Geospatial Statistical Approach to Evaluate Groundwater Salinity - Jordan

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Abstract

Wells in the study regions are located in very close proximity to each other, causing the cones of depression to interfere with each other, leading to the increase of the drawdown and salinity. The statistics revealed that the wells' clustering play a significant role on degrading the groundwater quality. The Average Nearest method applied with a high confidence limit showed that all of the wells in the study area are clustering based on the wells' location. The Calculate Distance Band from Neighbor Count method was used and determined that the distance of 3,900 m in the Azraq, 1,000 m in the Dhuleil, and 1,150 m in the JRV are critical distances to test the clustering based on the values of TDS in groundwater. The General G-statistic method employed using the obtained distance confirmed that the wells based on the value of TDS are clustering.

Introduction

Jordan is located in the Middle East and covers an area of about 88,538 km^2 (Fig.1). Water resources is limited and the country is known to be one of the most water scarce countries in the world (Bajjali et al. 2015). The eastern Mediterranean Sea and the Arabian Desert areas affects the climate of Jordan. This makes the climate of the country hot, dry in summer, and short, cool in winter. Precipitation in the country is rare and sporadic, but vital and considered a primary source of recharge for shallow aquifers (Bajjali, 2012). Around 80% of Jordan's area receives an average annual precipitation of less than 100 mm, while the average rainfall in the mountain heights ranges between 300 and 600 mm a year (WAJ 2003).

In the past 30 years, the demand for water has been growing rapidly and water consumption for agriculture has increased and lead to over-abstraction and long-term declines in water levels. The agricultural activities consume the highest percent of water resources and the water consumption for irrigation fluctuated between 66% and 78 % for the years between 1985 and 2005. In 2017, the amount of groundwater used for irrigation increased dramatically and estimated to be 276 million cubic meters (MCM), while the available renewable and non-renewable groundwater resources are appraised to be 418 MCM (Al-Hadidi, 2018). Over the years, overexploitation of groundwater at different basin has resulted in declining water levels and elevated the total dissolved solid (TDS) of groundwater. The TDS or salinity increased in some wells to a level that the groundwater become unusable for any purpose.

