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RESEARCH PAPER

Quantifying Spatio-Temporal Changes of Groundwater Level in Arid Regions

P. Dehghan[1], Hosein Azarnivand[1,*], Arash Malekian[1]

[1] *Faculty of Natural Resources, University of Tehran, Karaj, Iran.*

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Abstract
Groundwater is known as the most important source of fresh water and its management is extremely important in arid and semi-arid regions, where there is a scarcity of surface water due to the lack of enough rainfall. Excessive water harvesting and improper water management can cause a decline in groundwater levels, which can lead environmental, social and economic crises. Therefore, this valuable resource must be exploited correctly and accurately. To achieve this aim, it is necessary to know the extent of its changes. Hence, in this study, the groundwater level changes in Semnan and Damghan plains, Iran have been investigated. For this purpose, Piezometric well data from 1994 to 2018 were used. Groundwater level zoning in two study regions was carried out using Inverse Distance Weighting (IDW), Kriging, and Co-kriging methods and the best zoning method was selected by Taylor diagram and Nash-Sutcliffe Model Efficiency Coefficient (NSE). Results of these two methods indicated that IDW and Kriging models are the most accurate way to zoning the groundwater level in Semnan and Damghan plains, respectively. The results of groundwater level maps showed that both plains have a decreasing trend in groundwater level over the time. Most of the water level dropping has been occurred in the east and south of Semnan plain and the eastern parts of Damghan plain which may be due to the concentration of agricultural areas in these parts. In Semnan plain, the depletion of groundwater is from 1.59 to 33.56 meters in April and from 1.55 to 35.40 meters in October, while in Damghan plain is from 3.76 to 30.97 and from 3.85 to 30.60 in April and October, respectively.

Keywords: Groundwater, Semnan, Damghan, Taylor diagram, Interpolation.

Introduction

Groundwater resources play a vital role in arid and semi-arid regions and supply fresh water to the ever population increasing (Mishra and Kumar, 2015). Unfortunately, various natural and anthropogenic factors in recent decades have caused critical conditions in groundwater levels in most arid and semi-arid areas. In these regions, groundwater is the largest and a crucial source of high-quality water around the world (Jing et al, 2019), which is threatened by some factors such as excessive exploitation and drought. This resource provides the most of total water supplies over the world (Morris et al, 2003) in arid and semi-arid regions. Generally, surface water resources (e.g. rivers, lakes, wetlands, and so on) are scarce and unreliable, so groundwater is the main water resource in these areas (Hotzl, 2012). Water scarcity in these regions is a major problem that can affect other natural resources, such as vegetation and soil and this problem threatens these areas in various ways (Mirjalili et al., 2016). Shahabi et al. (2014) reported that in arid and semi-arid regions plants inevitably supply their water needs from groundwater, thus, vegetation growth is closely related to groundwater. Groundwater has some advantages over surface water such as higher quality and lower pollution (Raheli and Salman Mahini, 2014). Therefore, proper measures should be taken to preserve and exploit

[*] Corresponding author e-mail: hazar@ut.ac.ir

these valuable resources. Studying the quantity and quality of these resources and their specific relationship to land surface features is one of these measures (Thomas and Tellam, 2005). Nonetheless, some tools can help to achieve this purpose. Using new technologies can improve decision making and provide appropriate solutions. Geographic Information System (GIS) is an applied science, which is very profitable and can speed up the process of planning, identifying critical cases, and so on (Akbari et al., 2009).

Over recent years, countless researches have been carried out about quantifying groundwater level changes and their crisis. Akbari et al (2009) investigated the depletion of groundwater level using GIS in Mashhad plain aquifer. The results showed that groundwater table decreased by about 30 meters in central and western regions of aquifer. It was turned out that the most important factors in groundwater level depletion are drought, growth of population, overexploitation, increase in agricultural lands and number of wells. Rayne and Forest (2012) checked 67 groundwater monitoring wells in British Columbia, Canada, and reported that only 6% of monitoring wells had increasing trends, while 34.3% of them had decreasing trends, and 59.7% of them had no significant temporal variation. Ajdary and Kazemi (2014) quantified the groundwater level changes and changes in its chemistry in Shahrood, northeastern Iran. The results indicated that rainfall fluctuations had no effect on the process of decreasing groundwater level. Jing et al. (2019) researched on groundwater in Thuringian basin, and Nägelstedt subbasin basin in Germany. By simulation results, they found it is expected that groundwater volume and level will slightly increase under future climate scenarios.

