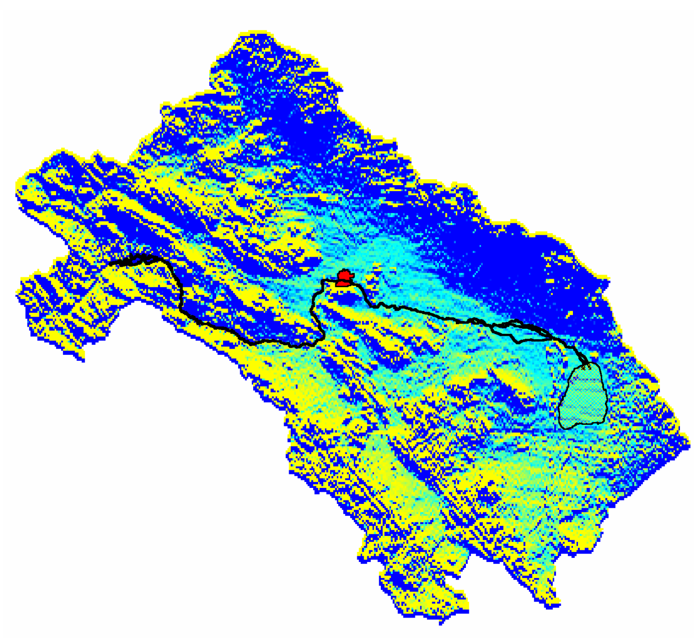
Sustainable Irrigation and Water Management in the Zayandeh Rud Basin, Iran

Spatial Analysis of Groundwater Trends: example for Zayandeh Rud Basin, Iran

P. Droogers, M. Miranzadeh



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P. Droogers, M. Miranzadeh

Abstract

Irrigated agriculture depends on reliable water services. In many cases canal water is the main source, but not always reliable, and groundwater is used as a backup system. Sustainability of groundwater use can be assessed by a trend analysis of datasets comprising several years. Trends can be analyzed by looking at individual observation wells or by using spatial interpolation techniques (gridding) to consider areal trends. A dataset comprising about 60,000 groundwater observations from Zayandeh Rud Basin, Iran, was used to develop, test and explore a methodology for such a spatial analysis. From the available gridding methods, kriging, with the default linear variogram with slope=1, anisotropy=1 and no nugget effect, was selected as the most appropriate one for the dataset considered. Options such as presentation of gridded data, interpolation and extrapolation, groundwater depth vs. groundwater level, and spatial resolution were explored and discussed. Finally some examples were given to clarify how the developed methodology can be used for assessing the sustainability of groundwater use in irrigated agriculture.

Introduction

Groundwater is an important source for irrigated agriculture, and if managed cautiously, a sustainable source. Conjunctive use of groundwater and surface water is a common practice in many irrigation systems around the world. In most cases, the bulk of the irrigation water originates from canals and groundwater is used as an additional source, especially if surface water is not reliable. The level of services of canal water delivery, the reliability, is equally important as the total water supplied (Droogers et al., 2000). In fact the dependability of groundwater as a reliable backup system for irrigation is one of the most important reasons for farmers to invest in pumps.

Sustainability of groundwater use is difficult to assess, as lateral groundwater flows are complex and require data-intensive groundwater simulation models. Also extraction of groundwater is hard to estimate as in most cases an unknown, but huge number of wells exist to extract water. At the same time, recharge rates from rainfall or irrigation are difficult to measure too. An analysis of the trends in groundwater levels can be a first step in assessing the sustainability of the groundwater system. Falling water tables over long time periods indicate that the system is not sustainable and is likely to collapse. Obviously, fluctuations within a year should not be considered as unsustainable, as long as the recharge, either by rainfall, irrigation or lateral flow, is ensured. If a system appears to be unsustainable, simulation models are the appropriate tools to explore options for more sustainable groundwater management.

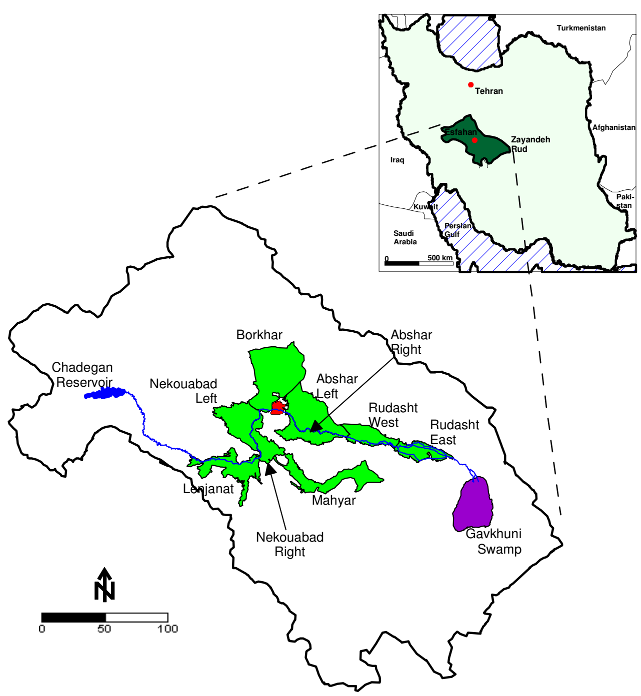

Figure 1. Overview of the Zayandeh Rud Basin, Iran, and the main irrigation systems.

Another threat to sustainable irrigation practice related to groundwater is water logging, and associated salinization. Huge areas around the world are facing these problems, caused by intensive irrigation practices over some decades. Similar to a decline in groundwater, an analysis of trends can be a first step to assess the sustainability of the system in terms of water logging hazard.

