Theses of the Doctoral Dissertation
entitled

GIS-based Analyses of the Aridification of the Danube-Tisza Interfluve

Kohán Balázs

Supervisor:
Dr. Papp Sándor CSc, ret. Associate Professor

Consultants:
Dr. Biró Marianna PhD, assistant research fellow
Szalai József, water management referent

Doctoral School:
Eötvös Loránd University, Faculty of Science,
PhD School of Earth Sciences
Head of Doctoral School: Dr. Nemes-Nagy József DSc, Professor

PhD Program:
Geography-Meteorology Doctoral Program
Head of PhD Program: Dr. Szabó Mária DSc, Professor

Institute of research
Eötvös Loránd University, Faculty of Science, Institute of Geography and Earth Sciences, Department of Environmental and Landscape Geography
University of Debrecen, Faculty of Science and Technology, Department of Natural Geography and Geoinformatics

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The Objectives and Research Questions of the Dissertation

The aim of the present study dealing with one of the most problematic areas of the Great Hungarian Plain was to prevent further environmental and agricultural damages caused by the decrease of the groundwater level. The main problem was the permanent lack of water characterizing the areas that lie on the higher parts of the Plain. Thus the objectives and research questions of the dissertation are connected to the depletion of the groundwater level.

The following research questions were formulated:

1. Throughout the past 30 years what were the methods used and what were the side factors associated with de depletion of the groundwater level by researchers dealing with this problem?
2. Is the present sampling network suitable to estimate the level of the groundwater with adequate accuracy?
3. How could the present sampling network be optimized?
4. What geomorphological correlations can be detected based on the data provided by the present sampling network?
5. How could the accuracy of the estimation of the groundwater level be improved using the method of co-kriging with the aid of a more densely sampled relief?
6. What is the extent of the lack of water that gathered in the studied period on the Kiskunsági-homokhát, based on the estimations carried out with the aid of the relief data?
7. To what extent do the side factors (weather, water exploitation, afforestation) mentioned in previous researches influence the depletion of the groundwater level?
8. What is the level of the groundwater that can be expected if the side factors mentioned above change in the future?
9. What solutions can be found to moderate the depletion of the groundwater?

Material and Methods

The changes in the groundwater level were analysed based on the time series with different lengths provided by groundwater sampling network belonging to the four Water Management Directorates of the Danube-Tisza Interfluve. In order to be able to extend the results of the measurements to the whole are, it was important to analyse the quality of the data and the spatial correlation between them.

In the first part of the dissertation I analysed the spatial relationship of the measurements at certain moments of time (instead of analysing the different groundwater levels as time series), in order to analyse the spatial structure of the groundwater level monitoring well system and to recalibrate it. The samples taken from a monitoring system at a given time slice represent one sample realization.

The highest expectation from a sample is to reflect all the important characteristics of the statistical population and to allow the approximation of the unknown z parameter's value in the x,y coordinates of the sample area with adequate accuracy (Kovács, J. and Kovácsné Székely, I. 2006a, b)

It is required that besides the above mentioned conditions, the functioning of the monitoring system should be as economical as possible. The higher the variability of z parameter is within an h distance, the denser the sampling should be. Variability can be described by means of several functions. In this particular work the range is to be used for estimating spatial sampling range (Kovács J et al. 2005).

In the second part of the dissertation in order to estimate the lack of water, I interpolated groundwater levels by co-kriging method, using the digital elevation model and the data provided by the sampling network of the Kiskunsági-homokhát, with the aid of the Geostatistical Analyst provided by the ArcGIS software package. Co-kriging is a mathematical method in which the distribution of a second, highly correlated variable (covariate) is used along with the primary variable to provide interpolation estimates.

In the third part of the dissertation my goal was to create the model of the groundwater level depletion between 1961 and 2010 analysing the importance of each side factor and to forecast the future changes in the groundwater level. In the third part I used the available GIS data and I carried out linear regression.

Results and Conclusions

The conclusions of the dissertation are as follow:

1. Throughout the past 30 years what were the methods used and what were the side factors associated with de depletion of the groundwater level by researchers dealing with this problem?

Based on the scientific literature that was processed in the dissertation, I can state that there has been several researchers dealing with the problem of the depletion of groundwater level. The researchers are all aware of the water management problems of the Danube-Tisza Interfluve, but they are specialized in different scientific disciplines. Thus their research methodology and their approach to the question are different in most of the cases. The research methodology varies from empirical observations to multivariate data analysis techniques and many others.

The natural and anthropogenic factors that may cause the problem were identified at an early stage of the research, at the beginning of the 1990ies (Pálfai 1990). These are as follow: the increased evaporation caused by the lack of precipitation and by general warming (weather), the increased evaporation caused by the increase of the surface of the afforested areas (afforestation), the immoderate exploitation of water (water exploitation), water regulation, the effects of hydrocarbon-miming (others).

While most of the researchers choose to deal with the effects of one of the side-factors, only a few of them undertook the quantitative assessment of the different factors. There are three scientific works in which the authors indicated the effects of n the natural and anthropogenic factors on the depletion of the groundwater level in percentage (Table 1).