Groundwater as a main resource of water can provide fresh water for agriculture, industry and drinking in Iran (Khosravi et al, 2018) and the quantity of this source are changing due to human activity (Mishra and Kumar, 2015), considering to quantity of groundwater is essential and one of the decisions factor (Peterson and Fulton, 2019) for management of this valuable water resource. Therefore, in the present study, the purpose is quantifying of groundwater level spatio-temporal changes in Semnan and Damghan using statistical analyses and GIS.

Materials and Methods

Study Area

Semnan and Damghan plains are located in Semnan province, Iran. These plains are located in southern part of Alborz Mountain range and northern part of Kavir desert. There are agricultural lands around the urban areas in these two plains. In recent decades, rapid development of agriculture and increasing water demand have led to over-harvesting and decrease in groundwater levels in these plains. Most of the harvested water in agriculture is from deep and semi-deep wells. Table 1 and Fig. 1 show the properties of Semnan and Damghan plains and the location of these plains areas in Iran and used piezometric wells, respectively.

Table 1. Properties of Semnan and Damghan plains

Plain	Longitude	Latitude	Elevation (m)	Area (ha)
Semnan	35° 21' 36" - 35° 39' 18"	53° 14' 12" - 53° 35' 56"	967-1332	54148.5
Damghan	35° 51' 57" - 36° 09' 26"	54° 04' 14" - 54° 26' 14"	1047-1309	73250.7

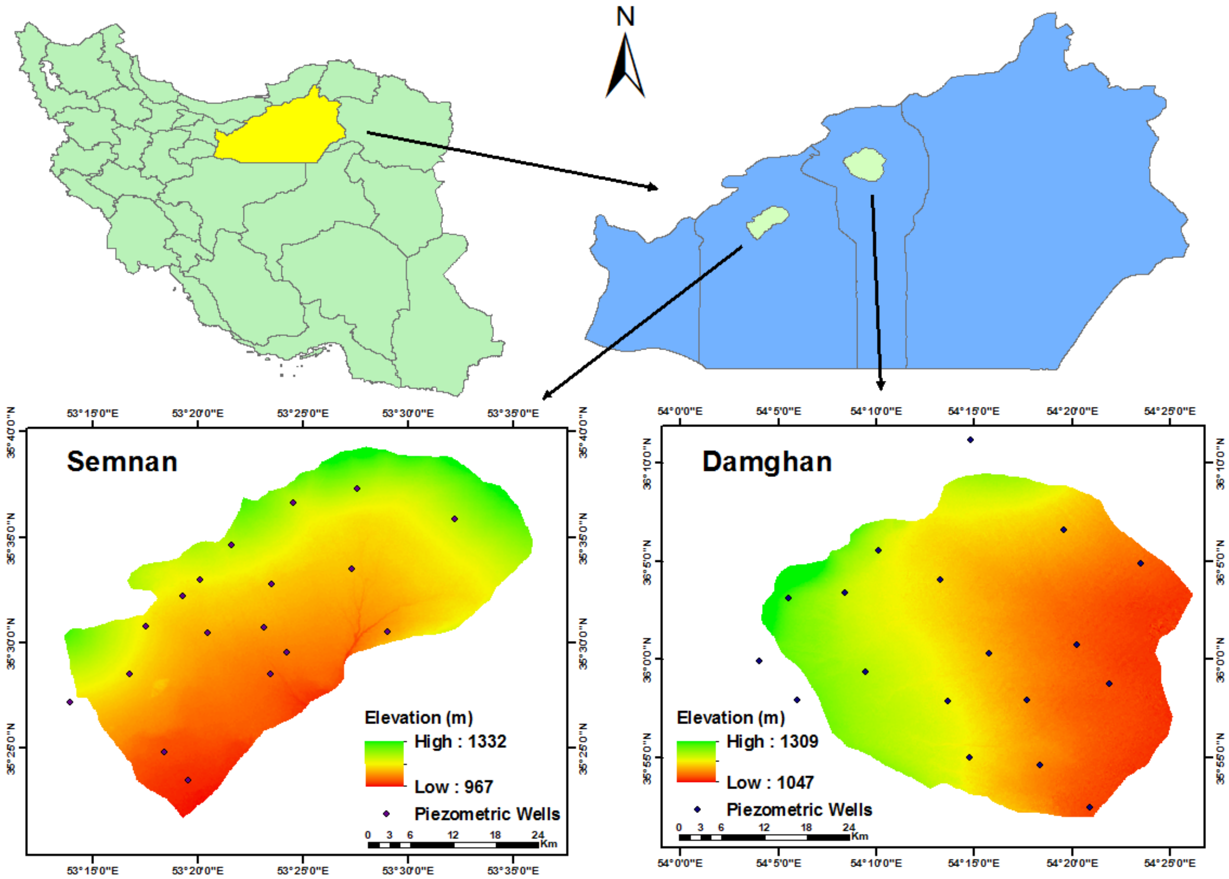

Figure 1. Location of Semnan and Damghan plains and piezometric wells in Iran

Methodology

In this research, to study groundwater level fluctuations in Semnan and Damghan, monthly data of 18 piezometric wells in both plains were collected during the 25-year statistical period, from 1994 to 2018. Table 2 indicates the statistics summary of groundwater level data.