Looking at individual wells in the location of interest can be used to analyze trends in groundwater fluctuations. However, the use of spatial interpolation techniques enables to analyze the entire region of interest, rather than some specific points in the region. A number of spatial interpolation techniques are available, each adopted to the characteristics of the dataset under study.

This paper will deal mainly with the techniques to analyze groundwater trends, emphasizing the use of spatial interpolation techniques. As an example a dataset from the Zayandeh Rud in Iran is used, comprising about 700 wells and 60,000 observations. The objective of the paper is clearly towards the development and testing of a consistent methodology, rather than an analysis of the sustainability of the groundwater use in Zayandeh Rud. The latter one can be found elsewhere (Miranzadeh and Droogers, 2001).

Data

Data for this study originates from the Zayandeh Rud basin in Iran. Zayandeh Rud is a closed basin with an area of 41,500 km^2 and no outlet to the sea (Figure 1). The main river, the Zayandeh Rud, runs for some 350 km roughly west-east from the Zagros mountains to the Gavkhuni Swamp. The majority of the basin is a typical arid and semi-arid desert.

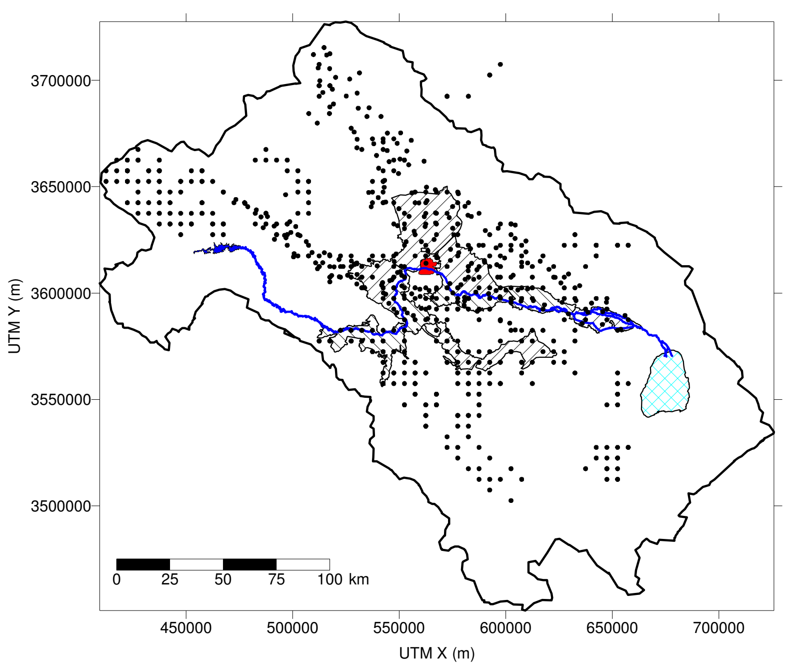

Figure 2. Distribution of observation wells in Zayandeh Rud.

Table 1. Some characteristics of the Zayandeh Rud groundwater dataset.

Year	Records	Depth (m)		
		Average	Minimum	Maximum
1987	61	32.14	5.29	66.27
1988	700	33.35	1.43	117.63
1989	2236	34.08	1.21	121.10
1990	3010	32.04	1.11	123.50
1991	4569	29.76	1.00	125.71
1992	4763	29.01	1.03	128.33
1993	4850	28.66	0.80	137.90
1994	5181	30.18	1.29	139.25
1995	5810	30.27	1.12	142.50
1996	6847	30.63	1.02	144.11
1997	7322	30.10	0.85	146.53
1998	5446	32.36	0.70	147.85
1999	5185	33.34	0.70	148.76
2000	3692	34.60	1.40	148.75
Total	59672			

Rainfall in Esfahan, which is situated in the planes at an elevation of 1800 m, averages only 130 mm per year, most of the rainfall occurring in the winter months from December to April. In the Zagros mountain, elevations up to 2500 m, annual average rainfall is around 1600 mm. During the summer there is no notable rainfall. Temperatures are hot in summer, reaching an average of 30^{o}C in July, but are cool in winter dropping to an average minimum temperature of 3^{o}C in January. Annual potential evapotranspiration is 1500 mm, and it is almost impossible to have any economic form of agriculture without reliable irrigation. A more detailed description of the Zayandeh Rud Basin can be found in Salemi et al. (2000).

A huge database encompassing 59,672 observations from 716 wells over the period 1987 to 2000 was obtained from the Min. of Energy. Figure 2 shows the distribution of the wells over the basin. Locations of the wells were only known at a 5 x 5 km grid square, and each well was indicated by the center of this square. As a result of this, some wells were pinpointed at the same location. Considering the size of the basin this error was assumed to be negligible. Some characteristics of the dataset are provided in Table 1.

Data was collected on a monthly basis, but not on a fixed day of the month. As the Persian calendar was the base for this monthly schedule, the converted dataset into the Gregorian calendar has some months with two values and other months without a value. Therefore, data were obtained for the 15th of a specific month using a simple linear interpolation between the two nearest observation dates.

All data were manually checked for errors by plotting the depth to groundwater for all the 716 wells and removing unrealistic outliers. It appeared that only few errors were included in the database and were removed.

Spatial Interpolation Techniques

Introduction

Wells are irregularly spaced over the basin, while groundwater levels are required for every point in the basin. Geostatistical analyses can be used to interpolate groundwater levels from unmeasured locations, by using observations from wells in the vicinity. Most commonly a spatial interpolation is performed not for one unknown location, but for the entire study area, using a method called “gridding”. One of the best packages to perform this gridding is Surfer from Golden Software (Surfer, 2000). Some of the text in this section originates from the help file of Surfer.