Researcher	Weather	Water exploitation		Afforestation	Water regulation	Others
		Shallow groundwater	Deep groundwater			
Pálfai 1990, 1995	50%*	6%	25%	10%	7%	2%
Szilágyi & Vörösmarty 1993	15%	n.a.	70%	15%	n.a.	n.a.
Völgyesi 2006	80%	n.a.	2%	13%	5%	n.a.

**In his later work Pálfai (2010) modified the proportion of the weather (2/3) and anthropogenic factors (1/3) but the proportion of the different anthropogenic factors is not detailed*

Table 1: The proportion of the factors influencing the groundwater level according to three different models

While each of the above mentioned models confirms the depletion of the groundwater level, the proportions they attribute to the effects of the side factors are different. The analyses are based on the data provided by the four Water Management Directorates of the Danube-Tisza Interfluve in each case, but there are differences in the delimitation of the area, in the data used to evaluate the side factors and in the applied research methodologies. Generally it can be stated that from the end of the 1990ies that the researches dealing with the problem of aridification were centred on climate change. Today, 80-90% of the researchers consider that the main cause of the depletion of the groundwater level is climate change (Ladányi *et al.* 2009, Ladányi 2010, Rakoncai 2011, 2013, Szanyi & Kovács B 2009).

The results of the models are widely influenced by the delimitation of the sample area and of the accuracy of the data used by them. Moreover, the above mentioned models are different in this respect, thus it is difficult to determine which of the obtained results is closer to reality. The most important question is whether the depletion of the groundwater level is a natural or an anthropogenic process. As the lack of water only characterizes the higher areas of the Danube-Tisza Interfluve and in different degree each area, I reached the conclusion that the effects of the side factors should be measured locally if we want to find the most suitable solution to the problem.

2. Is the present sampling network suitable to estimate the level of the groundwater with adequate accuracy?

The most obvious method to define the extent of the depletion of the groundwater level is to analyse the time series of the groundwater level detection wells. This method, however, would only describe the small area around the analysed detection well. Most of the spatial analyses, like the estimation of the lack of groundwater require the inter- and extrapolation of the measurements.

In order to answer the question I created directional empirical semivariograms, using the time series provided by the 321 groundwater level monitoring wells of the Interfluve. The variograms deriving from the 60 sample realisations chosen from available time series comprising 30 years show anisotropy and multiple sill structure.

The smallest significant range identified on the variogram has a direction of NE-SW and is of 5 km, while its perpendicular range has a direction of SE-NW and is of 11.67 km. The special ranges created by the before mentioned ranges have are ellipsis positioned in NW-SE direction.

In the studied period using the coordinates of certain groundwater level monitoring wells that provided data in that period of time, I covered the area of the Interfluve with the elliptic spatial ranges in order to define whether in certain moments of the past the network was suitable to make estimations with adequate accuracy or not. I reached the conclusion that before the second part of the 1990ies the coverage was incomplete and there were many areas that did not provide data, especially on the areas of the ridge, that show the most serious depletion of the groundwater level. In addition, there were overrepresented areas, too.

3. How could the present sampling network be optimized?

Based on relationship between the spatial ranges defined by the multiple sill directional empirical semivariograms and the research network described in chapter 4.4.1, the ideal (i.e. that can be established with a minimal number of wells) groundwater level monitoring well network has been plotted in EOV projection system on the bounding box of the Kiskunság sand region.

My conclusion is that the spatial variability of groundwater-level variations observed with the existing monitoring station network could be detected with half as many stations if they were located in a more optimal arrangement. Establishing a couple of new detection wells or repositioning a few of the existing ones, probably even finer spatial processes could be monitored, thus the progression of the depletion could be interpreted in a more profound way.

4. What geomorphological correlations can be detected based on the data provided by the present sampling network?

The above mentioned multiple sill structure originates from the geomorphological units with different scales. In my opinion in the largest regional structure that is characterized by a range around 20 and 30 km and anisotropy with a direction of NNE-SSW, the direction of the axis linking the highest parts of the Ridge can be observed, while the ranges reflect the variability related to the alluvial cone. The smallest ranges that were identified on the semivariograms were the results of a small number of pairs; therefore the actual smallest range was defined at the second sill with a value of 5 and 11.67 km. In this case the anisotropy has a NW-SE direction that reflects the axis and the extension of the mezo-forms of the area (Kiss T & Tornyánszki 2006).

The correlation between the groundwater level and the height above sea level of the area is very strong (R>0.9). The more varied the relief is, the more varied the levels of groundwater are, thus in order to achieve an accurate estimation the relief should be taken into consideration.

5. How could the accuracy of the estimation of the groundwater level be improved using the method of co-kriging with the aid of a more densely sampled relief?

Comparing the data provided by wells that are situated within a few kilometres with each other, it can observe that even these data are widely different in some cases. The differences are due to the fact that the geologic structure, their orographic situation the land cover of the surrounding area, the type and intensity of the anthropogenic factors and the interference between the above mentioned factors can be different (Kovács J *et al.* 2004). The estimation can be more accurate if these actors can be taken into consideration throughout the process. Taking into account the orographic situation is relatively easy, if we use the digital elevation model applied for the interpolation. Based on the cross-validations carried out during the research, I reached the conclusion that the accuracy of the estimation can be improved on the major territory of the sample area using co-kriging. However, in cases where the groundwater level does not run parallel with the surface (e.g. the steeper verges of the ridge) this method might not be accurate either.

