Geostatistial and Geochemical Approaches to Assess Groundwater Deterioration

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Abstract

Amman-Zarqa basin in Jordan is facing a situation of water scarcity in terms of quantity and quality. Agricultural practices have impacted the status of groundwater resources. This analysis has been done utilizing a geospatial information systems approach, and drawing upon chemistry to determine the source of this problem. Due to unsustainable agricultural practices and overexploitation of the aquifer, the water quantity has deteriorated and the water levels of wells have seen a drop of nearly 40 meters since the mid-1960s. This practice implies that discharge rates have not kept pace with recharge and suggests that this groundwater is not a renewable resource, and that once pumped out, the result would be the end of irrigated farming.

A wastewater treatment plant (KSWTP) was built in 1985 as a mitigation purpose to use its water for irrigation and to cut the use of groundwater to lessen further decline of the water levels in the wells. Using the reclaimed water in irrigation resulted in a rise in the water level at a rate of 20 cm per year downstream of KSWTP.

The water quality of groundwater deteriorated substantially up- and downstream of KSWTP and shifted from good to saline water that has restricted use. The high salinity in the groundwater is associated with return flow of the irrigation water and leakage from the treated wastewater of KSWTP along the Zarqa river bed.

GIS techniques using ArcGIS were applied to the well chemical dataset to create spatial distribution color coded maps. The Geostatistical Analyst is used to answer questions related to proximity of the wells from each other and their influence on lowering the groundwater levels and the increased groundwater scarcity. The agriculture wells were examined to verify if they are randomly distributed, or if they adhere to a pattern, either clustered or dispersed.

Keywords: salinity, irrigation, reclaimed water, over- abstraction, return flow, recharge, interpolation

Introduction

One of the most challenging issues that Jordan faces today is the scarcity of water. The country's population has continued to increase, combined with periodic massive influxes of refugees since early 1990s, and over-exploitation of water resources has made the country the fourth water-poorest country in the world. Its per capita share of renewable water resources is less than 150 m^3/year (MWI, 2009), which is significantly lower than the standard "water poverty line" of

1000 m^3 per person per year (UNDP, 2013). The largest user of Jordan's water resources is agriculture, which uses roughly 68% of the total water resources and it is concentrated in the Jordan Rift Valley (JRV) and the Highlands. Agricultural activities in the JRV rely mainly on surface water, while the Highlands rely on precipitation and groundwater.

The study area is located in the highland, which is part of the Amman-Zarqa basin and stretches northeast from the capital Amman to eastern desert (Fig.1). The area receives less than 150 mm of average rain per year and rainfall varies from year to year. However, the limitation of rain classifies the area as an arid region and places more limits on cultivating crops (WAJ, 2003). Most of the rain evaporates; the remainder flows into streams and other catchments or infiltrates into the ground to replenish shallow aquifers. Groundwater is the only reliable water source over most of the study area. The streams that flow across the study area are considered intermittent (wadi). The wadi flow only after intense rain as they convey runoff, then, almost all of that water evaporates or is transpired into the air by plants. The wadi water is difficult to utilize for irrigation as it lasts for a short period of time.

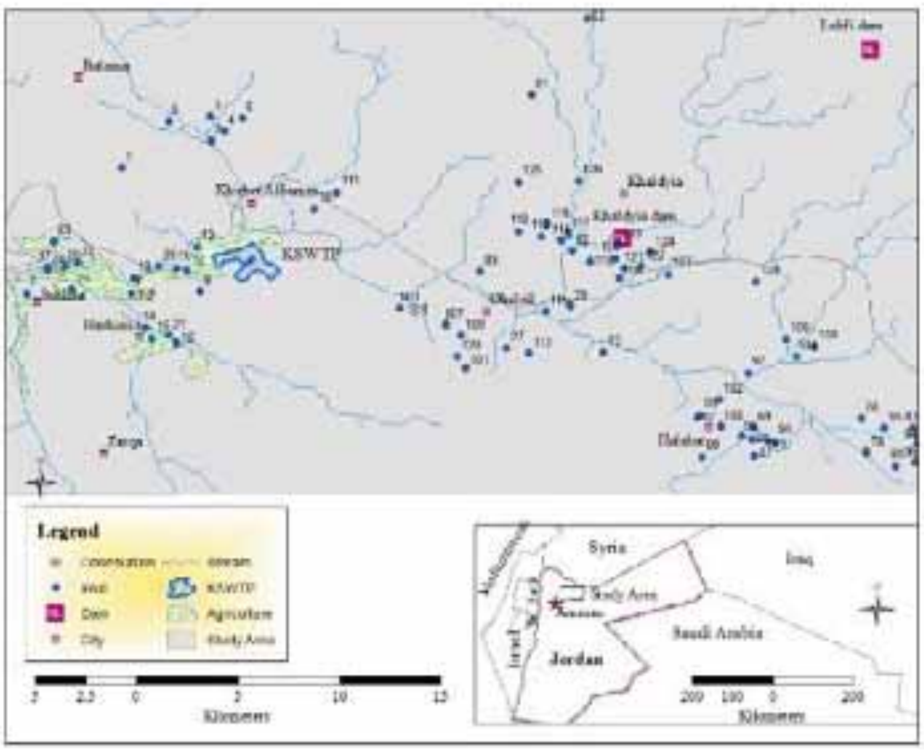

Fig.1 Site location of groundwater and KSWTP

The dry weather does not allow operating dry-farming: there has to be irrigation system The region is underlain by an enormous aquifer, which consists of thick basalt and limestone running in a northeast-southwest direction from the Syrian border, along the Zarqa River to Sukhna region in the basin, and groundwater is contained in an unconfined aquifers. Both aquifers are considered one aquifer as they are hydraulically connected. Several wells were drilled for irrigation purposes and the depth of the wells in the region is between 100 to 350 meters.

Before the development in the early 1960s the water table of the aquifers in the region was in equilibrium where recharge balanced the discharge. Several wells were drilled to meet the increase demand for irrigation and increase the crop yield. The rate of extraction increased overtime and the steady rate of pumping from multiple wells over the Dhuleil, Halabat, Khalidieh, and Samra areas led to a situation where cones of depression interacted and produced a regional drop in the water table. The aquifer in the region become an overdraft condition due to the fact that water was pumped from the aquifers faster than it could be recharged. This caused a severe decline in the water levels of the wells and the quality of groundwater (Bajjali, 1997 and Bajjali et al., 2015).