Gridding methods produce a regularly spaced, rectangular array of Z values, e.g. groundwater levels, from irregularly spaced XYZ data. The term "irregularly spaced" means that the points follow no particular pattern over the extent of the map, so there are many "holes" where data are missing. Gridding fills in these holes by extrapolating or interpolating Z values at those locations where no data exists.

A grid is a rectangular region comprised of evenly spaced rows and columns. The intersection of a row and column is called a grid node. Rows contain grid nodes with the same Y coordinate, and columns contain grid nodes with the same X coordinate. Gridding generates a Z value at each grid node by interpolating or extrapolating the data values.

Gridding Methods

An overview of the most commonly used gridding methods will be described briefly as well as some advantages and disadvantages in selecting one method over another.

Inverse Distance to a Power is fast but has the tendency to generate “bull's-eye” patterns of concentric contours around the data points. Inverse Distance to a Power does not extrapolate Z values beyond the range of data.

Kriging is one of the more flexible methods and is useful for gridding almost any type of data set. With most data sets, Kriging with the default linear variogram is quite effective. In general, Kriging is the most often recommend method. Kriging can extrapolate grid values beyond the data's Z range.

Minimum Curvature generates smooth surfaces and is fast for most data sets but it can create high magnitude artifacts in areas of no data. The internal tension and boundary tension allow control over the amount of smoothing. Minimum Curvature can extrapolate values beyond data's Z range.

Natural Neighbor generates good contours from data sets containing dense data in some areas and sparse data in other areas. It does not generate data in areas without data. Natural Neighbor does not extrapolate Z grid values beyond the range of data.

Nearest Neighbor is useful for converting regularly spaced (or almost regularly spaced) XYZ data files to grid files. When observations lie on a nearly complete grid with few missing holes, this method is useful for filling in the holes, or creating a grid file with the blanking value assigned to those locations where no data are present. Nearest Neighbor does not extrapolate Z grid values beyond the range of data.

Polynomial Regression processes the data so that underlying large-scale trends and patterns are shown. This is used for trend surface analysis. Polynomial Regression is very fast for any amount of data, but local details in the data are lost in the generated grid. This method can extrapolate grid values beyond the data's Z range.

Radial Basis Function is quite flexible. It compares to Kriging since it generates the best overall interpretations of most data sets. This method produces a result quite similar to Kriging.

Modified Shepard's Method is similar to Inverse Distance to a Power but does not tend to generate "bull's eye" patterns, especially when a smoothing factor is used. Modified Shepard's Method can extrapolate values beyond the data's Z range.

Triangulation with Linear Interpolation is fast. When applied to small data sets, Triangulation with Linear Interpolation generates distinct triangular faces between data points. Triangulation with Linear Interpolation does not extrapolate Z values beyond the range of data.

These nine methods have a huge range of additional settings to improve the gridding process depending on the dataset used. This will not be discussed here but can be found in Surfer's documentation.

The gridding methods described can be divided into two general categories: exact interpolators and smoothing interpolators. Exact interpolators honor data points exactly when the point coincides with the grid node being interpolated. The following methods are exact interpolators:

- Inverse Distance to a Power when no smoothing factor is specified
- Kriging without a nugget effect
- Nearest Neighbor under all circumstances
- Radial Basis Function when no R2 value are specified
- Modified Shepard's Method when no smoothing factor is used
- Triangulation with Linear Interpolation
- Natural Neighbor

Smoothing interpolators or smoothing factors can be employed during gridding when no strict confidence in the repeatability of your data measurements exists. This type of interpolation reduces the effects of small-scale variability between neighboring data points. When smoothing is used, weighting factors are assigned so the map is smoother.

The following methods are smoothing interpolators:

- Inverse Distance to a Power when a smoothing factor is specified
- Kriging with error nugget effect
- Polynomial Regression
- Radial Basis Function when an R2 value is specified
- Modified Shepard's Method when a smoothing factor is specified

Performance gridding methods

The nine methods described were used to generate grids for the basin using the data of January 2000 (Fig. 3). It's very clear that the selected gridding method has a tremendous impact on the final result.

Two methods are not able to extrapolate outside the range of the dataset: Natural Neighbor and Triangulation with Linear Interpolation. The Modified Shepard's Method is extrapolating groundwater level values outside the data range (white spots in Fig. 3). In this case the groundwater levels were interpolated from -867 to 674 m., while the observations range from 1.8 to 147.8 m. Polynomial Regression is showing only the general trend, as expected from north-west towards south-east. Finally the Nearest Neighbor is showing very abrupt changes and is therefore not very suitable to show spatial trends in this dataset, where gradients can be extreme.