Table 2. Statistics summary of groundwater level data in Semnan and Damghan plains (M, a.s.l)

Plain	Min	Average	Max	Standard Deviation
Semnan	971.00	1034.75	1074.85	24.35
Damghan	1029.06	1095.88	1172.18	42.65

After preparing the data, zoning was done in ArcMap 10.3 using April data as aquifer recharging time and October as aquifer discharge time. Afterward, the maps were be interpolated by three model; Inverse Distance Weighting (IDW), Kriging and Co-kriging. As a secondary variable the elevation of the study areas were used in Co-Kriging method. Then, the accurate model for interpolating was chosen using Taylor Diagram and Nash-Sutcliffe Model Efficiency Coefficient (NSE). Figure 2 shows the flowchart of the adopted methodology in the present study.

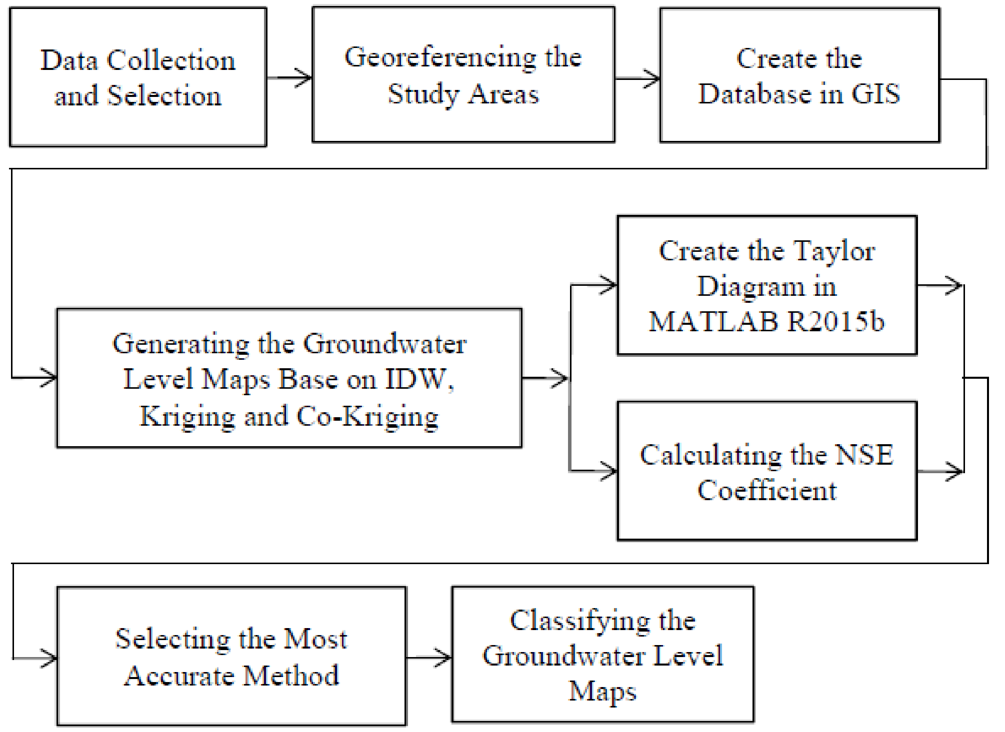

Figure 2. Flowchart of the adopted methodology

Geostatistical Interpolation Techniques

Interpolation was performed using Inverse Distance Weighting (IDW), Kriging, and Co-kriging models.

Inverse Distance Weighting (IDW): This model performs interpolation simply and weighs the data around the estimated point, obtains the unknown quantity and performs the interpolation. Therefore, each observed point which locally affects on unsampled points, decreases with increasing distance and the closer points are more weighted (Piri and Bameri, 2014). The IDW model is defined as follows:

$$X = \sum_{i=1}^{n}\left(\frac{Z_i}{D_i}\right) / \sum_{i=1}^{n}\left(\frac{1}{D_i}\right) \quad (1)$$

Where; X is an estimated value at an unsampled point, n is control points matrix used to estimate a grid point, i is power to which distance is raised and D is distances from each control points to an unsampled point (Fung et al., 2020).