The area is characterized with high fault systems that could affect the circulation of irrigated water and the infiltration rate of precipitation into the subsurface permeable layers. Wells that were drilled along a fault system to tap the highest permeable strata of the aquifer will very likely be affected by agricultural activities, facilitating rapid infiltration of the return flow of the irrigated water (Benson, 1995 and Bajjali et al., 2015).

This study will use the geochemistry and geostatistical techniques in GIS environment to answer the following questions: (1) what causes the groundwater levels to fluctuate differently upstream and downstream of KSWTP; (2) what factors affected the deterioration of water quality in the whole study region; (3) does the location of the wells have a pattern with regard to identifying hot and cold spot of the saline wells, and identifying the trend of the saline wells?

Data and Methods

ArcGIS was used to store groundwater basin, wells, dams, field boundary of the treatment plant, and streams. A tabular database contained more detailed information on groundwater wells, including depth and chemical data. Information collected from groundwater wells resulted in a database of chemical analysis upstream and downstream of KSWTP. This database served as the input for the geostatistical analysis. Groundwater was sampled from 120 wells and analyzed for Total Dissolved Solids (TDS) and nitrate (Appendix 1). The chemical analyses were analyzed in the Water Authority of Jordan (WAJ) laboratories.

Result and Discussions

I - Recharge – Discharge of Groundwater

Water levels in aquifers is a reflection image of a mass balance between recharge, storage, and discharge. If recharge amount increases discharge, the volume of water in aquifer will increase and water levels will rise; if discharge surpasses recharge, the volume of water in an aquifer will decrease and water levels will fall. Long term observation of water levels in wells convey information about the relationship between precipitation, infiltration, and pumping. The fluctuations can provide understanding about the climate and human activities, such as over-pumping, irrigation, return flow, and changes in land usage. Short term fluctuations can also occur in response to rainfall, pumping, and barometric-pressure variations (**Healy and Cook, 2002)**. Intensive pumping can lower the water table dramatically and generate an overdraft that can influence the quantity and quality of water and increase the cost of pumping.

Monitoring the water level in observation well No 1in the agricultural area located in Dhuleil area shows over the last 40 years a steady, long-term decline with or without seasonal variations. Figure 2 shows the historical record of water levels in observation well No. 1. Over the last 40 years, the well has seen a drop of nearly 43 meters. The decline was almost 1 meter per year between 1968 and 2012. There was no sign that the water level was able to recover during subsequent periods of recharge, which is limited in this area due to low rainfall. This is critical as an aquifer does not comprise 100% water, because the water is held between the fracture of the limestone and the fractures, joints and vesicles of the basalt that result from escaping gases develop at the top of the basaltic flow. The unconfined aquifer produces only a specific yield, which is usually less than 20% of its volume in water. So if a well pumps 20 centimeters of water from the aquifer, and there is no replenishment, the water level in the well will drop 1 to 2 meters that year. It became clear that this groundwater was not a renewable resource, and that once pumped out, it would result in the end of irrigated farming. The sharp decline in the water level clearly indicated that the aquifer had been extracted much faster than its recharge rate, so the sustainability of the groundwater, which is the main source in this region, was being used for present time. Groundwater in the area was subject to high extraction for irrigation purposes, while average rainfall is declining due to slight changes in climate (Bajjali, 2012). This might not be a big concern for the farmers, but it is a big concern for Water Authority of Jordan.

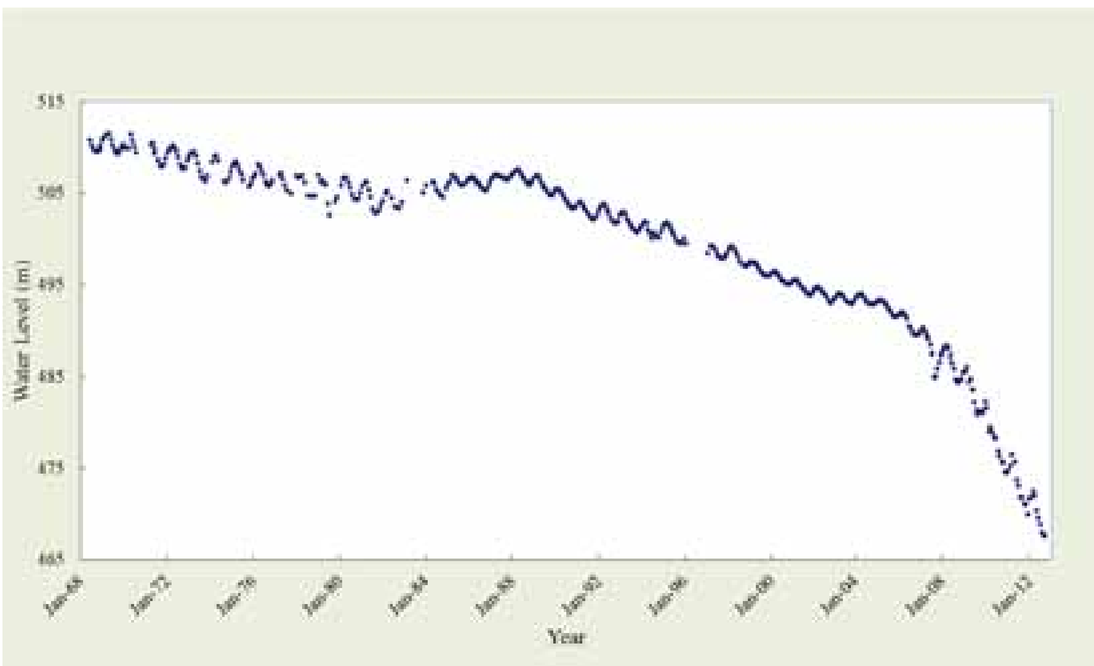

Fig.2 Groundwater Level Fluctuation in Observation Well 1

The severe drop in groundwater level caused by over-abstraction triggers the need for mitigation options such as integrated water cycle management and use of alternative water sources. Seawater and brackish groundwater desalination, as well as water reclamation and reuse, are applied in different countries as mitigation options (Bixio et al., 2006; Fritzmann et al., 2006).