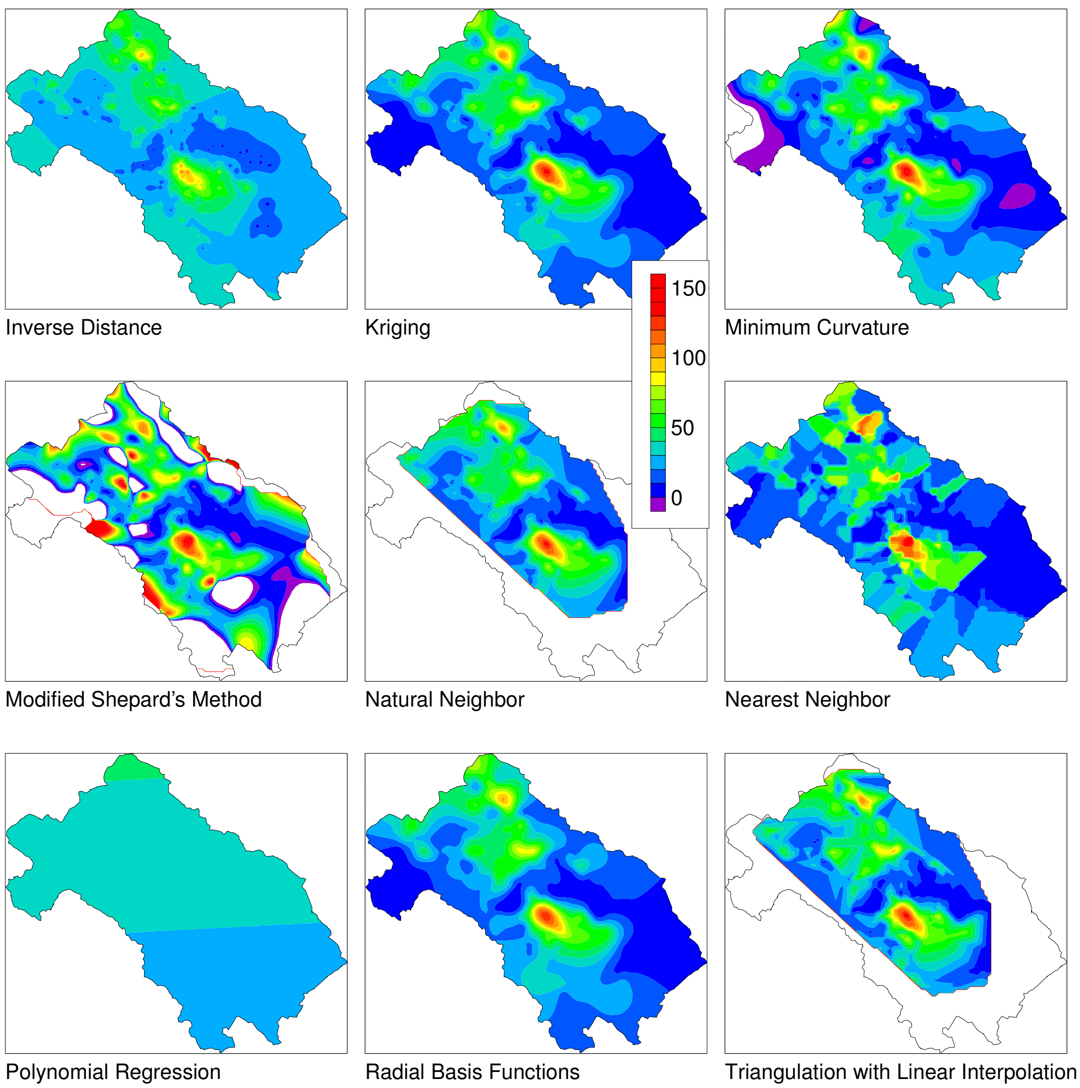

Figure 3. Spatial interpolation techniques used to grid data for January 2000. Data represents depth to groundwater in meters.

In conclusion, for the dataset used in this study, four methods give satisfactory results: Inverse Distance, Kriging, Minimum Curvature, and Radial Basis Functions. One of the characteristics of Inverse Distance to a Power is the generation of "bull's-eyes" surrounding the position of observations within the gridded area. Minimum Curvature has the tendency to create artifacts in areas of no data, as can be seen in the eastern part of the basin where no data is available, but trends are generated. In conclusion Kriging and Radial Basis Functions are the most appropriate gridding methods for this dataset. Somewhat arbitrarily we have selected to use Kriging instead of the Radial Basis Functions as Kriging is generally considered as the best and well-accepted method.

Kriging

Kriging is a geostatistical gridding method that has proven useful and reliable for many datasets (Journel, 1989). This method produces visually appealing maps from irregularly spaced data. Kriging attempts to express trends suggested in your data, so that, for example, high points might be connected along a ridge rather than isolated by bull's-eye type contours.

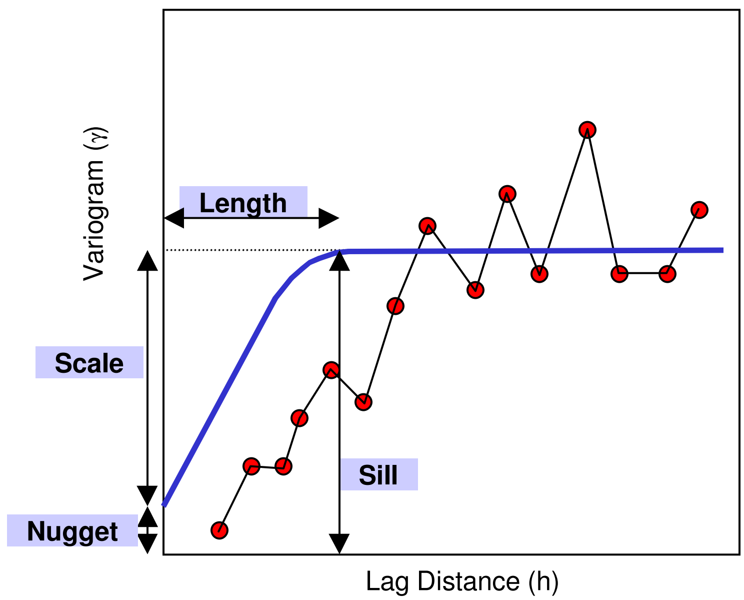

Figure 4. Hypothetical variogram with terminology used.