Kriging: In this model, the data around the estimated point is weighted and the unknown quantity will be obtained. The location information of the data is also included in the calculations and it is attempted to define a relationship between them. The correlation between the samples is presented as a mathematical model so that the variability of the spatial correlation can be simulated with the transform (Piri and Bameri, 2014). The equation of this model is given below:

$$Z_{OK}^{*}(X_0) = \sum_{i=1}^{n} \lambda_j Z(x_i) \quad (2)$$

Where; Z_{OK}^{*} and λ_j are the estimate of variable in X_0 point and statistical weights assigned to amount of Z in x_i point and n is number of observed values.

Co-kriging: This model is a multivariate type of Kriging model. It is a way to estimate the minimizing estimation error variance using spatial correlation between primary and secondary variables. The equation of Co-kriging model is as follows:

$$U_0=\sum_{i=1}^{n} a_i u_i + \sum_{j=1}^{m} b_j v_j \qquad (3)$$

Where; a_i is primary data at n nearby location, u_i is the secondary data around *m* location, b_j and v_j are kriging weights which should be computed.

Determine the Most Appropriate Interpolation model

After interpolating using three models, the next step is to choose the accurate one using Taylor diagram and Nash-Sutcliffe model efficiency coefficient (NSE).

Taylor Diagram

Taylor diagram provides a graphically way to summarize of matching a pattern with observations (Taylor, 2001) and a brief statistical summary of how wells patterns are according to their correlation, root-mean-square differences and variances. This diagram shows up the advantage of various patterns compared to observations data by being visualized as a series of points in a plot (Sigaroodi et al., 2014) and was constructed to assess scalar quantities (i.g. temperature and precipitation) (Xu et al, 2016) and in this study it has been used for evaluating groundwater. For using this method, Mean Squared Error Squared (RMSE) and Coefficient of Determination (R^2) are calculated to interpolate spatial zoning maps at aquifer charging time (April) and exploitation time (October) in ArcGIS 10.3. Then the Taylor diagram was drawn in MATLAB R2015b.

Root Mean Square Error (RMSE): RMSE provides a comparison between the predicted results of a model with the observed values. The formula is:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}(p_i-a_i)^2}{n}} \qquad (4)$$

Where; *n* is number of observation, *p* is predicted target, *a* is actual target.

Correlation Coefficient (R): A correlation coefficient is a statistical relationship between two variables and a numerical measure of some kind of correlation. This criterion is defined as (Taylor, 2005):

$$R = \frac{\frac{1}{N}\sum_{n=1}^{N}(f_n-\bar{f})(r_n-\bar{r})}{\sigma_f \sigma_r} \qquad (5)$$

Where; *R* is correlation coefficient, *N* is number of observations, σ_f is standard deviations of the test field σ_r is standard deviations reference field.

Standard Deviation: This criterion calculates the spread of the dataset about the mean value of them. The formula is:

$$SD= \sqrt{\frac{\sum_{i=1}^{N}(X_i-\bar{X})}{N-1}} \tag{6}$$

Where; *SD* is Standard Deviation, *N* is number of observations, X_i is the observed values and $\bar{X}$ is the average value of observations.

Nash-Sutcliffe Model Efficiency Coefficient

Nash-Sutcliffe Model Efficiency Coefficient (Nash and Sutcliffe, 1970) is used to choose the most accurate model and is to compare the observed and simulated (predicted) values. NSE values can range between -∞ and +1. The value of +1 reflects a perfect agreement between a model and observations and zero shows the model does not explain any part of the initial variance (Mathevet et al, 2006), in the other, the predictions of the model are as accurate as the mean of observed data. NSE will be less than zero if the mean of observations is a better predictor than the model. This criterion is defined as:

$$NSE= 1 - \frac{\sum_{n=1}^{N}(OBS_i-SIM_i)^2}{\sum_{n=1}^{N}(OBS_i-\overline{OBS})^2} \tag{6}$$

Where; *NSE* is Nash-Sutcliffe model efficiency coefficient, *N* is number of observed values, OBS_i is the observed values, SIM_i is the simulated values, and $\overline{OBS}$ is the mean of observed values.

After drawing the Taylor diagram and computing NSE and also comparing the results of these models, the most accurate model for zoning was selected. Then quantifying spatio-temporal changes in groundwater level was carried out in ArcGIS 10.3.

Results and Discussion

Three models including Inverse Distance Weighting, Kriging and Co-kriging were adopted for zoning the groundwater level fluctuations. The observations and predictions data of these models were used to calculate the indicators.