To lessen further decline in water level in the agricultural area, the Water Authority of Jordan decided to use the reclaimed water for agriculture. Khirbet Samra Wastewater Treatment Plant (KSWTP) was erected along the Zarqa River for treating wastewater from the cities of great Amman area in 1985, downstream of the agricultural area Dhuleil-Halabat-Khalidieh region (Fig.1). The capacity of the plant increased over the years from 68,000 m^3/day to 267,000 m^3/day (RSS, 2012). The plant treats around 72% of all the wastewater in the country. The treated wastewater discharges via the Zarqa River to the King Talal Dam (KTD), and spills out downstream until it reaches the Jordan Rift Valley (JRV) area, where it is mainly used for irrigation (WAJ, 2004). The WAJ in 2006 modified the water standards, which allows using reclaimed water for irrigation of crops that will not be eaten raw, and use it for groundwater recharge to the aquifer not connected to domestic water supply.

After construction of the KSWTP, the area downstream of the plants started to rely on reclaimed water in addition to groundwater for irrigation. Groundwater levels remarkably started showing a constant rise in the wells downstream of KSWTP. Despite huge extraction rates from wells for irrigation, the groundwater levels increased. The rise in water level was almost 20 centimeters per year after the KSWTP was built, and the rise in the water levels was observed in the wells that were in close proximity to the Zarqa River channel (Bajjali et al., 2015**)**. Observation well No. 2, situated within 5 km downstream of KSWTP and in close proximity to Zarqa River, recorded about a nine-meter rise in water level during 1968-2012 (Fig.3). The rise in the water levels in the wells is attributed to irrigated wastewater infiltration to groundwater, and the infiltration commonly occurs unplanned and uncontrolled. The infiltration could occur directly from the streambed that receives discharge from treatment facilities (Eckert and Irmscher, 2006), or indirectly from excess agricultural irrigation in downstream riparian areas (BGS et al., 1998). The return irrigated water infiltrates back to the aquifer, acting as an artificial recharge.

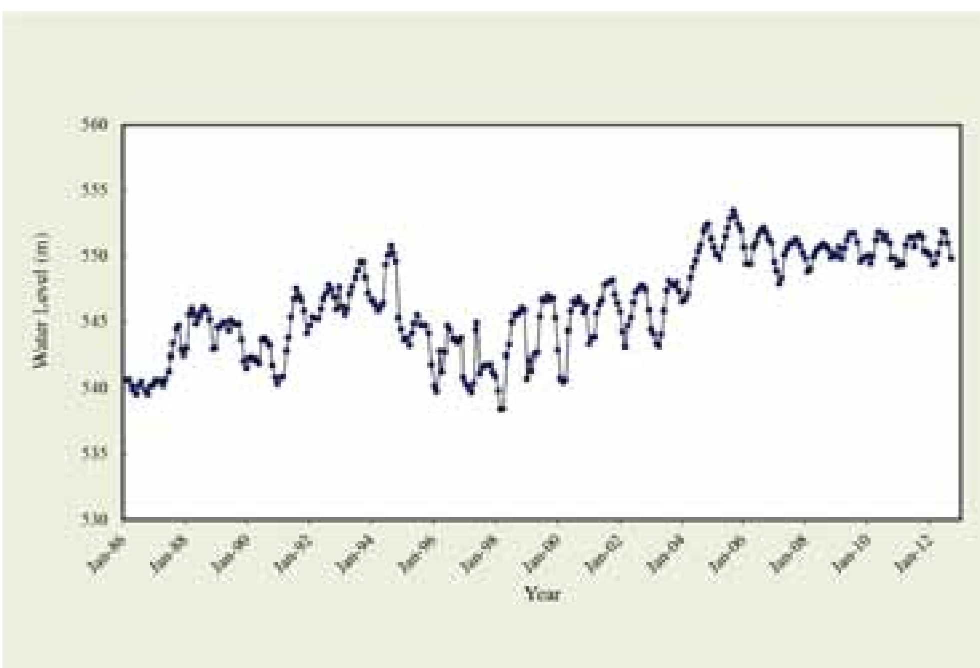

Fig.3 Groundwater Level Fluctuation in Observation Well 2

II - Groundwater Quality

The wells upstream of KSWTP penetrate mainly the basalt aquifer, and in the early 1960s, these wells yielded very good quality water and the salinity ranged between 265 and 448 ppm. However, continuous pumping of groundwater for agricultural activities over a period of 50 years has deteriorated the quality of water in the agricultural areas upstream of KSWTP (Fig 4). The salinity of some wells have increased almost 5 to 14 times above the initial level for the period from 1965 to 1989 (Bajjali 1997).

Over-abstraction worsened the groundwater in three ways. First, the withdrawal rate was much higher than the actual recharge rate, which caused the groundwater levels to decline steadily since 1968 (Fig.2). Second, the quality of groundwater deteriorated considerably and shifted from good quality to saline water that has restricted use; and some of the wells were closed due to high salinity. Third, the drop in water level caused an increase in the cost of pumping.