Figure 2 shows the distribution of the wells in the three regions of the study area: the Azraq, the Dhuleil, and the JRV regions. The figure shows that the productive wells drilled very close to each other. This nearness cause the cones of depression of the pumping wells to interfere with each other, so each individual pumping well overlap with the cone of depression of other wells, triggering more dropdown in the water table (Moench and Prickett, 1972).
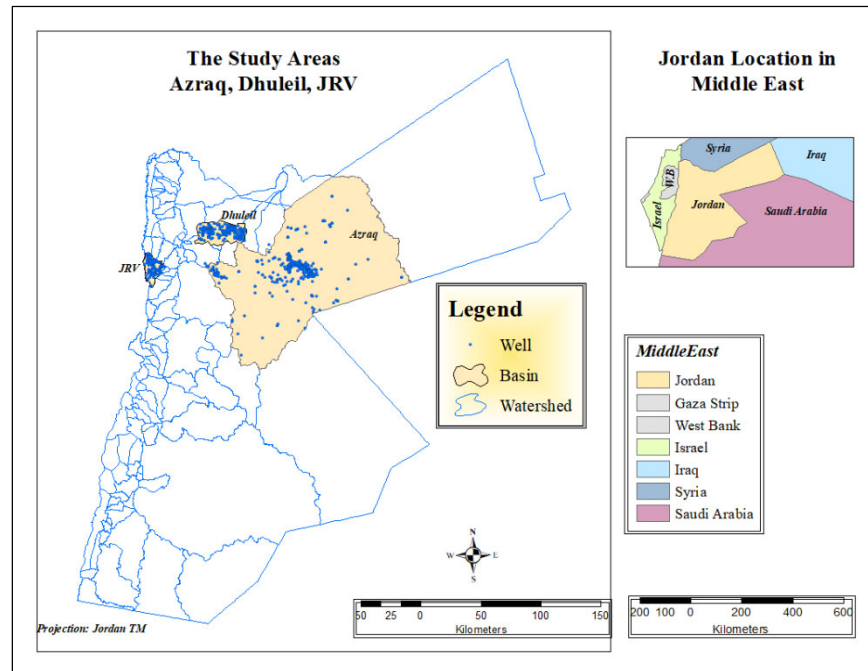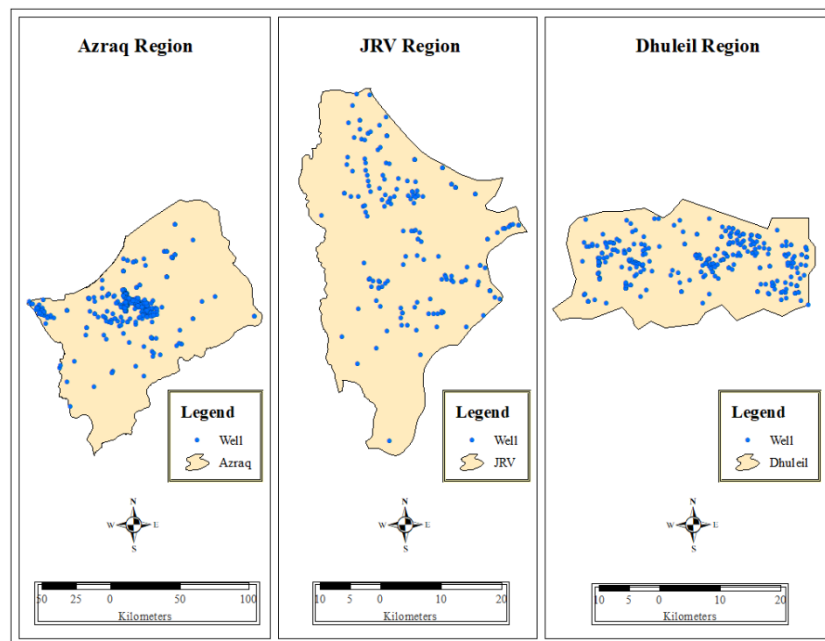
Fig.1 Location of Study Area in Jordan

Fig.2 Location of groundwater in the three regions of the study area

The consequences of the drawdown of the wells deteriorate the quality of the groundwater by increasing its salinity (Blaszyk and Gorski, 1981). The research is using various spatial statistics approaches to asses if the closeness of the wells exhibit clustering pattern and demonstrate salinity deterioration.

Methodology

The groundwater wells, groundwater level from some observation, and electrical conductivity (EC) data obtained from the Ministry of Water and Irrigation (MWI) and from the author previous publications. The EC represent the salinity or total dissolved solids. Around 1,000 Groundwater wells from three regions in Jordan integrated into ArcGIS as shapefile registered in customized UTM. The analyzing pattern and mapping clusters techniques in the spatial statistics tool used to evaluate the clustering based on wells locations and the value of salinity.

Water Level and Salinity Fluctuation in the Study Areas

Groundwater level fluctuation and salinity trend in the three regions assessed by use of GIS and graphical techniques. The three regions are part of the Azraq, Amman Zarqa, and JRV Basins.