Taylor Diagram

Taylor diagram was employed to further quantify forecasting accuracy interpolation models. For this purpose, R^2 and RMSE between model observations and predictions and SD for the observations data were used as the primary indicators. Using these indicators the Taylor diagram for Semnan and Damghan plains were drawn in MATLAB R2015b. Fig 3 represents the Taylor diagrams for both plains. As it can be seen, in Semnan (Fig 3. A), all models have a slightly variety of correlation between the observed and predicted data, but IDW model has smaller RMSE and the closer standard deviation to the observed. The distance from the reference point shows the RMSE. Thus IDW model is more accurate than others in Semnan plain. On the Other hand, in Damghan plain (Fig 3. B), Kriging model is the most accurate model, because of having the closer standard deviation to the observed and slightly higher correlation between predicted and observed data, than other models. Therefore, IDW and Kriging models are the ideal models in Semnan and Damghan plains, respectively, based on Taylor diagram.

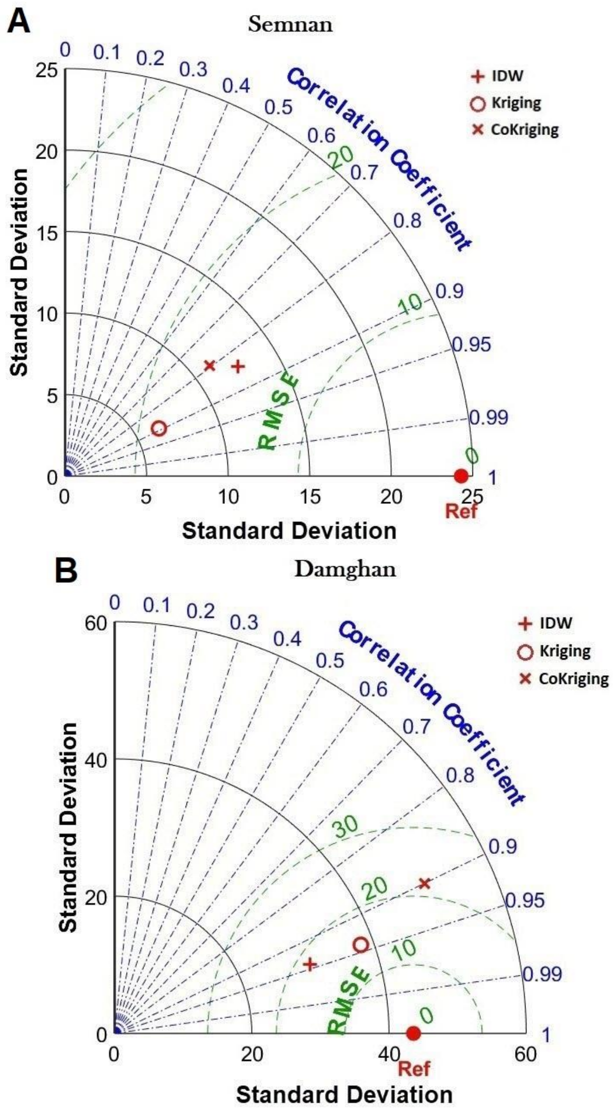

Figure 3. Scatterplot of displaying a comparison of three models on a Taylor diagram (A: Semnan, B: Damghan)

Nash-Sutcliffe Model Efficiency Coefficient

In addition to Taylor diagram, NSE was adopted to select the most accurate model for interpolating models. Using the observed and predicted data this indicator was calculated for each plain. The results of NSE are shown in table 3. By comparing the value of each model, it can be seen that the value of IDW model in Semnan plain and the value of Kriging model in Damghan plain are more merit models than others. Therefore, IDW and Kriging are the most accurate models in Semnan and Damghan plains, respectively, based on NSE.

Table 3. The result of Nash-Sutcliffe Model Efficiency Coefficient

Model \ Plain	Semnan	Damghan
IDW	0.47	0.75
Kriging	0.35	0.78
Co-Kriging	0.38	0.47

Groundwater Maps

Based on the results of Taylor diagram and NSE the most accurate model for interpolation are IDW and Kriging in Semnan and Damghan plains, respectively. Therefore, the groundwater level maps were generated based on these models and then classified into different classes. In both study area, Co-Kriging model was not the idea one, which can reflect that the height cannot affect on the groundwater level.

Based on the amplitude of the values of maps and the amount of changes every 20 meters, it is considered as one class. The groundwater changes during 1994–2018 in two months including April (recharging time) and October (discharging time) in Semnan and Damghan are shown in Fig. 4 and 5, respectively. The areas of lower classes, which represent lower groundwater level, have been increasing annually in both April and October months from 1994 to 2018. On the other hand, the higher classes, which indicate higher groundwater levels, have been decreasing annually in these months (Fig 4 and table 4). This reflects the decreasing trend of groundwater level in in Semnan plain and means that the groundwater levels have been decreasing since the beginning of the study period up to 2018. This depletion rate is mostly seen in the north and northeast of Semnan. So that the area of 1060-1080 class in 1994 April, increased from 13720 hectares to 441.7 hectares in 2018 at the same month.