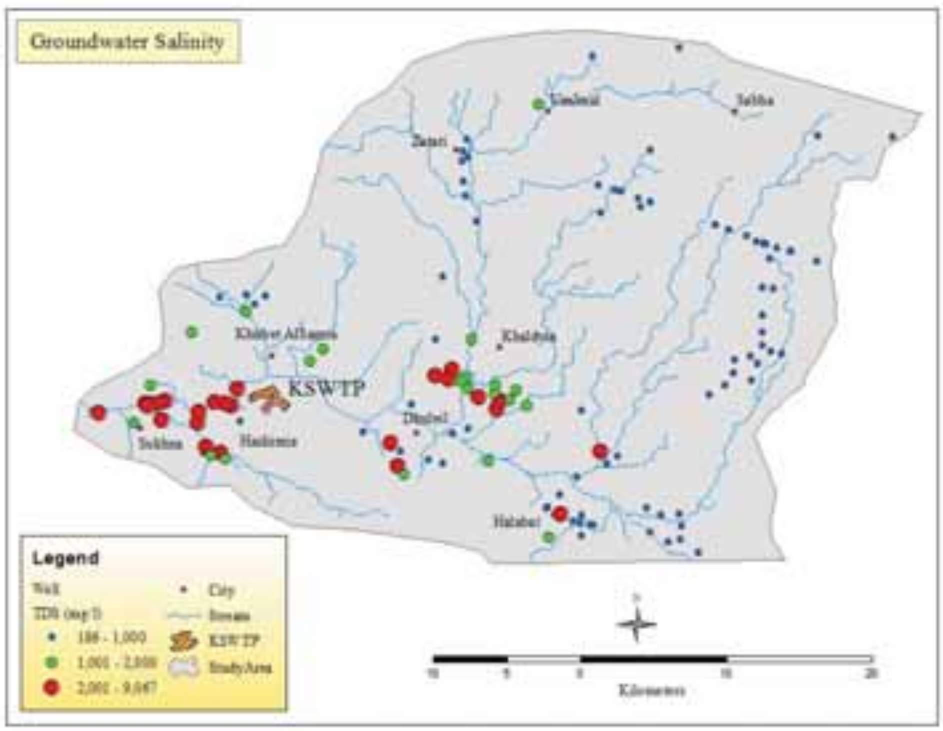

Fig. 4 Groundwater Salinity in the Study Area

Salinity in the limestone aquifer and the alluvium deposits was also significantly increased downstream of KSWTP areas due to two major factors: return flow from groundwater and reclaimed water. The return irrigated water infiltrated back to the aquifer and acted as an artificial recharge, as in the area upstream of KSWTP. The high salinity groundwater was associated with the shallow wells located in close proximity to KSWTP.

Deterioration of water quality up- and downstream of KSWTP was due to high salinity and nitrate. Salinity could be increased due to several factors such as cycling salting, rock weathering, invasion of saline water from a deeper aquifer, and return irrigated water (Marie and

Vengosh, 2001). The most likely source of potential salinity throughout the study area is local irrigation (Bajjali et al., 2015). It is believed that continued irrigation from the groundwater aquifer is causing a buildup of salinity in the soil and the aquifer. The various techniques such as open channel, sprinkler, and drip irrigation that have been used for irrigation since the early development made the irrigation water subject to intensive evaporation. Irrigation water evaporates from the soil and the roots of plants, and precipitates salts above and below the soil surface. Incessant irrigation from the groundwater wells and reclaimed water in the same agricultural area would continually precipitate and simultaneously dissolve the accumulated salts from the soil surface and the unsaturated zone. The salt is flushed from the soil repeatedly by the irrigation water, causing the solute to infiltrate down-gradient into the subsurface, thereby increasing the salinity of groundwater. This practice has continued for more than four decades near the productive wells. The white color of the soil surface throughout the study area in dry seasons is evidence of salt accumulation (Bajjali, 1997).

In the case of wells downstream of KSWTP, another source could simultaneously be responsible for increasing the salinity. The source could come from direct river loss by leakage through the riverbed. This leakage was recorded through the rise in the water table in observation well 2, which is located within 1 kilometer downstream from KSWTP (Fig. 3).

Nitrate is another chemical parameter that was found in high concentrations in some wells throughout the study area. Nitrate is an indicator of organic and inorganic sources of contamination and its concentration in groundwater in the entire study area had increased beyond the level of natural abundance of nitrate in groundwater. The levels also increased above the World Health Organization's standard of 45 ppm for drinking purposes up-downstream of KSWTP (WHO, 2011). Urea (46 % nitrogen content) is a common chemical fertilizer and used significantly and without control in the agricultural area to increase soil fertility and crop yields

III - Geostatistical Analysis

Statistics in GIS is a very useful approach that allows researchers in the field of water resources to obtain meaningful information related to the data in terms of the characteristics of features. One issue that the paper will address is how the wells are distributed in the basin and if the wells' locations and water quality of the groundwater form a pattern that are related to the source of contamination or other physical setting that contribute to establishing this pattern. Certain parameters such as salinity, nitrate, or others can be examined to analyze the degree of clustering. Knowing the cause of the cluster is useful to identify ways and methods that can be used to avoid the negative clustering. The analysis also allows the researchers to examine if certain chemical parameters of the groundwater wells in certain regions exhibit strong relationships.

Another statistical tool will identify the distribution patterns of features in a specific geographic area. It is a very well-known rule in GIS analysis, which is based on Tobler's First Law that stated all things are related, but nearby things are more related or similar than distant things (Tobler, 1970). In this paper, the "Average Nearest Neighbor," "Hot and Cold Spot," "Trend

Analysis," and the "Inverse Distant Weighting" (IDW) tools will be run to perform spatial analysis in ArcGIS.

Average Nearest Neighbor (ANN) tool

The ANN tool will detect if the features are clustered or dispersed. This tool will be used and tested with some degree of confidence level. The statistical approach behind this method is that the tool will measure the distance from each feature in the dataset to its single nearest feature neighbor and then calculate the average distance of all measurements. The tool then creates a hypothetical dataset with same number of features, but placed **randomly** within the **study area**. The tool will be run again and measure the nearest distance to its nearest neighbor feature and calculate the average. The average distance of the random hypothetical data will be assessed with the real data. The tool generates two parameters:

1: Nearest Neighbor Index (I) is generated as follows

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

Where D_r: is the average distance between each feature and its nearest neighbor of the real data and D_h is the average distance from a hypothetical data

$$D_r = \frac{\sum_{i=1}^{n} d_i}{n}$$

$$D_h = 0.5\sqrt{\frac{A}{n}}$$

where d equals the distance between feature i and its nearest neighbor feature, n corresponds to total number of features, and A is the total area (in map unit) enfolding the features

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

A pattern that falls at a point between dispersed and clustered is said to be random

2: **Z-score**

A z-score will be calculated and it is vital to make a decision to accept or reject the null hypothesis. The z-score is calculated as follow:

$$Z = \frac{D_r - D_h}{SE}$$

$$SE = \frac{0.26136}{\sqrt{n^2/A}}$$

The z-score is associated with the confidence level and it is up to the researchers to adopt which confidence level they are willing to use to test their hypothesis

Each confidence level is associated with a z-score, which is simply a standard deviation. For a 90 % confidence level, the z-score is between -1.65 and + 1.65. For a 95% confidence level the z-score is between -1.96 and +1.96 (Table 1)

Table 1 z-score, p-value, and confidence level

Z-score (Standard Deviations)	p-value (Probability)	Confidence level
-1.65 or +1.65	0.10	0.90
-1.96 or +1.96	0.05	0.95
-2.58 or +2.58	0.01	0.99

To run the Nearest Neighbor Index, a null hypothesis has to be proposed and the null hypothesis states that the features in the study area lack any pattern. This means that the features are not clustered or dispersed, but randomly distributed. If we assume to test the hypothesis with a 95% confidence level, then we are assuming that the features are randomly distributed. After running the test, the z-score value that is generated falls between -1.96 and +1.96 and the p-value larger is larger than 0.05. Based on this result, we have to accept the null hypothesis, which means that the features are randomly distributed. However, if the z-score falls outside that range, for example -2.0 or +2.0 standard deviations, we have to reject the null hypothesis and the observed features are clustering or dispersed.