Azraq Region: Water level and Salinity Trend

Azraq basin is one of the biggest basins in Jordan, where groundwater is the main and an important source for economic development especially for agriculture and domestic use. Several wells drilled to meet the increasing demand on water in the early eighties. Groundwater abstraction has increased over the years mainly from the basaltic and carbonate water bearing formations. Groundwater pumping has increased significantly and the abstraction tripled between 1983 and 2003, where the abstraction increased from almost 20 MCM to 60 MCM respectively (Al-Hadidi and Subuh 2001). The pattern of groundwater withdraw is believed to be mining as the amount of discharge exceeds the recharge rate by almost 2.25 times (HCST 1999). The overexploitation lowered the water table of the upper aquifer considerably and some wells dropped up to 20 meters. The groundwater demand and supply in the basin caused a general dropdown in the water table and the fluctuation of water level was different in magnitude for different location depending on the abstraction rate. The assessment of the fluctuation of the water table from number of observation wells shows that the water declining at an average rate of 0.55 meter /year (HCST 1999). The water table in the observation well (F1043) in the center of the basin declined sharply (Fig.3).
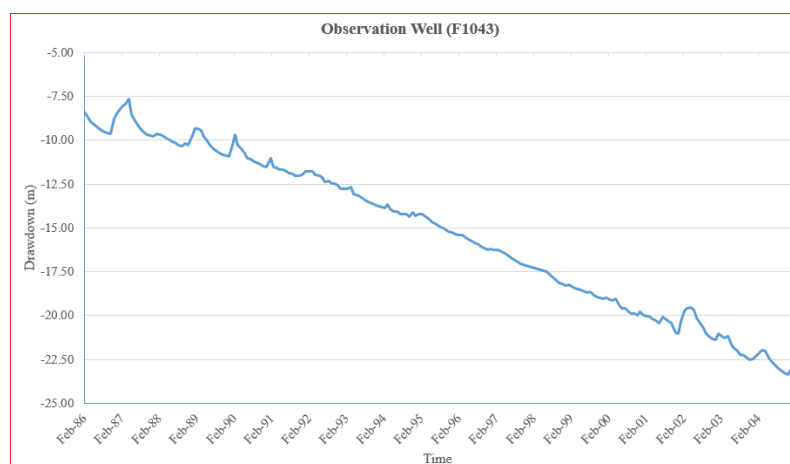

Fig. 3 Groundwater Fluctuation in Azraq Observation Well (F1043)

The graph shows that the water level of the groundwater declined 14.72 meters between 1986 and 2004, at a rate of around 0.81 meter per year, with no evidence of considerable replenishment. The consequences of the declining trend in water levels at various locations caused the natural springs in the

Azraq oasis that discharged fresh, good quality water for thousands of years to dry out completely (Bajjali and Al-Hadidi, 2006).

The TDS of the wells varies tremendously and range from fresh less than 500 mg/l up to brackish water higher than 4,000 mg/l. In the Azraq depression, which is located in the centre of the basin, the salinity recorded in some wells to be around 80,000 mg/l (Fig.4). The TDS increased unevenly at different locations and in different well fields. Water salinity also from the same well over the years show a trend of increase. For example, the TDS in AWSA-15 well increased slightly between 1998 and 1994, but the salinity increased sharply after 1995 (Fig.5). This shifted the water quality from fresh drinkable water to brackish undrinkable water.
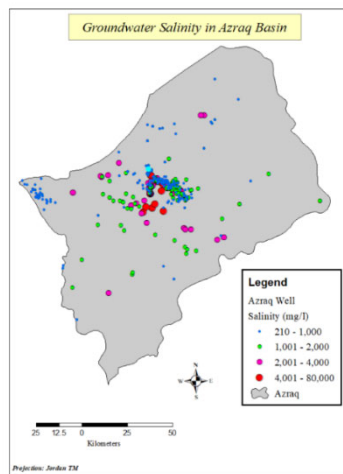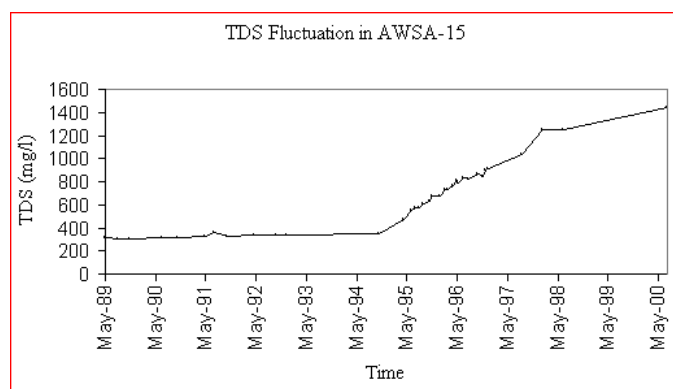