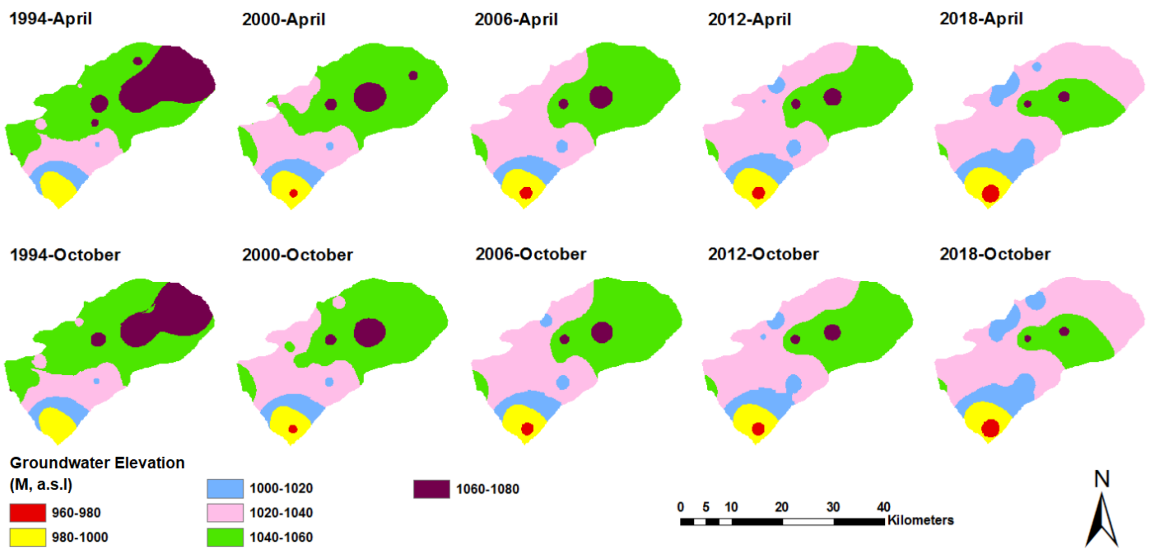

Figure 4. Maps of groundwater fluctuations in Semnan

Table 4 displays the area of each class of groundwater level in Semnan plain based on IDW model. It can be seen that the area of 1020-1040 (the lowest level) class has been appeared since 2000 (red area in Fig 4), and this class reaches to 816.4 hectares in 2018 October. The highest (1020-1040) class has drastically decreased over the time.

Table 4. Area of classes in Semnan plain during 1994-2018 based on IDW model (ha)

Year / Class	1994 April	1994 October	2000 April	2000 October	2006 April	2006 October	2012 April	2012 October	2018 April	2018 October
960-980	0.0	0.0	163.6	188.2	383.1	388.2	397.9	409.7	776.8	816.4
980-1000	2756.7	2826.3	3020.3	3066.7	3095	3110.3	3228.9	3267.2	3191.9	3201.4
1000-1020	2738.8	2879.2	3038.9	3161.3	3519.1	4047.7	4714.8	5181.1	7032.8	7954.4
1020-1040	8388.4	9354.2	14570	16748.8	20714	21209.2	23551.7	24037.1	30906.5	31722.2
1040-1060	26544.6	28040	30470	28428	24902.1	24053.6	21240.4	20335.7	11798.8	10113.6
1060-1080	13720.0	11048.8	2885.7	2555.5	1535.2	1339.5	1014.8	917.7	441.7	340.5

According to Fig 5 and table 5, the areas of lower classes (1020-1040), have been increasing annually in both months from the beginning of the study period. In contrast to these classes the higher classes have been decreasing annually in both April and October months. This issue displays that there is a decreasing trend in groundwater level in Damghan plain. On the other hand, the highest groundwater levels (1160-1180), decreases from 1429.7 hectares in 1994 April to 223.8 hectares in 2018 April. The most of the groundwater level dropping has been occurred in the southern and eastern parts of the plain, which may be due to the concentration of agricultural land in these two areas.