Does the location of the wells have a pattern?

The water level of the wells upstream of KSWTP in the Dhuleil-Halabat-Khalidieh region experienced heavy pumping due to the intense agricultural activities. The water level dropped almost 1 meter per year between 1968 and 2012. Over-abstraction of each well tapping the basalt aquifer and drilled in close proximity to each other caused critical drops in the water level. This diverted the local groundwater to move towards the pumping wells, dropping the local water table in a 3D "cone of depression" shape. The average nearest neighbor technique was used to analyze the wells' location and assess if their spots were random or clustered. For the pattern analysis, a null hypothesis was proposed stating that the wells were distributed randomly and had no effect on the severe decline of water level of the observation well in the study area.

The ANN tool was run using the 129 wells and the enfolding area, which was 1,374 km^2. The result of the analysis is represented as a bell shaped graph showing the amount of clustering, the Nearest Neighbor Index (I), and the z-score (Fig 5).

Given the z-score of -7.0, there is less than 1% possibility that the wells in the study area could be the result of random chance. The "I" ratio is 0.67, which is less than 1, therefore the null hypothesis is rejected and the distribution of the groundwater wells are considered clustered. This means that increased pumping from wells located close to each other resulted in an even wider and steeper-sloped cone of depression, which led to more dewatering of the aquifer.

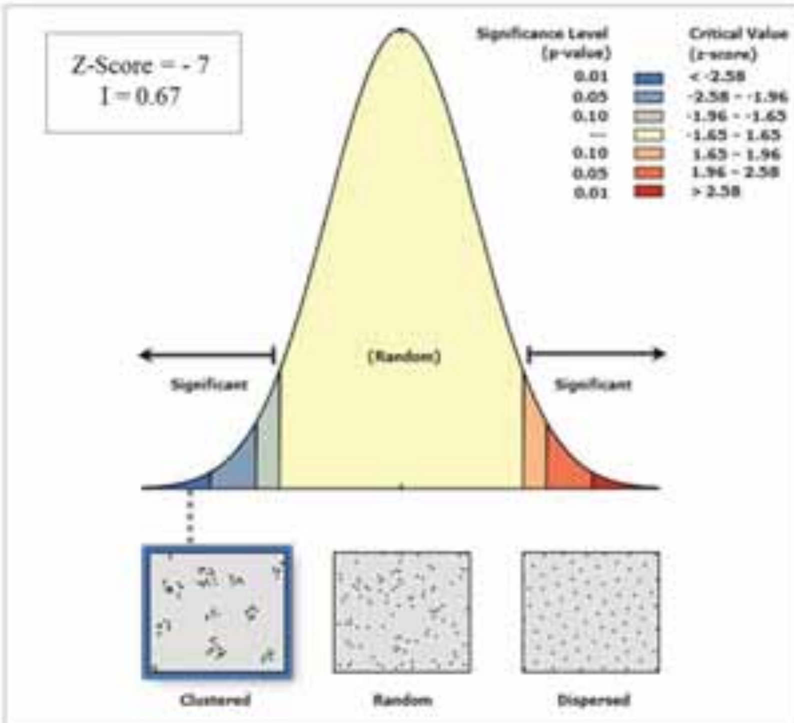

Fig. 5 Average nearest neighbor of wells' locations

Hot and Cold Spot using Cluster and Outlier Analysis

This model uses the cluster/outlier tool to perform a hot and cold spot analysis using the spatial statistics tool. The analysis is a spatial cluster that statistically identifies features with values similar in magnitude. To do this task, the tool calculates Anselin Local Moran's I value, a z-score, a p-value, and a code representing the cluster type for each feature. The z-score and p-value represent the statistical significance of the computed index value. The analysis is generated as follows:

$$I = \frac{x_i - \hat{X}}{S_i^2} \sum_{j=1,\ j \neq i}^{n} w_{i,j}\,(x_i - \overline{X})$$

where x_i is an attribute for feature i, $\overline{X}$ is the mean of the corresponding attribute, w (i, j) is the spatial weight between i and j and:

$$S_i^2 = \frac{\sum_{j=1,\ j \neq i}^{n} w_{i,j}}{n-1} - \overline{X^2}$$

with n equating to the total number of features

$$ZI_i = \frac{I_i - E[I_i]}{\sqrt{V[I_i]}}$$

where

$$E[I_i] = -\frac{\sum_{j=1,\ j \neq i}^{n} w_{i,j}}{n-1}$$

$$V[I_i] = E[I_i^2] - E[I_i]^2$$

The method of calculation is using the inverse distance, which is not in the user control, and it will generate new features that will be classified as hot and cold spots in the study area. The tool will generate a map with different color symbols. The red and blue symbols signify the hot and cold spots respectively. The hot-spot feature or group-of-cluster features are associated with a positive z-score (> 2) and surrounded by similarly positive z-scored features. The blue symbol is a cold spot well or cluster wells that are associated with a negative z-score (< -2) and surrounded by contrarily z-scored wells.

Does the salinity of the wells demonstrate hot spots?

The analysis of groundwater wells express that within the study area there are hot and cold spots. The wells based on the z-score are symbolized into five classes. The most relevant ones are the red and the blue dots (Fig. 6).

The red dot represents the hot spot wells and these wells have positive z-score values. These hot spots wells could have high or low TDS, and they are also considered a hot spot because they are surrounded by similar TDS values. This means the high TDS wells are found close to each other and the low TDS wells are also found close to each other forming a cluster. The hot spots are found in three distinct localities; to the east of the study area, upstream of KSWTP in Dhuleil and Khalidieh area, and downstream of KSWTP. To the east, three wells were identified as hot spots with FID no 62, 63, and 84. These wells have very low TDS (210 to 327 mg/l) and surrounded by low TDS wells. These 3-wells are located in the eastern side of the study area and far from the agricultural activities. The rest of the wells in Dhuleil and downstream of KSWTP were identified as hot spots and all surrounded by high TDS.

