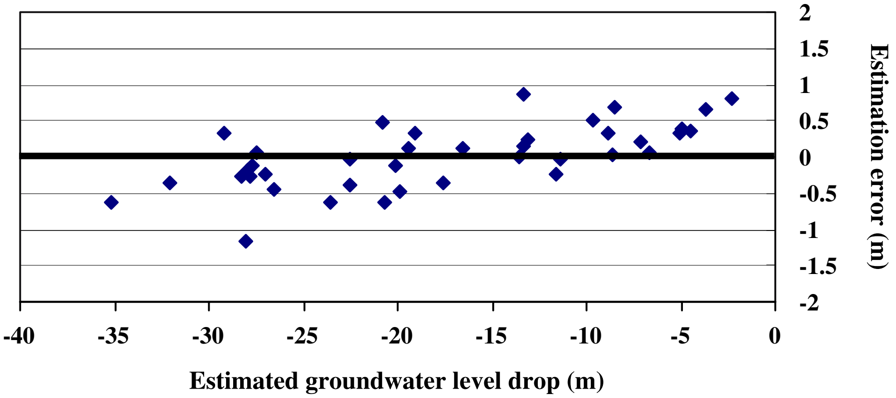


Figure 10 Correlation between estimated values of groundwater level drop and associated estimation error.

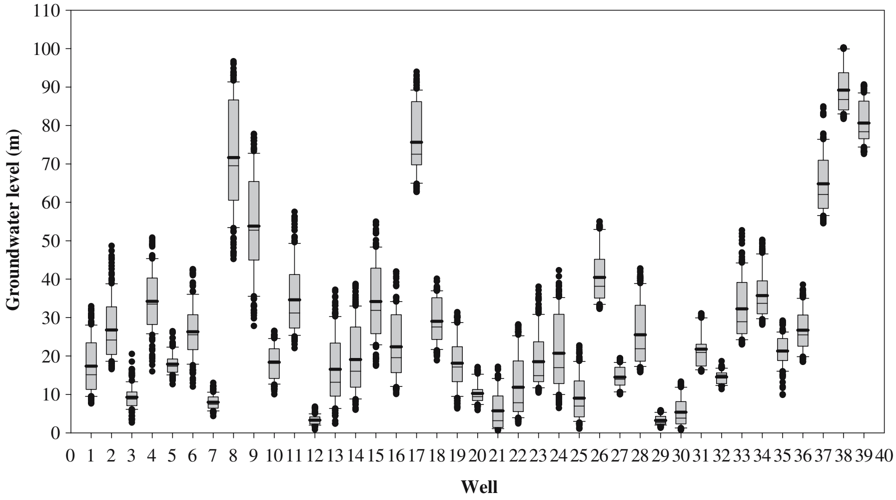


Figure 11 Statistical analysis (box-plot) of the measured groundwater level time series.

About 77% of wells have range values less than 12 months with an average and standard deviation of 7.2 and 1.64, respectively. The average value of 7.2 proposed that, in general, water table level for any given time is affected by about 7.2 months earlier from that specific time. Similar conclusion is reported by Tuckfield (1994) and Cameron and Hunter (2002) as well. However, water table level in summer might be the direct effect of aquifer recharge in the preceding months, especially winter. So, trying to recharge the aquifer in winter has direct effect on the water table level in the next month. Since, cropping pattern in the study area is very extensive in spring and summer, therefore, applying water saving strategies such as water harvesting systems are very useful in improving the management of the water resources in the area, especially northern and eastern parts which are the critical regions in the study area.

Based on the results, it is understood that the aquifer system has relatively similar characteristics throughout the plain because both the piezometric wells are widespread across the Darab plain, and 77% of wells have nearly similar variograms, however. Among the variograms models, the spherical model was the dominant kind of variogram that fitted the data.