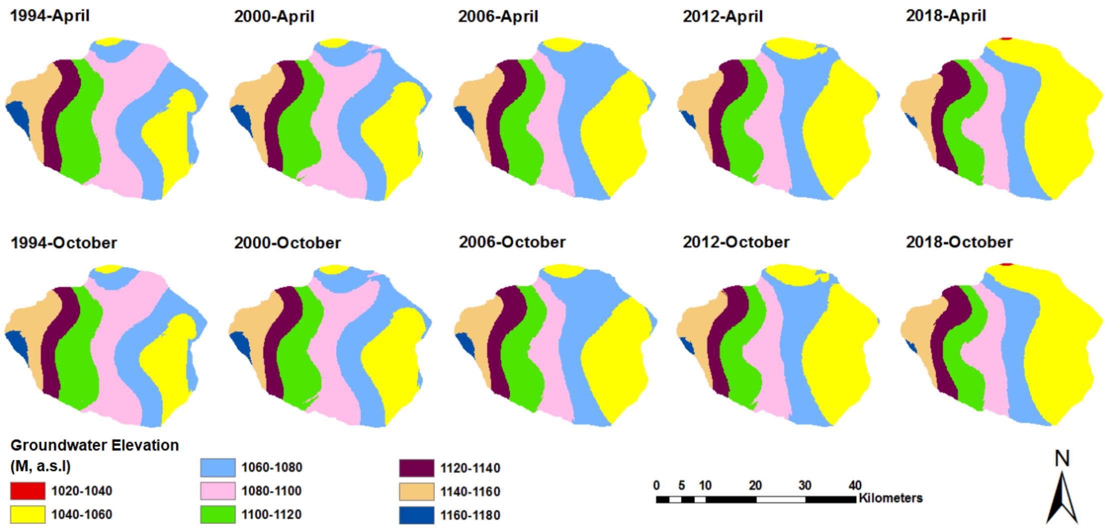

Figure 5. Maps of groundwater fluctuations in Damghan

Table 5 indicates the area of each class of groundwater level in Damghan plain based on Kriging model. As it can be easily seen, the area of 1020-1040 (the lowest level) class has been appeared (red area in Fig 5), while this class had not been in the early years. The highest class (1160-1180) has strongly decreased over the time.

Table 5: Area of classes in Damghan plain during 1994-2018 based on Kriging model (ha)

Year / Class	1994 April	1994 October	2000 April	2000 October	2006 April	2006 October	2012 April	2012 October	2018 April	2018 October
1020-1040	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.2	71.6
1040-1060	10460.8	11329.0	14312.1	14854.8	19194	19688.5	23856.8	24520.0	28275.8	28668.2
1060-1080	17006.3	16647.6	16738.7	17316.9	19132.6	18901.0	15903.9	15351.2	13002.3	12657.6
1080-1100	19064.3	18834.8	17766.5	16162.5	10814.1	10641.2	11125.5	11212.6	10661.2	10588.4
1100-1120	12212.2	11993.7	10625.6	11121.5	10756.1	10840.5	10024.7	9739.9	9171.3	8981.1
1120-1140	6412.1	6321.3	6140.5	6283.2	6510.6	6584.8	6390.1	6204.8	6488.6	6432.4
1140-1160	6665.3	6872.2	6627.1	6485.6	6022.2	5801.6	5522.5	5871.3	5362.5	5662.9
1160-1180	1429.7	1252.1	1040.2	1026.2	821.1	793.1	427.2	350.9	223.8	188.5

Fig. 6 shows fluctuations of groundwater in two plains over the study period. As it can be observed, in Semnan the most drop of water is occurred in northern parts and the southern parts have lower depletion of groundwater in April and October months. In Damghan plain, lower depletion have been occurred in the central parts of the plain and northern and southern parts has faced with more depletion.