Fig. 4 Salinity in Azraq Basin

Figure 5 TDS fluctuation in AWSA - 15 well

The increased salinity of groundwater in the Azraq region attributed to different reasons such as return flow, mixing water of different strata, salt industry, and salt intrusion. Return flow is when the groundwater used as the main source for irrigation year-round. Continuing use the water throughout the year allows the crops to use some of the water and the excess water returns back to the aquifer with the signature of the evaporation effects that has more salt concentration. The mixing water come from the different layers of the basalt aquifer. The basalt aquifer consist of six lavas separated by different permeable eroded materials, and each permeable layer represents a separate path to the groundwater. The

heavy pumping causes the water to discharge from different depths and layers of different salinity. The salt industry attributed to the salt production in Azraq region. The production of salt produced in summer time between June and August by pumping the highly saline wells to the surface into large shallow beds that can accommodate up to 400 m^3 of water. The pumped water then directly exposed to the sunlight and the salted water evaporated, and the residual salt was excavated and trucked to the salt factory for processing (Ronay, 1993). Salt intrusion is due to the movement of saline water under hydraulic pressure from the deep aquifer to the upper aquifer. This happen due to over-pumping, which caused the water table of the fresh upper unconfined aquifer to drop below the piezometric surface of the lower saline confined aquifer (El-Waheidi et al., 1992). The lowering causes the saline water in deep aquifer to intrude the fresh upper aquifer and deteriorate its quality.

Dhuleil Area: Water level and Salinity Trend

Dhuleil area is part of the Amman-Zarqa basin and the groundwater development for agricultural started in the early 1960s. Many wells in the region drilled for irrigation and the pumping rates increased throughout the whole area caused a severe decline in the water levels in the wells (Bajjali 1997). Observation well No 1 shows a dramatic continual decline in water table over the years and the sharp decline is clear after 2005 (Fig. 6). The groundwater level in the well dropped as much as 43 meter in 44 years, almost 1 m per year between 1968 and 2012 (Bajjali et al., 2015).

The immense decline in groundwater level caused the government in 1985 to build the Khirbet Al-Samra wastewater treatment plant (KSWTP) to lessen the extensive use of groundwater. KSWTP treating huge amount of wastewater from cities with high populations. The reclaimed water from KSWTP then discharge into the Zarqa River and used in conjunction with the groundwater wells for irrigation. Despite the continuous over-pumping from wells downstream of KSWTP for irrigation, the water level in the wells demonstrate continuous rise and not decline. The rise in water level during 1985–2012 was 9.16 m, almost 34 cm per year (Fig. 7). The rise in water table attributed as a local recharge from the treated wastewater from the KSWTP (Bajjali 1997).
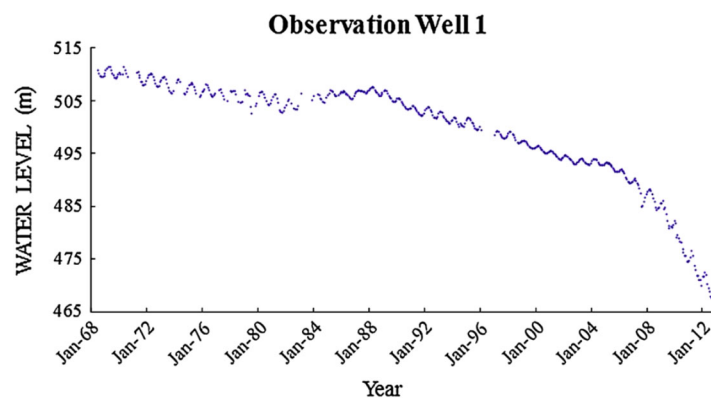