There is only one well with a blue dot and it is identified as a cold spot (z-score < -2). The well has a low negative z-score and it is surrounded by wells with dissimilar TDS values. The well has very low TDS (186 mg/l) despite its close location downstream of KSWTP. The well is considered a hand-dug well and it collects water during the wet season from precipitation and surface runoff. All the wells that surround the hand-dug well had very high salinity and their TDS ranged from 2,113 to 9,067 mg/l.

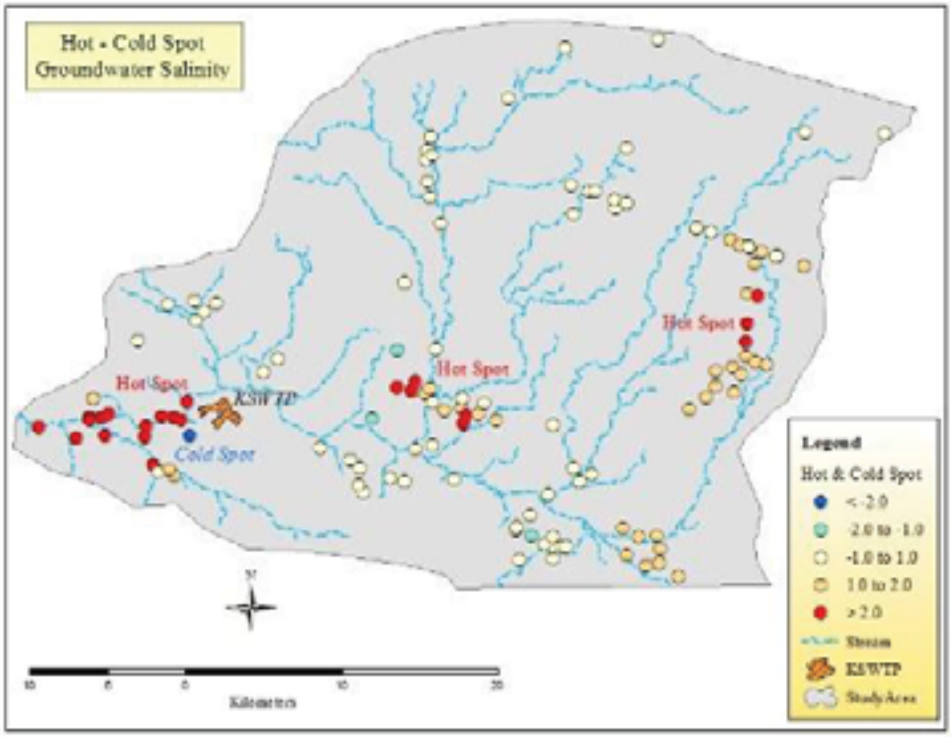

Fig. 6 Hot and Cold Spots of Groundwater Salinity

Trend Analysis

This is a simple way for describing large variations and its function is to find general tendencies of the sample data, rather than to model a surface precisely. The trend analysis calculates the coefficients of a best-fit polynomial surface to fit a set of spatially distributed data points (Bailey and Gatrell 1995). In ArcGIS the trend analysis tool provides a three-dimensional perspective of the data. The locations of the features are plotted on the X, Y plane and the Trend Analysis tool can help identify trends in the input dataset. The tool approximates features with known values using a mathematic polynomial equation. The equation then can be used to estimate values of other points. The aim of this method is to develop a general kind of spatial distribution of an observable fact. The surface can be modeled using a linear or trend surface. Linear trends describe only the major direction and rate of change, while the trend surface provides progressively more complex descriptions of spatial patterns. For example, the 3-D order trend can be described as follows:

$$Z = b0 + b1X + b2Y + b3X2 + b4XY + b5Y2 + b6X3 + b7X2Y + b8XY2 + b9Y3$$

where; Z is the interpolated parameter.

X and Y are the coordinates of the wells.

b coefficient estimated from the control points.

Does the salinity of the wells reveal a trend?

Trend surface analysis here is used to find general tendencies of the salinity of the groundwater wells. The analysis provide a 3-D perspective of the salinity values of the groundwater wells. The TDS values are plotted on a graph where the values are then projected onto the X - Z plane and the Y - Z plane as a scatterplot. The graph shows two trends: Y- Z plane dips from north to south in blue color and the X - Z plane dips from west to east in green color (Fig. 7). The north-south line is weaker than the west-east trend, suggesting that the general groundwater salinity pattern in the study area decreases from west to east. This observation corresponds with the fact that all groundwater salinity downstream of KSWTP, which is located in the west, has a higher concentration than the rest of the study area.