The base for kriging is the variogram (Cressie, 1991). A variogram is a measure of how quickly things change on the average. The underlying principle is that, on the average, two observations closer together are more similar than two observations farther apart. A hypothetical variogram is presented in Figure 4. There are two independent variables (the direction q, the separation distance h) and one dependent variable (the variogram value). A variogram specifies the underlying data by the following terminology:

nugget effect: quantifies the sampling and assaying errors and the short scale variability (i.e. spatial variation occurring at distance closer than the sample spacing).

scale: is the vertical scale for the structured component of the variogram. Each component of a variogram model has its own scale.

sill: is the total vertical scale of the variogram (Nugget Effect + Sum of all component Scales). Linear, Logarithmic, and Power variogram models do not have a sill.

length or range: is the horizontal range of the variogram. (Some variogram models do not have a length parameter; e.g., the linear model has a slope instead.)

variance: is the mean squared deviation of each value from the mean value. Variance is indicated by the dashed horizontal line in the diagram shown above.

Through the experimental data in the variogram models can be fitted, which can be used in the kriging spatial gridding. A wide range of variogram models exists and some of the more popular are: Spherical, Exponential, Gaussian and Linear.

A variogram is required for performing spatial interpolation by kriging. However, variogram modeling is not an easy or straightforward task. The development of an appropriate variogram model for a data set requires the understanding and application of advanced statistical concepts and tools: this is the science of variogram modeling. In addition, the development of an appropriate variogram model for a data set requires knowledge of the tricks, traps, pitfalls, and approximations inherent in fitting a theoretical model to real world data: this is the art of variogram modeling. Skill with the science and the art are both necessary for success. An example of a comprehensive variogram modeling for an irrigation district in Zayandeh Rud is presented by Gieske et al. (2000).

Given these difficulties in variogram modeling and the huge number of dates to be analyzed, it was decided to use a linear model with slope=1, anisotropy=1 and no nugget effect. It has been proven that with most data sets, Kriging with the default linear variogram is quite effective (Surfer, 2000).

Display Options

The gridded data can be displayed in several map formats, which can give a completely different impression from the dataset. Some options to consider will be discussed here and some examples are presented (Fig. 5). As dataset we use again the depth to groundwater for January 2000, gridded using Kriging as explained in the previous chapter.

Map B and C look very different, giving the impression that groundwater depths are lower in C. However, this is only caused by the fact that for C another color scheme was used than for B. Especially when comparing different periods color scale and minimum and maximum data plotted should be similar. The contour interval over which the dataset is plotted can also give misleading impressions. Comparing Map B and D it looks as if in B much more spatial variation in groundwater depths occurred. An interesting way of presenting the data is by using vector maps, Map F, to represent the gradient in groundwater depths. This map is somewhat misleading as the actual groundwater flows depend on the hydro-geological characteristics. Moreover, the depth to groundwater is less relevant, but the hydraulic head, defined using a standard reference level, is important. This will be discussed in the next section. Finally, wireframes (Map G and H) can be used to present the data, which give nice pictures, but are somewhat difficult to interpret.