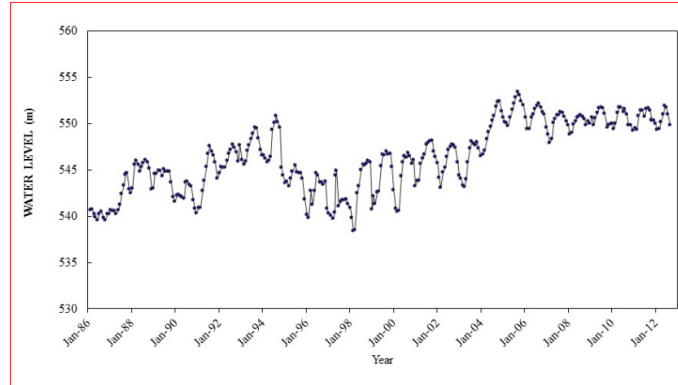**Fig. 6 Groundwater level fluctuation Upstream of KSWTP**

Fig.7 **Groundwater level fluctuation Downstream of KSWTP**

Some groundwater wells in the region up-and-downstream of KSWTP deteriorated significantly, and their salinity changed significantly. This situation caused some saline wells to be discarded and the one with less severe salinity used only for restricted irrigation. The observed high salinity upstream of KSWTP attributed to salt accumulation in the top soil due to the irrigation. The high salinity downstream of KSWTP attributed to irrigation and leakage from the treated wastewater along the Zarqa River bed. The continued irrigation from groundwater aquifer cause the salt to buildup in the soil by evaporation and then infiltrate into the subsurface. This condition allows the dissolved salt to infiltrate to the subsurface and rising the salinity. Figure 8 shows that the TDS concentrations in the wells up-and-downstream of KSWTP varies significantly. Some wells demonstrate salinity higher than 4,000 mg/l in both locations. Nevertheless, the location downstream of the KSWTP demonstrate the highest salinity, where the TDS reached up to 9,000 mg/l in one well that located in close proximity to the plant.
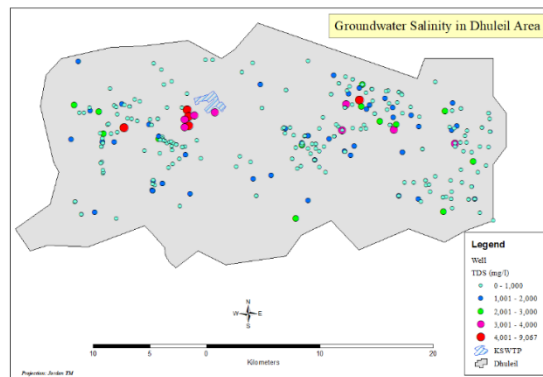

Fig. 8 Salinity in Dhuleil Region

JRV Area

The JRV is a long and narrow depression, and part of the rift system that extends from east Africa through the Red Sea to Turkey. The area is located below sea level and groundwater wells drilled to serve as a source of water for irrigation. The over-exploitation of groundwater caused declining in water table at different rate in various locations. The rate of water declining ranged from 0.18 meter in the area of Wadi Al Arab and up to 9 meter per year along the Zarqa River (Good et al. 2013). Figure 9 shows the fluctuation of water table in the observation well (AB1341) between 1982 and 2018. The graph shows that the recharge is obvious between January 1982 and October 1993. The water table rose 19.16 meters,

almost 1.74 meter per year. Nevertheless, the water table starts to decline after October 1993 and September 2003. Since the well tapping the alluvium aquifer and the water table shows a slight fluctuation, this indicates that the aquifer receive recharge. Nevertheless, the rate of recharge is insignificant than the rate of discharge.
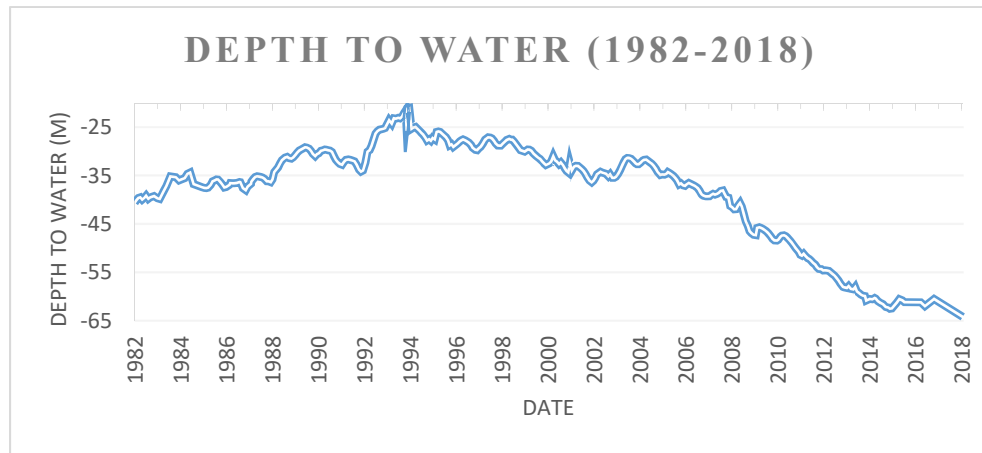