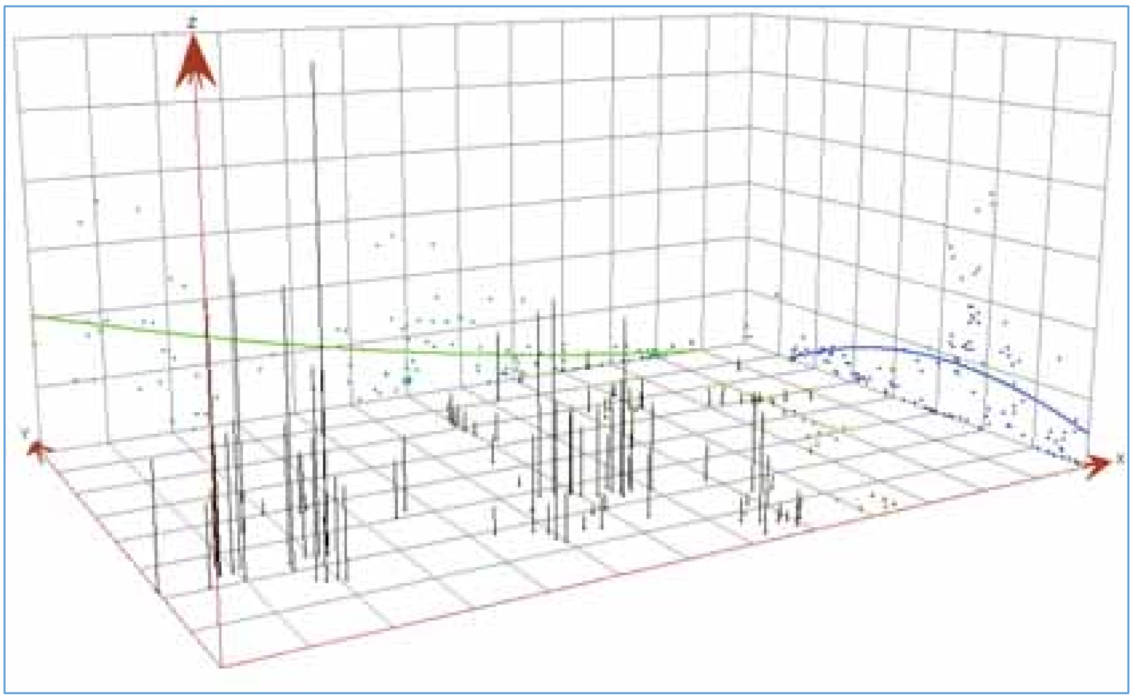

Fig. 7 Trend analysis of groundwater salinity

3-Spatial Interpolation using IDW

Geostatistical approaches deal with problems of spatial data, interpolation and mapping. Interpolation was originally developed for estimation of ore reserves in mining (Einax and Soldt, 1999). There are various interpolation methods of time series analysis that have been adapted and extended to spatial data (Myers, 1991).

IDW is used to interpolate the salinity in the study area. Spatial interpolation is simply defined as a process to estimate unknown values from points with known values. The models generate prediction surfaces and also uncertainty surfaces, giving an indication of the validity of the predictions. In this study, the unknown salinity values at locations where there were no groundwater wells were estimated through an interpolation technique from known salinity values measured at various locations. The model is used to create an interpolated grid based on the measured salinity of the wells. A reclassification function for the interpolated salinity grid was defined. A new value was assigned to each class based on the range of the salinity in the study area.

IDW is a very popular technique in GIS and considered one of the simplest interpolation methods. There are a variety of methods that use weighted moving averages of points within a zone of influence. Interpolation techniques in which interpolated estimates are made based on values at nearby locations and weighted only by distance from the interpolation location (Fisher et al., 1987). In general the simplified formula for IDW is

$$V_0 = \frac{\sum_{i=1}^{n}(\frac{Vi}{Di})}{\sum_{i=1}^{n}(\frac{1}{Di})}$$

where, V_0 is the predictable value at a point 0, V_i is the V value at control point i, D_i is the distance between control point i and 0, and n is the number of known values used in the evaluation.

The weights are a decreasing function of distance and the user has control over the mathematical form of the weighting function. The size of the neighborhood can be expressed as a radius or a number of points.

A 1.13-order polynomial trend was found to be the best practical solution for the salinity data interpolation in the study area. The 1.13-order trend allowed the best representation of the groundwater distribution up- and downstream of KSWTP (Fig.8).

The interpolation map is classified into five classes (Table 2). The classification is based on the salinity recorded in the wells and on the concept of the water-rock interaction, where salinity below 1,000 mg/l is considered fresh and above 1,000 mg/l is brackish. The total area that was interpolated as fresh water is around 58.6% and the rest is interpolated as a brackish area.

The resulting interpolation map is smooth and the surface shows a trend in increasing the salinity from east to west. Figure 8 shows that map of groundwater salinity up- and downstream of KSWTP and it reveals two regions of high salinity above 2,000 mg/l. The highest salinity was recorded in the first region, which is downstream of KSWTP. The salinity in this region was the highest and ranged between 2,000 to 9,000 mg/l. This high salinity was due to influence of the reclaimed water on the groundwater through the process of irrigation and return flow. The second region was upstream of KSWTP, where the salinity ranged between 2,000 and 3,000 mg/l. The percentage of the high salinity of more than 3,000 mg/l was in region 1, downstream of KSWTP. This region is relatively small, only 2.7% and shows a rise in water table due to return flow from irrigation (Fig.3). This mean that the vertical permeability of the unsaturated zone in this area is high and can be used as an artificial recharge to replenish the aquifer and improve its water quality.

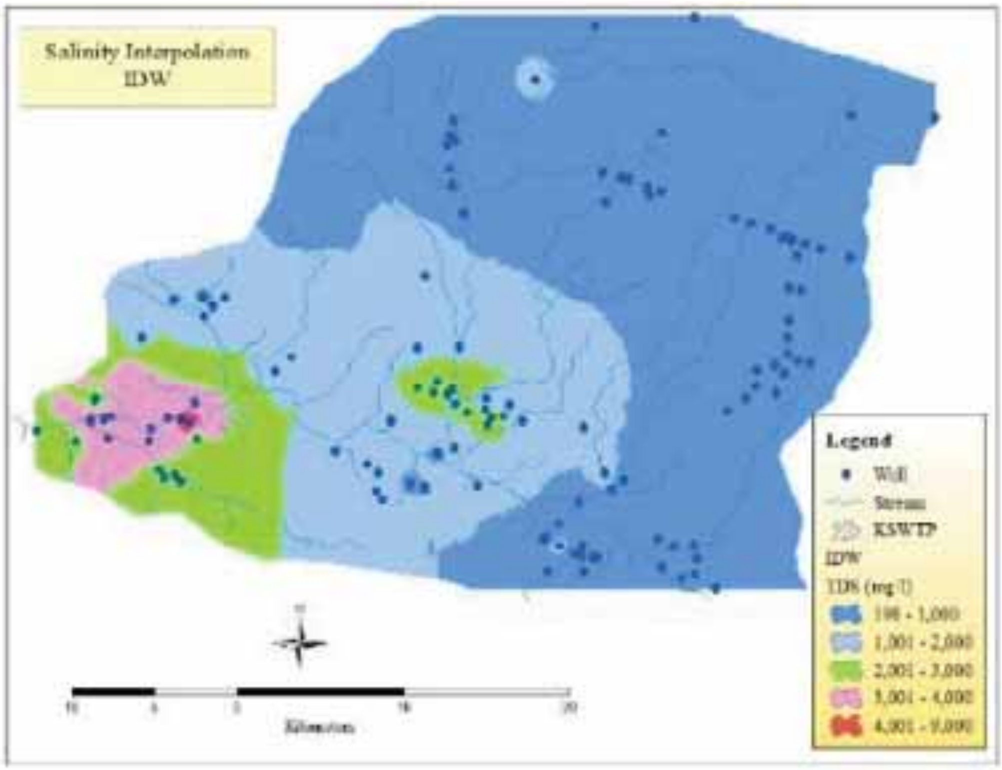

Fig. 8 Groundwater salinity interpolation using IDW

Table 2 Class, TDS, Area, and Percentage

Class	TDS (mg/l)	Area (km^2)	Percentage (%)
1	< 1,000	1099.33	58.66
2	1,001 – 2,000	511.35	27.29
3	2,001 – 3,000	212.44	11.34
4	3,001 – 4,000	49.09	2.61
5	> 4,000	1.76	0.09

Conclusions

Water reserve is scarce in Jordan and the largest user of the country's water resources is agriculture, which uses 68% of the total sources. The area relies on groundwater for cultivating crops. In the early 1960s, the water table of the aquifer in the region was in equilibrium where recharge balanced the discharge. The extraction rate increased overtime beyond the aquifer's sustainable yield and the intensive pumping has impacted the quantity and quality of groundwater resources. The water levels of wells have seen a drop of nearly 40 meters, which suggests that recharge rates have not kept pace with withdrawals. It became clear that this groundwater is not a renewable resource, and that once pumped out, its loss would result in the end of irrigated farming.