6. What is the extent of the lack of water that gathered in the studied period in the Kiskunsági-homokhát, based on the estimations carried out with the aid of the relief data?

Using the weighted arithmetic mean of the porosity values characteristic to the Kiskunsági-homokhát in our calculations, the results show that in 2010 there was less water with 0.4904 km^3 than in 1981 in the territory of the Kiskunsági-homokhát. After dividing this amount with the territory of the Kiskunsági-homokhát, the result was 400 mm, thus there was a yearly decrease of 13.33 mms. Comparing the groundwater level surfaces of 1981 and 2010, created by co-kriging, it is obvious that there was a considerable decrease in the groundwater level on the major parts of the Kiskunsági-homokhát. Even though in 2010 the precipitation exceeded the average precipitation of the last 30 years with 80% (there was a precipitation of 950 mms), the level of groundwater did not exceed the values measured in 1981 on the major part of the ridge.

7. To what extent do the side factors (weather, water exploitation, afforestation) mentioned in previous researches influence the depletion of the groundwater level?

Learning from the contradiction of previous studies, I carried out multivariate regression analysis in order to determine the effects of each side factor. The sample is situated in the eastern part of the Kiskunsági-homokhát. Its borders are marked by the Thiessen polygon created from fourteen detection wells providing a complete time series from 1961 to 2010.

The conclusions reached based on the multivariate regression analysis are as follows:

- Unlike previous researches (Pálfai 1990), according to which the subject year and the previous five years should be taken into account, according to my own analysis it is sufficient to count with the previous two years.
- Up to 1970 the level of the groundwater was defined mainly by the weather conditions. After 1980 there were other, non-climatic factors that exerted influence in the depletion of the groundwater level.
- Had the climatic factors determine the groundwater level after 1980, than in years with abundant precipitation, the level of the groundwater would have been similar to the groundwater levels measured in 1960, as the results show.
- In the period between 1960 and 1980 the groundwater level reached the bottom of the canals these evidently decreased the groundwater level. After this period this phenomena is no longer present.

- Based on the result of the backward elimination technique, the level of the groundwater is significantly influenced by the following independent variables*:* the precipitation measured in the two antecedent years to the subject year, the changes in the afforested areas and the changes in the amount of the exploited water. As omitting the precipitation of the subject year is not indicated, I used this variable in my calculations, too. The functions of the two models are as follows:

$$T_i = 191.0560 - 0.0461\,Cs_i - 0.1889\,Cs_{i-1} - 0.0876\,Cs_{i-2} + 0.0155\,\mathrm{E} + 0.0469\,\mathrm{Vkt}$$

and

$$T_i = 159.2386 - 0.1799\,Cs_{i-1} - 0.0751\,Cs_{i-2} + 0.0147\,\mathrm{E} + 0.0569\,\mathrm{Vkt}$$

where

T_i – the depth of the groundwater level in year i (cm)
Cs_i – weighted amount of precipitation in year i (mm)
E – the area of the afforested areas (ha)
Vkt – the amount of the supplied water (1000 m^3)

- The forecasted values of the two models had an average variance of 22 cms from the measured values.
- The effect of the afforested areas and the water exploitation on the groundwater level were estimated from the water levels extrapolated from climatic data. Due to the results the average decrease of the groundwater level was influenced by the afforestation with 43%, while by the water exploitation with 57% in the studied period (1981-2010).

8. What is the level of the groundwater that can be expected if the side factors mentioned above change in the future?

Based on the coefficients of the estimation function, the level of the groundwater decreases with 0.015 cm, if the territory of the afforested areas in increased with 1ha, if all the other variables remain unchanged. If the amount of the exploited water grows with 1000 m^3, the level of the groundwater decreases with 0.05 (if all the other variables remain unchanged). For example, if a territory of 1000 ha was afforested, the depth of the groundwater would increase by 15 cm. It is important to note, however, that the result are only valid on the territory marked by the 14 monitoring wells, and only if the rest of the variables remain unchanged.

9. What solutions can be found to moderate the depletion of the groundwater?

The natural factors, like the amount of the precipitation cannot be influenced. Therefore I consider that the problem of the groundwater level depletion could be handled by modifying the anthropogenic factors. This should be done by the following means: ceasing the illegal water exploitation and optimizing the legal water exploitation (e.g. by water recycling, improving irrigation methods, applying wastewater cleaning); instead of increasing the surface runoff, increase of the residence time and infiltration (e.g. establishing water reservoirs, improving the existing water governing objects); spreading farming methods that require less water and are adapted to the natural conditions; establishing local water supply systems at places where they are sustainable. The most important aspect is that the problem should be solved by such a conception that is adapted to extreme weather conditions and would provide the water demand of the local people, agriculture and industry in the long run.

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