Fig.9 Groundwater level fluctuation in JRV

The salinity of groundwater wells reveals wide variability that ranged from 117 mg/l to 15,900 mg/l. Nevertheless, the majority of groundwater documented high salinity all over the region (Fig.10). The percentage of well with salinity higher than 1,000 mg/l is around 66%. The salinity higher than 4,000 mg/l recorded at various locations and mainly in the eastern part of the study area.

The high salinity attributed to water circulating through evaporates and the saline Dead Sea and Lisan formations and due return flow from irrigation. The subsurface flow originate from the eastern highland toward the JRV and the eastern formation include evaporates deposits mainly gypsum (Farber et al. 2007). The infiltrated water dissolve these highly dissolvable materials contributing saline water. The Dead Sea and Lisan deposits are also contributors to water salinities in the JRV (Salameh, 2002). The alluvial aquifer receives local recharge from surface runoff in wintertime through intermittent stream, which mainly use as a source for irrigation. The return flow of the irrigated water contribute to the salinity of groundwater.
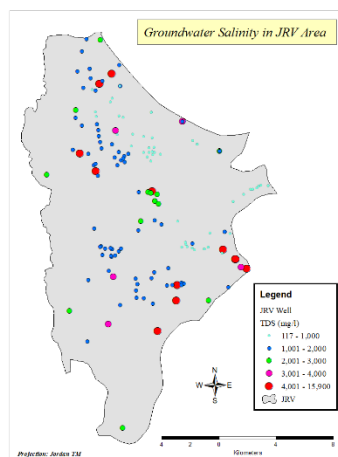

Fig. 10 Salinity in JRV Region

Analyzing Pattern using Geostatistical Methods

The groundwater that deteriorated in the three regions due to excessive pumping from different wells are located close to each other. The operating wells that are in close proximity to each other cause their cones of depressions to intersect leading to further decline in water table and salinity deterioration. The Average Nearest Neighbor and General G-statistics statistical approaches applied to asses this phenomenon.

Average Nearest Neighbor (ANN)

The method examines with some degree of confidence, if the wells in each study region reveals a pattern of clustering or dispersion. The technique calculate the distance between each well and the closest well to it and then calculating the average distance of all measurements for each study region. Then a made-up dataset with same number of wells generated and placed randomly within the same region. The GIS function will be run again and measure the nearest distance to its nearest neighbor well and calculate the average. The average distance of the random imaginary data and real data will be assessed based on two generated parameters: the nearest neighbor index (**I**) and standard normal variate (**Z-Score**)

The nearest neighbor index is calculated as follow

$$I = \frac{D_r}{D_h}$$

Dr is the calculated average distance of the real data

Dh is the average distance from the imaginary data

> If I < 1 the data show clustering
> If I > 1 the data show dispersion
> If I = 1 the data is randomly distributed

The Dr and Dh are compared using the normally distributed Z-Score. The Z score is a measure of statistical significance, and its value is vital to make a decision to either accept or reject the null hypothesis. If the Z-score is less than the value of the adopted confidence limit (i.e. 95% (-1.96), the null hypothesis will be rejected and it will confirm that a clustered pattern exists.