Few wells have range values that extend over one or even two years. Since no exact and accurate detail information about the hydrological structure of the plain under study is available, no more conclusions can be made. However, based on the current knowledge such differences might be originated from different well depths, geological formation, and various sedimentary layers thicknesses. Nevertheless, performing similar studies are recommended for other plains with available data to elucidate the unknown factors that may influence on the variograms parameters. Also, applying the geostatistics methods on the hydrogeological characteristics of an aquifer having enough data can be beneficial in interpreting such findings and cases and the present study envisages some utilization of geostatistics.

In order to assess the accuracy of the fitted variograms, kriging with cross-validation was used to estimate the groundwater level at all of the known measurements. High R^2 values obtained from kriging estimations clearly proved that the variograms are chosen correctly and the estimations are accurate. For those 30 values that have range values less than 12 months, the R^2 values range from 0.80 to 0.99. Therefore, it is possible to monitor the groundwater levels for longer time intervals, for example, seasonally or every four months. This will lead to lower costs of labor and funding. Meanwhile, those wells having low fluctuations of groundwater levels can be monitored in longer time intervals even yearly. In this way, more time and funding could be saved which in turn, can be spent for monitoring other water resources in neighboring regions. Obviously, supervision and managing water resources in arid regions require extra human energy and financial support which can be supplied through proper management practices.

Kriging can be used to estimate the groundwater level for unknown location or time. Figures 12 and 13 show the variogram and regression line between measured and estimated groundwater level for piezometric well no. 6, respectively, as an example. Uni-

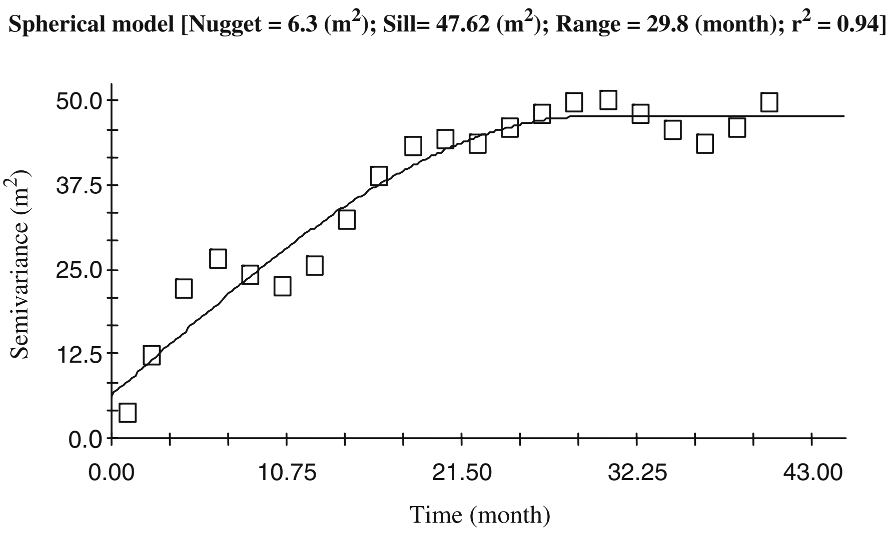
Table II Properties of the fitted variograms of temporal analysis for groundwater level (GWL) for each piezometric well