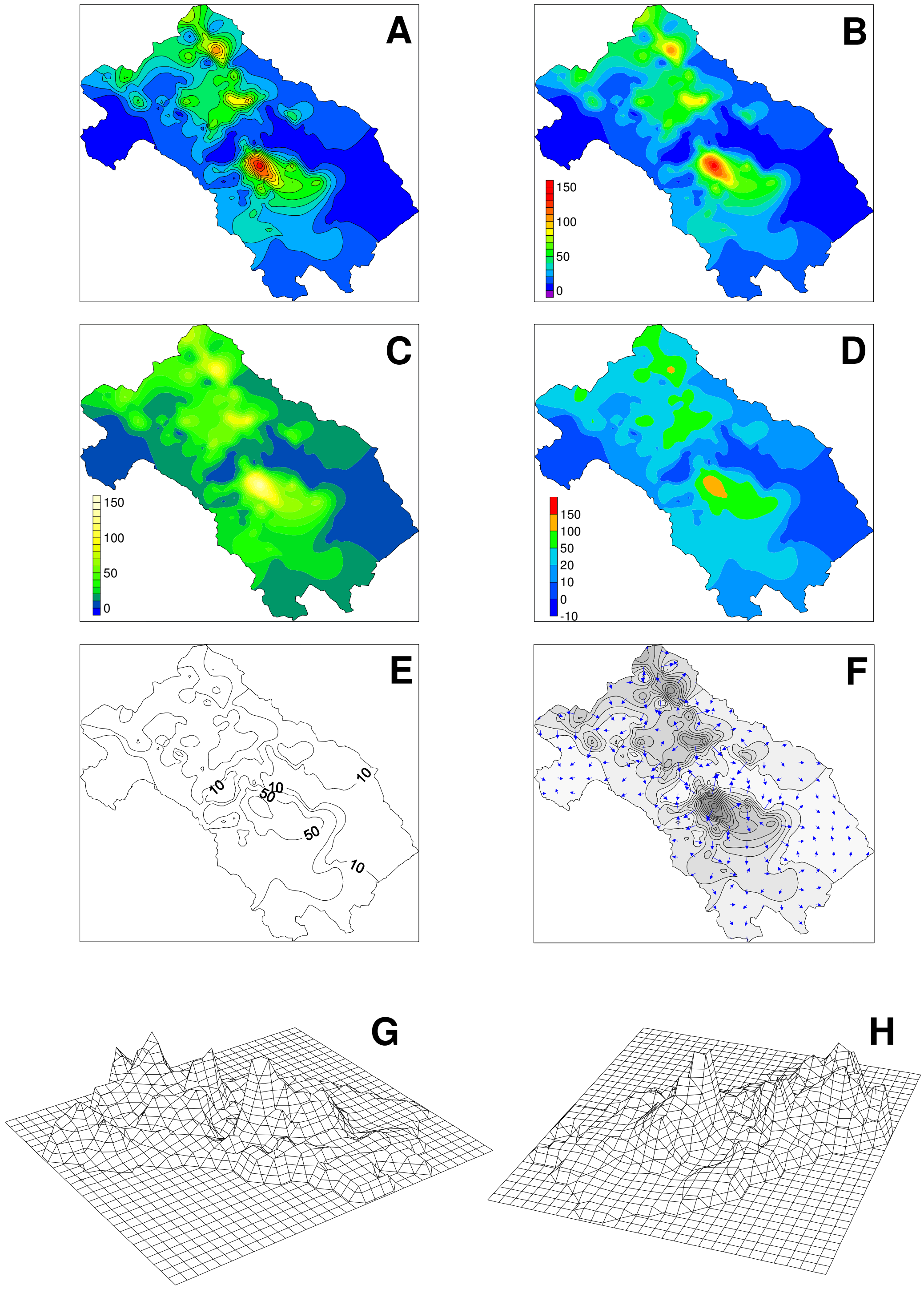

Figure 5. Different display options using the same gridded data representing depth to groundwater (meters) for January 2000.

From Figure 5 it is clear that the same dataset can be presented in many different formats and care should be taken to select the appropriate format. No general guidelines can be given on what the best way to present data is. Dataset characteristics and personal preferences should be considered as well as the objective of the figure.

Groundwater depth vs. level

So far, all data presented were related to depth to groundwater measured from soil surface. In terms of agricultural water management, and more specific the use of groundwater for irrigation, this depth to groundwater is the most important parameter. However, in terms of groundwater flow, the hydraulic head, measured as the height relative to a fixed level, is the dominant factor. For the same dataset, depth to groundwater as well as hydraulic head are presented in Figure 6.

The overall trend in hydraulic heads shows a west to east gradient with some local variation.

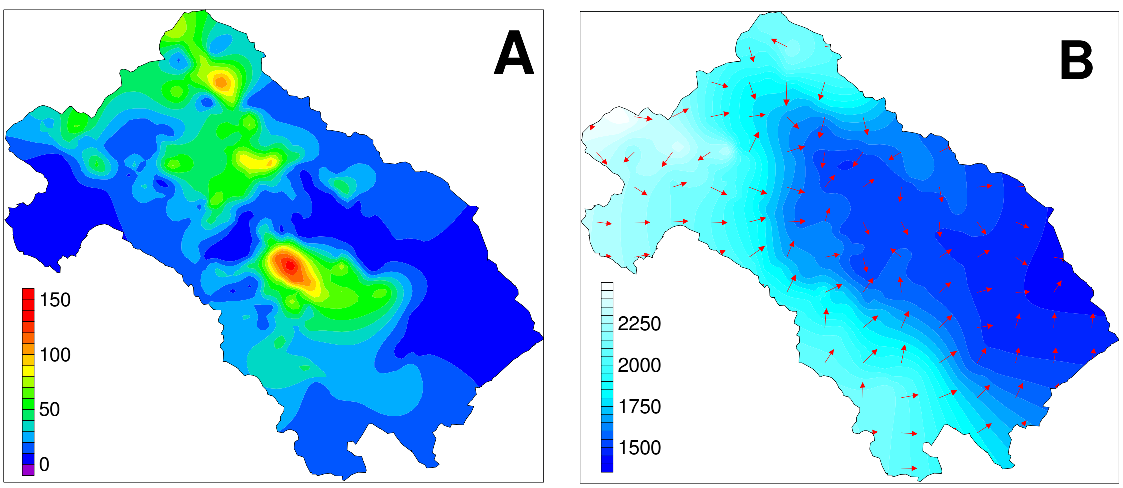

Figure 6. Depth to groundwater (A) and groundwater levels (B) to a reference base (hydraulic head) for January 2000. All values in meters.

Interpolation and Extrapolation

Interpolation between known observations to estimate values for unknown locations is the main objective of gridding. In general, if sufficient datapoints are available around the unknown location the result will be reliable. However, extrapolation assumes that trends outside the dataset range are similar to the ones within the dataset range. This assumption is, especially dealing with datasets limited to a basin, often false. From Figure 2 it is clear that some parts of the basin are not covered by wells and extrapolation was used to create a basin wide grid. Figure 2 shows also that within the main irrigation systems and the valleys sufficient data are available to have a reasonable amount of confidence in the gridded data. Further analyses and conclusions will therefore be limited to the main irrigation systems in the basin. Obviously, datapoints outside the irrigation systems are used to perform the gridding, so no extrapolation is required.