Testing the Distribution of Wells in the Three Regions

The ANN method used with a null hypothesis that the wells in all the three regions are randomly distributed. The ANN output process creates an HTML file with a graphical summary of the results. The HTML shows a graph with the following values: Observed Mean Distance, Expected Mean Distance, Nearest Neighbor Index, p-value, and Z-score. These values are essential to interpret the wells pattern in the three regions. The calculated "I" index and the Z-score for the Azraq basin is 0.304 and -28.81 respectively (Fig11 and Table 1). Because the "I" is less than 1 and Z-score less than -2.58. This means that the calculated difference between the observed pattern and random pattern is statistically significant. This conclude that the wells in the region exhibit clustering pattern. The ANN approach repeated to test the distribution pattern

in the Dhuleil and JRV regions with hypothesis that the wells are randomly distributed (Fig.12-13 and Table 1). Given that the generated nearest neighbor index (I) is less than 1 and the calculated Z-Score -17.6 in the Dhuleil and -8.96 in the JRV is less than -2.58 (Table 1), there is less than 1% possibility that the wells in these regions could be the result of random chance. Therefore, the wells also in these two regions exhibit clustering patterns.
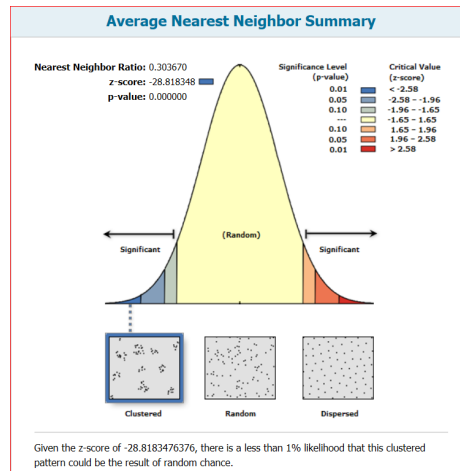
Fig. 11 Average Nearest Neighbor for Azraq Region

Table 1 Nearest Neighbor Index, p-value, Z-score, and the pattern

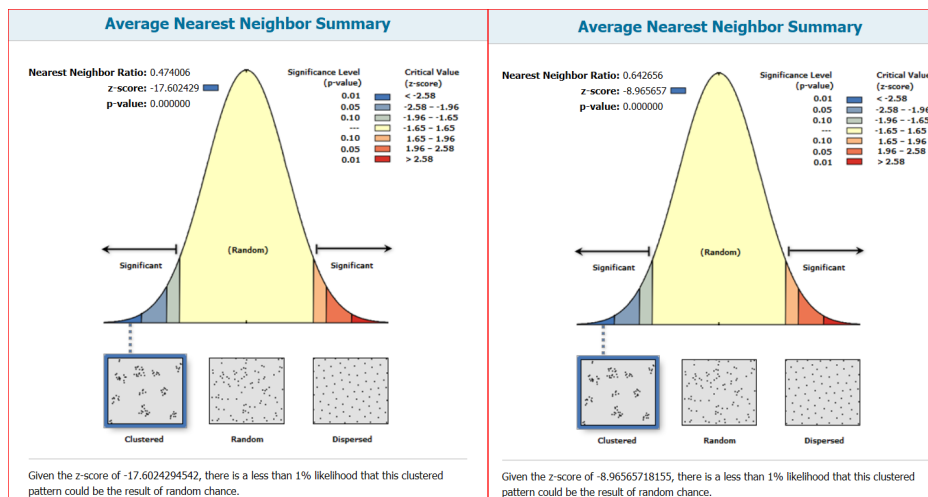| Region	I	Z-Score	p-Value	Pattern
Azraq	0.304	-28.81	0.01	Clustered
Dhuleil	0.474	-17.6	0.01	Clustered
JRV	0.643	-8.96	0.01	Clustered

Fig.12 ANN for the Dhuleil Region   **Fig.13 ANN for the JRV Region**

General G-statistics approach

Other parameters associated with the wells' locations such as the water salinity can also tested to verify if their concentration distribution showing trend or pattern. The examining pattern can be tested using the "High/Low Clustering (Getis-Ord General G)" method. To use this method a rational distance should be determined within the context of neighboring wells that have TDS values. Neighboring wells inside the threshold distance receive a weight of one and exert influence on the calculation. Neighboring wells outside the critical distance receive a weight of zero and have no influence on the wells computations.