As a mitigation option, the KSWTP was built in 1985 so that its water could be used as reclaimed water for agriculture, and to lessen the further decline in the water levels of the groundwater wells. The continuous heavy pumping from the wells downstream of KSWTP caused the water level to rise around 20 cm per year since 1985. A slight recharge returned to the aquifer from excess irrigation water and leakage from the reclaimed water through the river bed of the Zarqa River. The infiltration process replenished the groundwater, but also deteriorated the quality of groundwater.

The quality of groundwater deteriorated considerably up- and downstream of KSWTP due to a shift from good to saline water that has restricted use. In addition, some of the wells were closed due to high salinity. The high salinity in the groundwater is associated with return flow of the irrigation water and leakage from the treated wastewater of KSWTP along the Zarqa river bed.

Water levels and salinity concentrations of wells measured up- and downstream of KSWTP are characterized by their high variability. So, a careful and objective evaluation and interpretation of the obtained results requires the use of statistical methods. The Average Nearest Neighbor method was applied and it found that the distribution of the wells was clustered. This resulted in a wider and steeper-sloped cone of depression, which led to more dewatering of the aquifer.

The hot and cold spot tool identified three hot spots with high salinity and one cold spot downstream of KSWTP. The trend analysis tool found the general tendencies of salinity of the groundwater wells. The west-east trend was found to be strong, suggesting that the general groundwater salinity pattern in the study area increased toward the west. The IDW techniques helped detect areas of different pollution states. The IDW interpolation map revealed two regions of high salinity above 2,000 mg/l. The highest salinity was recorded downstream of KSWTP and ranged between 2,000 to 9,000 mg/l. The area of salinity of more than 3,000 mg/l was only 2.7% and it was located downstream of KSWTP. This area can be used to artificially recharge the aquifer to replenish it and improve its water quality.

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Appendix 1 Chemical Data

ID	Depth	TDS	NO3	ID	Depth	TDS	NO3	ID	Depth	TDS	NO3
	m	ppm	ppm		m	ppm	ppm		m	ppm	ppm
1	426	1,280	2.0	44	450	692	18.6	87	404	280	8.5
2	292	1,427	83.5	45	346	464	11.1	88	350	284	11.2
3	300	524	24.9	46	445	427	14.1	89	267	268	6.3
4	300	488	28.6	47	169	870	4.9	90	615	367	20.7
5	340	451	7.4	48	135	365	6.8	91	570	642	2.7
6	300	840	53.8	49	136	753	7.4	92	160	669	15.6
7	103	1,716	66.0	50	367	751	20.1	93	200	204	8.2
8	90	5,330	154.0	51	382	628	18.4	94	283	607	5.5
9	5	186	7.4	52	342	484	1.2	95	257	191	7.0
10	-	5,135	145.0	53	400	804	2.1	96	165	246	8.4
11	120	3,705	187.0	54	380	410	9.7	97	350	390	1.2
12	76	9,067	324.0	55	359	749	16.6	98	-	1,124	0.3
13	85	3,510	119.0	56	137	401	13.6	99	132	536	13.8
14	175	2,761	20.7	57	267	204	7.5	100	140	2,340	138.0
15	289	1,392	8.3	58	321	205	8.1	101	130	1,133	35.8
16	128	1,888	14.0	59	350	204	8.5	102	121	218	10.1
17	-	2,950	40.5	60	303	806	16.7	103	161	710	25.0
18	250	2,816	39.4	61	358	600	15.9	104	106	960	32.0
19	30	2,604	28.6	62	395	327	0.0	105	234	333	1.9
20	298	2,736	31.6	63	350	210	13.0	106	90	2,210	101.0
21	102	2,069	15.8	64	350	240	0.0	107	85	2,080	89.4
22	12	2,929	43.4	65	350	262	18.8	108	105	499	26.6
23	100	1,636	28.8	66	350	200	8.0	109	-	755	25.4
24	-	2,658	20.5	67	351	230	8.2	110	100	3,965	145.0
25	35	5,566	45.6	68	350	236	7.7	111	200	1,670	3.4
26	79	2,113	32.5	69	142	486	9.7	112	100	2,145	85.2
27	130	476	10.2	70	330	625	15.1	113	210	826	22.9
28	371	918	20.9	71	423	424	12.6	114	100	1,872	80.6
29	373	310	9.9	72	415	282	8.9	115	155	352	1.0
30	400	319	5.1	73	445	1,811	50.1	116	101	4,160	119.0
31	339	629	15.2	74	170	208	8.2	117	100	1,950	76.4
32	400	626	12.7	75	-	1,472	28.6	118	98	3,835	142.0
33	386	428	10.3	76	350	196	7.6	119	100	2,015	94.3
34	407	387	12.6	77	351	197	7.5	120	100	1,950	85.0
35	305	471	11.7	78	219	243	9.9	121	100	2,535	116.0
36	320	294	9.1	79	324	205	8.3	122	101	1,911	88.0
37	351	417	10.3	80	170	215	6.8	123	95	1,326	51.3

38	103	1,363	58.5	81	400	789	0.0	124	192	1,307	50.5
39	210	511	12.3	82	250	1,600	25.3	125	165	352	26.0
40	395	436	14.2	83	245	218	9.4	126	125	1,056	36.7
41	400	541	17.9	84	124	235	12.2	127	94	1,950	97.2
42	375	873	30.5	85	386	216	7.1	128	97	960	32.0
43	386	540	17.1	86	596	454	18.5	129	99	2,020	15.1