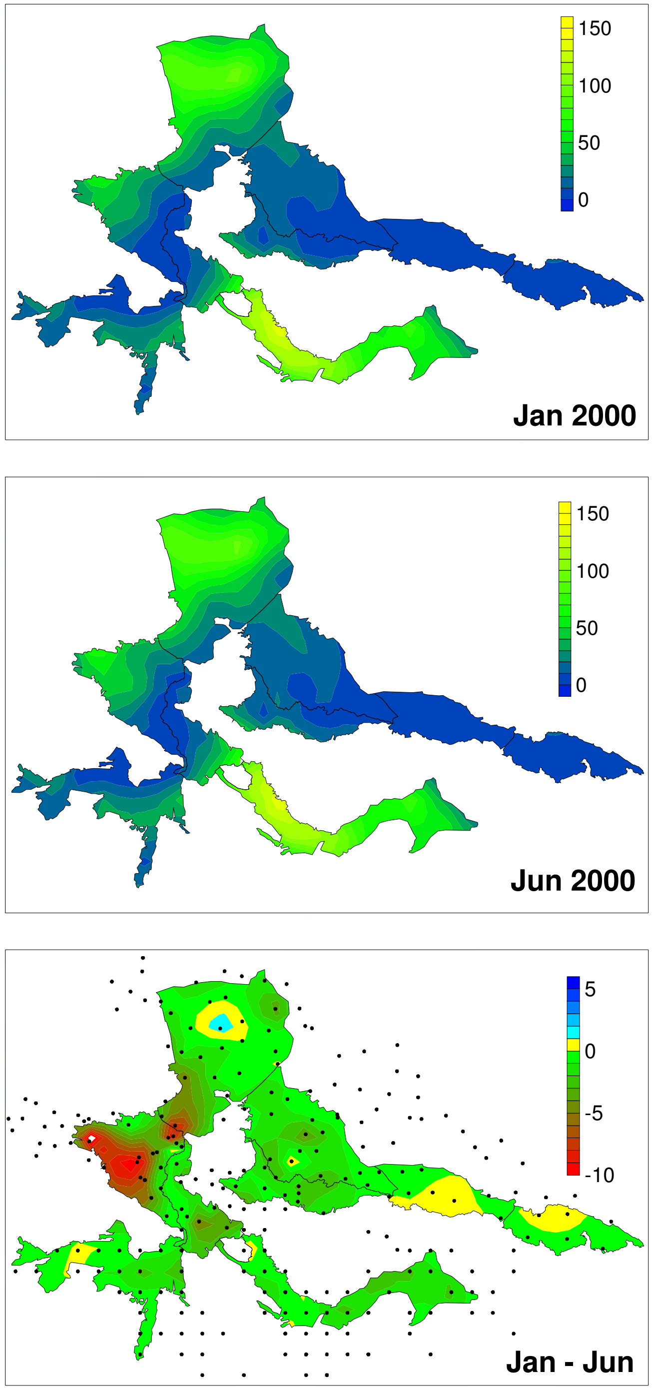

Figure 7. Depth to groundwater (in meters) for the main irrigation systems in Zayandeh Rud Basin for January and June 2000 as well as the difference between these two months.

Figure 7 shows an example of clipping the data to only the irrigation systems. In this map all the points in the basin were used for gridding, so points outside the irrigation systems are used for interpolation to assess groundwater depths inside the systems. This was done for January and June 2000 and the difference between these months was calculated too. In most areas water levels dropped around one to three meters, with some extremes in mainly Nekouabad Left Bank down to 10 meters. Most likely this drop in water level originates from the intensive pumping for rice irrigation in this area.

Before strong conclusions can be drawn, the distribution of datapoints should be considered to ensure a proper interpolation. The dots in Figure 7 show these observations, indicating that most areas are well covered by observations. Interesting to note is that data accuracy appears to be very high. Keeping in mind that an exact interpolator was used, so all observations are gridded to their actual value without smoothing, no outliers can be found. The rise in groundwater in the center of the Borkhar system, for example, is shown by more then one observation.

Irrigation system trends

As an example to show the kind of analyses that can be performed at irrigation system scale, Nekouabad Left Bank irrigation system has been used. No detailed analyses and discussions will be presented here, but only the methodology will be demonstrated. Actual analyses can be found elsewhere (Miranzadeh and Droogers, 2000).

Figure 8 shows the gridded depth to groundwater for January and June 2000 and the difference between these two. A denser grid was used to improve accuracy of the analysis. A decline in groundwater can be clearly observed in the system, and, as expected, decline was bigger further away from the river. Average groundwater levels in the system has dropped from 27 m to 33 m. A picture of this decline over the first months in 2000 is displayed in Figure 9.

Discussion

A broad range of options exists to deal with spatially distributed groundwater observations to explore trends. The kriging method with a default linear variogram appears to be the most convenient for the given dataset. A more comprehensive spatial interpolation can include a complete variogram analysis, but this requires substantial time as well as skills. No clear picture of the sustainability of the groundwater system in the basin or the irrigation system is presented here, but can be found elsewhere (Miranzadeh and Droogers, 2001).

From the limited number of available packages to perform the spatial interpolation, Surfer is superior. Surfer combines a huge number of interpolation options with a user-friendly interface and excellent presentation options. Moreover, Surfer has strong scripting capacities enabling the analysis of multiple year and month datasets in a fast and consistence manner.