The Calculate Distance Band from Neighbor Count (CDBNC) method implemented to find the critical distance to run the "General G-statistic method to identify the clustering in each region. The CDBNC use the Euclidean distance to obtain the minimum, maximum, and the average distance to each well with nearest neighbors of wells. The obtained average distances of the wells in the three regions using five wells neighbors are listed in table 2.

Table 2 Average Distance (m)

Region	Average Distance (meter)
Azraq	3,600
Dhuleil	1,200
JRV	1,150

High/Low Clustering (Getis-Ord General G)"

The High/Low Clustering tool measures the concentration of high or low TDS values of the wells in the three study areas. For a chosen critical distance d, G(d) is calculated in as follow

$$G(d) = \frac{\sum_{i-1}^{N}\sum_{j-1}^{N} w_{ij}(d) x_i x_j}{\sum_{i-1}^{N}\sum_{j-1}^{N} x_i x_j}, j \neq i$$

Where X_i is the value of the ith point and $w_{ij}(d)$ is the weight for point i and j for distance d.

The High/Low Clustering tool generate HTML file, which contain graph and four values: Observed General G, Expected General G, Z-score, and p-value. The result of the tool interpreted within the context of the null hypothesis, which states that there is no spatial clustering of TDS values. If the null hypothesis is rejected, then the sign of the Z-score becomes important. If the z-score value is positive, the observed General G index is larger than the expected General G index, indicating high values for the attribute are clustered in the study area. If the Z-score value is negative, the observed General G index is smaller than the expected index,

indicating that low values are clustered in the study area. A set of distance interval based on the obtained average distance in Table 2 will be tested in each region.

A set of distances from 2,700 to 4,200 m at 300 m interval tested in the Azraq region. The highest Z-score of 2.09 obtained for the distance of 3,900 m. This indicates that at this distance, the TDS clustering is the highest (Table 3). In the Dhuleil a set of distances from 800 to 1,600 m at 200 m interval tested and the distance of 1,000 m is the best distance for clustering and in the JRV a set of distances from 1,000 to 1,600 m at 150 m interval tested and the distance of 1,150 m is the best distance for clustering.

Table 3 Distance (m), Z-Score, and Pattern

Region	Distance (m)	Z-Score	Pattern
Azraq	2700	1.84	High Clustering
	3000	1.54	Random
	3300	1.76	High Clustering
	3600	1.99	High Clustering
	3900	2.09	High Clustering
	4200	2.04	High Clustering
Dhuleil	800	2.78	High Clusters
	1000	3.85	High Clusters
	1200	3.11	High Clusters
	1400	2.35	High Clusters
	1600	1.61	Random
JRV	1000	2.07	High Clusters
	1150	4.23	High Clusters
	1300	4.03	High Clusters
	1450	3.57	High Clusters
	1600	2.56	High Clusters

Conclusion

The study area located in three arid regions where the groundwater are the main source. The overexploitation of these resources led to deterioration in term of water table declination and elevated the salinity. The water table decline at a rate of 0.55 meter per year in Azraq, and the salinity-recorded concentration higher than the seawater salinity. The water level in the Dhuleil region behaved differently, upstream of the treatment plant, it dropped one meter per year between 1968 and 2012, while downstream it rose almost 0.3 meter per year between 1985 and 2012. Some wells in the Dhuleil demonstrate salinity higher than 4,000 mg/l, but one well in close proximity and downstream of the plant-recorded salinity close to 9,000 mg/l. In the JRV, the water table declined at different rate and ranged from 0.18 to 9 meter in different locations. The salinity of groundwater wells reveals wide variability and the eastern part of the JRV recorded salinity higher than 4,000 mg/l.

The results of the ANN and Getis-Ord General G methods confirmed that the wells in the three regions are clustering based wells' location and water salinity.

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