Well no.	Model	Nugget (m^2)	Sill (m^2)	Range (month)	Nugget/Sill	R^2
1	Spherical	0.01	5.45	6.98	0.0018	0.965
2	Spherical	0.01	8.3	6.62	0.0012	0.994
3	Spherical	0.001	2.39	7.38	0.0004	0.988
4	Spherical	0.001	15.31	7.78	0.00007	0.986
5	Spherical	0.01	3.67	6.77	0.003	0.991
6	Spherical	6.3	47.62	29.8	0.132	0.94
7	Spherical	0.044	2.9	6.6	0.015	0.97
8	Spherical	0.10	45.83	8.83	0.002	0.994
9	Spherical	0.90	73	15.52	0.012	0.78
10	Spherical	0.01	4.38	3.8	0.002	0.966
11	Spherical	0.01	19.63	6.5	0.0005	0.982
12	Spherical	0.001	0.72	5.67	0.001	0.984
13	Spherical	0.01	7.38	7.97	0.001	0.998
14	Spherical	0.01	6.37	6.51	0.002	0.994
15	Spherical	0.01	15.51	7.13	0.0006	0.992
16	Spherical	0.01	7.01	8	0.001	0.912
17	Spherical	0.01	12.87	18.72	0.0008	0.99
18	Spherical	0.43	4.16	18.92	0.1	0.98
19	Spherical	0.79	5.4	7.53	0.15	0.998
20	Spherical	0.007	0.689	5.68	0.01	0.99
21	Spherical	0.001	2.21	9.96	0.0005	0.986
22	Spherical	0.001	1.14	7.12	0.0009	0.872
23	Spherical	0.001	1.87	5.28	0.0005	0.987
24	Exponential	0.01	12.97	18.3	0.0007	0.91
25	Exponential	0.001	2.53	10.2	0.0004	0.791
26	Spherical	0.001	3.17	10.23	0.0003	0.999
27	Spherical	0.001	0.584	7.73	0.001	0.999
28	Spherical	0.001	3.13	6.47	0.0003	0.99
29	Exponential	0.055	0.286	13.53	0.192	0.593
30	Spherical	0.001	0.811	7.06	0.001	0.996
31	Spherical	0.063	1.27	10.36	0.05	0.998
32	Exponential	0.01	6.85	35.1	0.001	0.546
33	Gaussian	0.05	3.27	4.9	0.015	0.99
34	Spherical	0.001	2.26	6.86	0.0004	0.903
35	Gaussian	0.48	6.02	5.45	0.079	0.996
36	Spherical	0.01	5.74	26.59	0.002	0.993
37	Spherical	0.01	6.25	6.45	0.002	0.954
38	Spherical	0.001	2.3	9.62	0.0004	0.996
39	Spherical	0.01	3.91	25.04	0.003	0.996

versal kriging (kriging with a trend model) was applied due to the presence of a long-term trend in the data set of all piezometric well. Since a periodic trend was seen in data set, a sine function was used to model the trend (Goovaerts, 1997). Kumar and Ahmed (2003), Pucci and Murashige (1987), Rouhani and Wackernagel (1990), Sophocleous et al. (1982) and Tonkin and Larson (2001) also reported a trend in the data set of groundwater level and used the universal kriging to geostatistically analysis their data. More details on universal kriging can be found in Goovaerts (1997), Ma et al. (1999) and Noshadi and Sepaskhah (2005).

F test (Snedecor & Cochran, 1967) was performed to determine the difference between regression (solid) and 1:1 (dashed) lines ($\alpha = 0.01$) for all the 39 wells. Results showed that while all the intercepts were not statistically different from zero, however, the slopes

Figure 12 Fitted variogram for the temporal analysis of the groundwater level time series (hydrograph) of well no. 6.