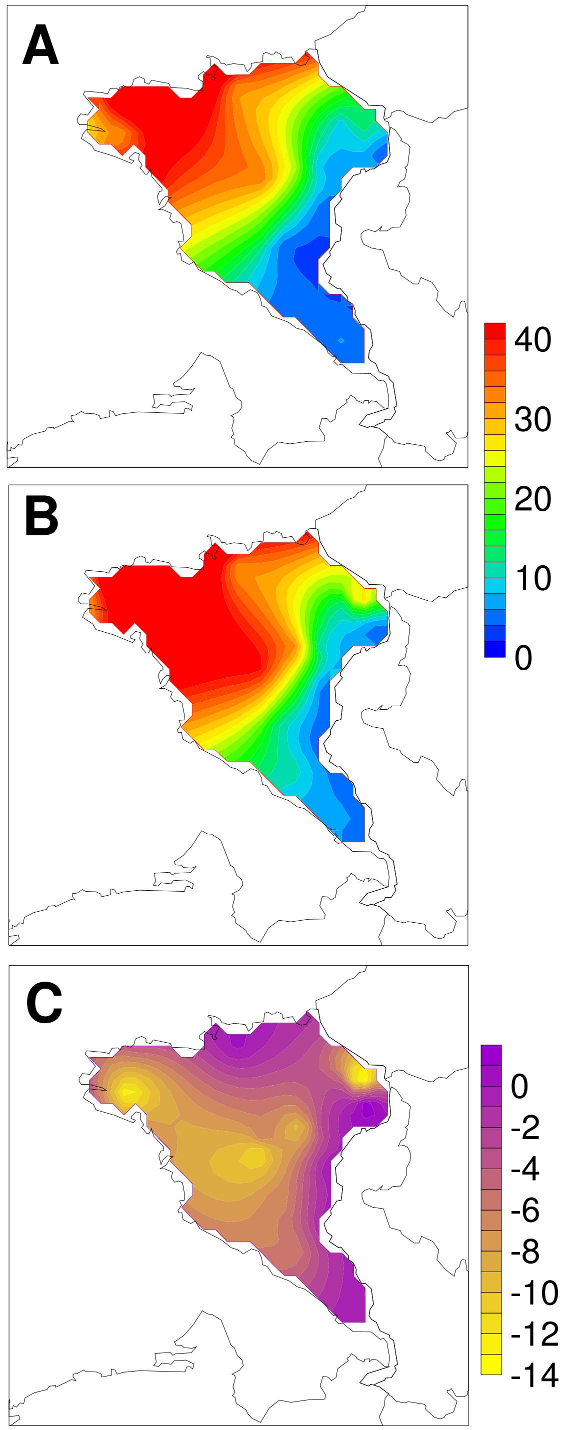

Figure 8. Depth of groundwater level for Nekouabad-Left Bank irrigation system (in meters). Displayed are January 2000 (A), June 2000 (B), and the difference (C).

The techniques applied here are useful to analyze these trends at a basin level as well as at irrigation system level. Results of such an analysis can be used in two ways. First, results can be a valuable contribution to understand water resources in the past, by combining these figures with supply and demand analyses (e.g. Sally et al., 2001). Second, groundwater depths and hydraulic heads as well as differences between years and months will result in a clear picture of the historical trends which can be used to indicate expected groundwater levels in the near future.

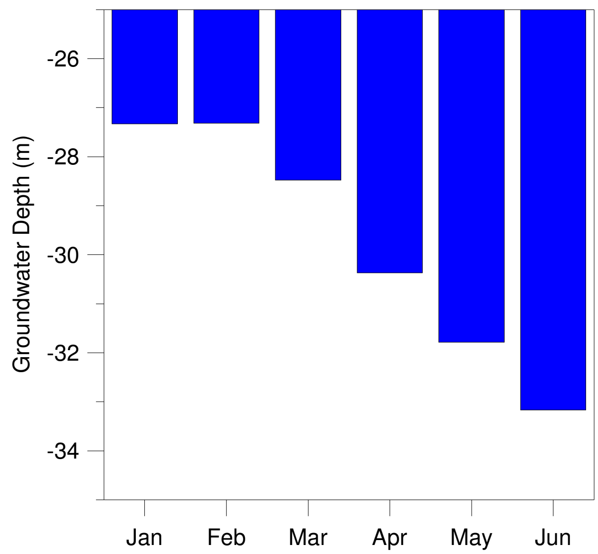

Figure 9. Average groundwater levels for Nekouabad Left Bank irrigation system for January 2000 to July 2000.

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References

Cressie, N.A.C. 1991. Statistics for Spatial Data, John Wiley and Sons, Inc., New York, 900 pp.

Droogers, P., G. Kite, and H. Murray-Rust. 2000. Use of simulation models to evaluate irrigation performance including water productivity, risk and system analyses. Irrigation Science 19: 139-145.

Gieske, A. M. Miranzadeh, and A. Mamanpoush. 2000. Groundwater chemistry of the Lenjanat District, Esfahan Province, Iran. IAERI-IWMI Research Report 4.

Journel, A.G. 1989. Fundamentals of Geostatistics in Five Lessons, American Geophysical Union, Washington D.C.

Miranzadeh, M., and P. Droogers. 2000. Impact of drought on groundwater levels in irrigated agriculture. (in preparation)

Salemi, H.R., A. Mamanpoush, M. Miranzadeh, M. Akbari, M. Torabi, N. Toomanian, H. Murray-Rust, P. Droogers, H. Sally, and A. Gieske. 2000. Water Management for Sustainable Irrigated Agriculture in the Zayandeh Rud Basin, Esfahan Province, Iran. IAERI-IWMI Research Report 1.

Sally, H., H. Murray-Rust, A.R. Mamanpoush, and M. Akbari. 2001. Water supply and demand in four major irrigation systems in the Zayandeh Rud Basin, Iran. IAERI-IWMI Research Report 8.

Surfer. 2000. Surface Mapping System, Surfer version 7.02. Golden Software, Inc. http://www.goldensoftware.com

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13. **Water Supply and Demand Forecasting for the Zayandeh Rud.** (2002). H.R. Salemi and H. Murray-Rust.
14. **Water Resources Development and Water Utilization in the Zayandeh Rud Basin, Iran.** (2002). H. Murray-Rust, H.R. Salemi and P. Droogers.
15. **Groundwater resources modeling of the Lenjanat aquifer system.** (2002). A. Gieske and M. Miranzadeh.