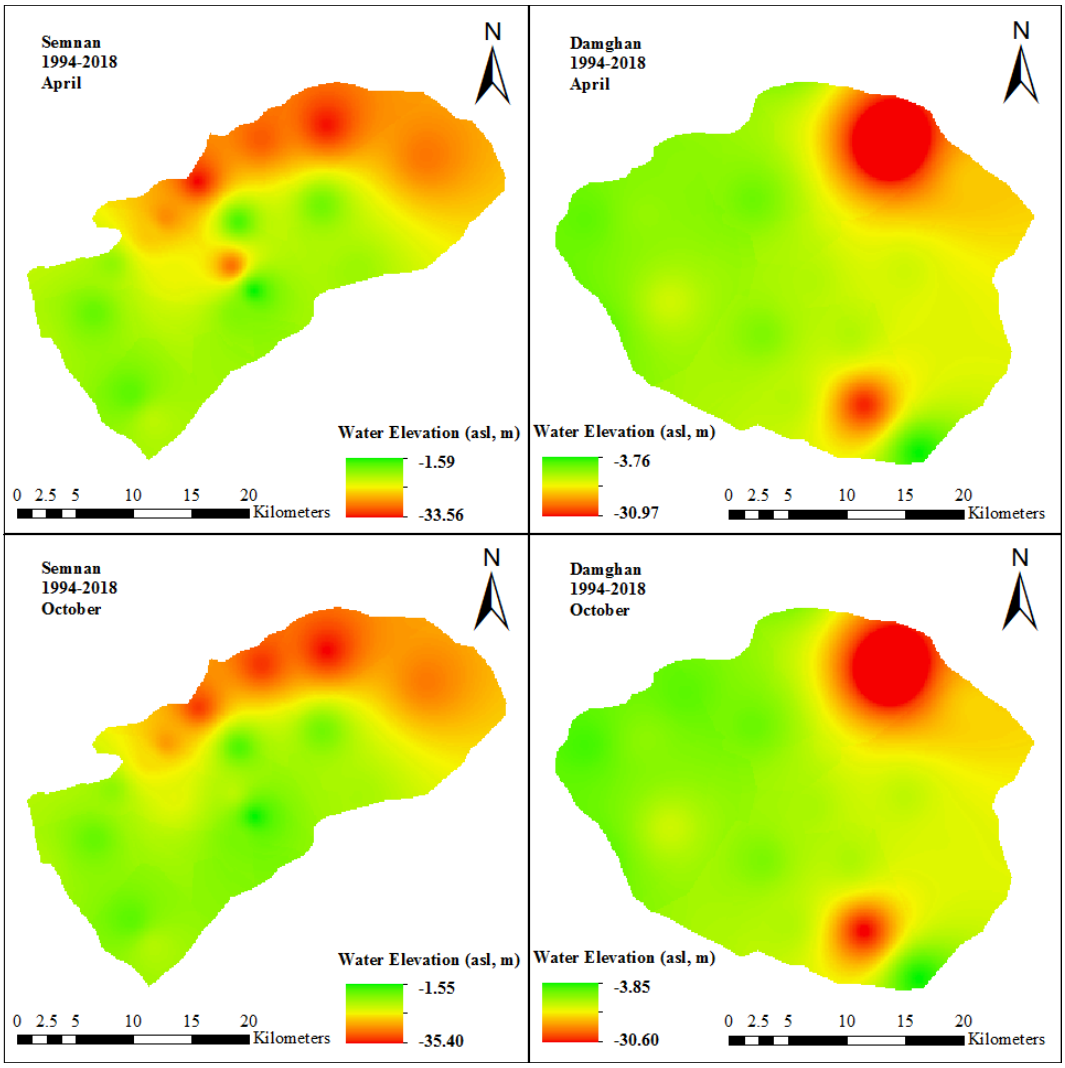

Figure 6. Maps of groundwater fluctuations over the time (Left: Semnan, Right: Damghan)

Conclusion

Groundwater has a crucial role in industrial and agricultural consumption in arid and semi-arid region, thus, unplanned and excessive use of groundwater can cause major problems such as destroying the aquifer, dropping the groundwater level and decreasing its quality in these regions. Important goals of water management are to prevent decreasing of quantity of these resources and its overuses. Therefore, conservation and management of these valuable resources has importance.

In this research, groundwater level fluctuations in Semnan and Damghan plains located in Semnan province were investigated using piezometric wells monthly data during 25 years, from 1994 to 2018, and GIS. Taylor diagram and NSE were adopted to choose the most accurate model for interpolating. According to the results, both of the models recognized IDW and Kriging models as the ideal models for groundwater level zoning in Semnan and Damghan plains, respectively. This shows the high ability of Taylor diagram to choose the accurate models to zoning. In this diagram R^2, RMSE and SD are used. So this is one reason that this model has high ability to use for selecting the most accurate item. After preparing the groundwater level zoning maps, classified maps showed that the trend of water quantity is decreasing in both Semnan and Damghan plains. The groundwater level in Semnan plain has been decrease and class 960-980 has come into being, which did not exist in the early years.

Also, in Damghan plain, class 1160-1180 has come into being, which did not exist in the early studied years.

The most of the groundwater level dropping has been occurred in the southern and eastern parts of Semnan plain and eastern parts of Damghan plain. There are many factors contributing to the groundwater dropping level. Recent decades of droughts, rising temperatures and reducing in rainfall can be some reasons for this issue. It also may be due to the concentration of agricultural areas in these regions. It is recommended to adopt proper management to prevent decreasing groundwater level and investigated groundwater level fluctuations along with land use and land cover, because both of them can effect on each other.

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