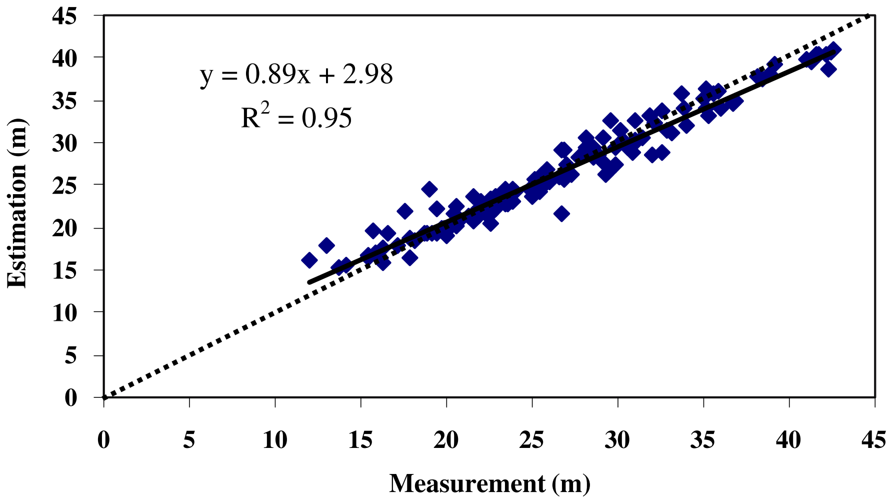
were all significant and different from one, showing the intercepts can be considered equal to zero (Ahmadi & Niazi Ardekani, 2006; Sepaskhah et al., 2005). The slopes ranged between 0.8 and 0.98 with the average and standard deviation of 0.94 and 0.044. It shows that the groundwater level is, on average, underestimated by 6%. These precise estimations clearly mention that frequent and low interval measurements of the groundwater level are not really necessary, if a strong temporal structure exists in the system. Depending on the level of management and environmental condition of the system, the manager can decide to monitor the groundwater levels from short to long intervals, e.g., monthly or seasonally.

Comparing the magnitudes of underestimations by spatial (3%) and temporal (6%) analysis clearly shows that geostatistics has performed a little better on spatial than temporal analysis. However, it is recommended that the same procedure should be repeated for other aquifers having enough data to reveal more findings on the spatio-temporal behavior of the aquifer system.

5 Conclusion

Water resources management in arid regions needs to be paid much more attention due to the precious worth of water in these areas as the most important element of

Figure 13 The best fitted line (*solid line*) between the measured and estimated groundwater level and 1:1 line (*dashed line*) for the groundwater level time series (hydrograph) of well no. 6.



sustainable environment. There are many management tools that would help managers to decide how to supervise and handle efficiently with the available water resources. Geostatistical methods has been introduced and proved as an applicable and reliable tool to be used for better management and conservation of water resources and sustainable development of any area (Kumar et al., 2005; Reghunath et al., 2005). In this research using geostatistics, the spatial analysis was performed on groundwater level drop and temporal analysis was carried out on groundwater level fluctuations monitored monthly during 12 years (1993–2004). Results showed that geostatistics can reveal stochastic structure of groundwater level variations in space and time. Spatial analysis showed a strong structure of groundwater level drop. Applying ordinary kriging with cross-validation resulted in acceptable estimations of groundwater level drop in presumably unknown points. Temporal analysis showed that groundwater level fluctuations have temporal structure, as well. Performing the universal kriging with cross-validation resulted in very acceptable estimations of groundwater level in a series of measured groundwater levels. As a whole, the average range of the variograms for the spatial and temporal temporal analysis was about 9.7 km and 7.2 months, respectively.

While kriging underestimated the drop of the groundwater levels by 3% in spatial analysis, groundwater levels were underestimated by 6% in temporal analysis, showing a little bit better performance of kriging in spatial analysis. However, both spatial and temporal estimations are accurate. Due to acceptable performance of kriging in estimation, it is possible to monitor the groundwater fluctuations in longer time intervals, and also estimate the values of water table level in spatial and temporal scales for unknown location and time. Therefore, it is concluded that applying geostatistics, one can obtain better insight on the water resources systems and proposes valuable solutions for those critical conditions which water resources are in danger. A result of applying geostatistics in water resources management in the present research, was identification of the areas where suffer from drastic decline in groundwater level and determination of corresponding uncertainty (error) of prediction the decline in groundwater level for different parts of the area under study. Hence, it is necessary to immediately practice water conservation methods and water harvesting systems in the study area to prevent the causes of more damages to the available water resource. However, similar studies are suggested to be conducted on other plains having various hydrogeological conditions to reveal the unknown properties that may affect the variograms and their parameters that directly affect the estimations.

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