UNIVERSITY OF MISKOLC
MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES
Head of the Doctoral School:
Prof. Dr. Péter Szűcs, professor

HYDROGEOTHERMAL INVESTIGATION OF BÜKK KARST WATER SYSTEM WITH COMPLEX KARST HYDROGEOLOGICAL METHODS

THESIS BOOKLET

AUTHOR:
Rita Miklós
hydrogeological engineer

SCIENTIFIC SUPERVISORS:
Prof. Dr. Péter Szűcs, professor
Dr. László Lénárt, honorary professor

Institute of Environmental Management
Department of Hydrogeology and Engineering Geology

Miskolc, 2022

1. Aims

In the previous decades, a number of researches have focused on getting to know the Bükk karst system as thoroughly as possible. The cold karst system plays key role in the Bükk region, as it provides excellent quality water and supplies a daily drinking water to about 400,000 people. The area of Bükkalja has become more and more important in the last decade and a half in terms of thermal karst water extraction, and it continues to do so to this day. Intensive balneological thermal karst water production has been growing in the last decade in the Eger-Egerszalók-Demjén region. In Miskolc and its surrounding the extracted thermal karst water is used for balneological purposes in addition to drinking water, and since 2012 Central Europe's geothermal heating plant with a capacity of 60 MW_t - installed on the Bükk thermal karst system - also operates here.

Most researchers agree that the cold and thermal karst systems in the Mountains are related (Darabos, et al., 2014; Lénárt, 1994; Lénárt, 2008; Lénárt, 2022; McIntosh, et al., 2011). ; Szilágyi, et al., 1980), although there are differences in the assessment of the strength of the relationships. For this reason, I consider it particularly important to examine this area in details. The objectives of the dissertation include the examination of the relationship, hydraulic continuity between cold and thermal karst system, and the numerical proof of this with different methods.

In my work, using complex methods in two research areas (Egerszalók-Demjén and Miskolc and its surroundings), my aim is to investigate and clarify the geothermal conditions of the thermal karst system. I use available geological and hydrogeological information (data from hydrocarbon exploration drillings, data from hydrogeological logs and producers' declarations), hydrochemical and isotopic results of on-site water sampling in order to get the most accurate picture of the subsurface temperature distribution, changes, their direction, the exact state of the strategically important thermal karst water in the investigated sites.

2. Applied methods, results – Hydrogeothermal investigations of the Bükk thermal karst system

Based on the distribution of the available data, I selected two study areas in Bükkalja, which were Egerszalók-Demjén and its area, and Miskolc and its surrounding. In addition to the fact that I had a sufficient amount of data on these two areas, both areas are of great importance for the production of thermal karst water nowadays.

In my work, I set up the development history model of the two study areas, and then I performed well-level 1D modeling using PetroMod software. Using the available measured bottomhole temperature data, I checked and verified the modeling results. In the classic case, the software serves the purposes of hydrocarbon research, so I investigated the possibility of applying it to the karst system. The maximum difference between the modeled and measured results was set at 15 %. In my work, 75 % of the modeling results performed for the 24 wells were acceptable.

Based on the drilling data in the Egerszalók-Demjén area, I determined the surface envelope of the Eocene-Triassic carbonate aquifer. In the investigated area I had several sets of drilling data available, which did not include bottomhole temperature measurement data. In order for these datasets to be usable, I calculated geothermal step values from the data sets of 12 wells. Based on the obtained data, I determined that the geothermal step and the depth in the studied area show a non-linear relationship with each other. The relationship showing the best fit can be described by a logarithmic relation, which I expressed by the equation $Gl_i=9,6212*\ln(z_i)-51,0165$ (where: Gl_i [m/°C] - geothermal step at the examined point, z_i [m] - bottomhole depth in the same place) (Fig. 1). In order to check the accuracy of the obtained equation, I compared the data calculated with its help as well as the measurement data. The average of the deviations was 14.9 %, so I consider the equation acceptable, but the possibility of the error percentage must be kept in mind during the calculations.

Using the established equationn, I determined tomographic temperature distribution maps at 5 depth levels using data of 40 wells/drillings, thus characterizing the horizontal temperature distribution of the area per layer and the vertical direction between the layers.

Furthermore, along two sections (Fig. 2), a temperature distribution was made in a vertical extent, and the depth of the 30 °C isotherm in the area was determined (Fig. 4–5).

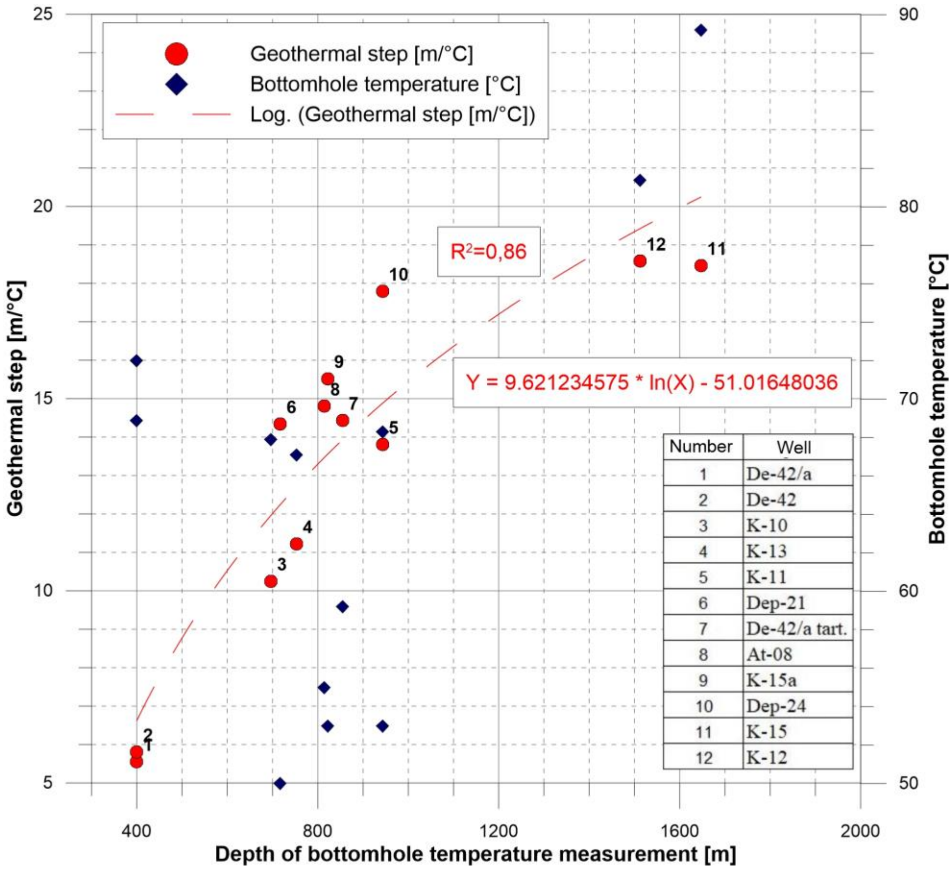

Figure 1. The equation used to determine the characteristic geothermal step (GL) in the Egerszalók-Demjén area, according to (R^2 = 0,86), giving the data of the geothermal step and the bottomhole temperature of the used thermal water wells

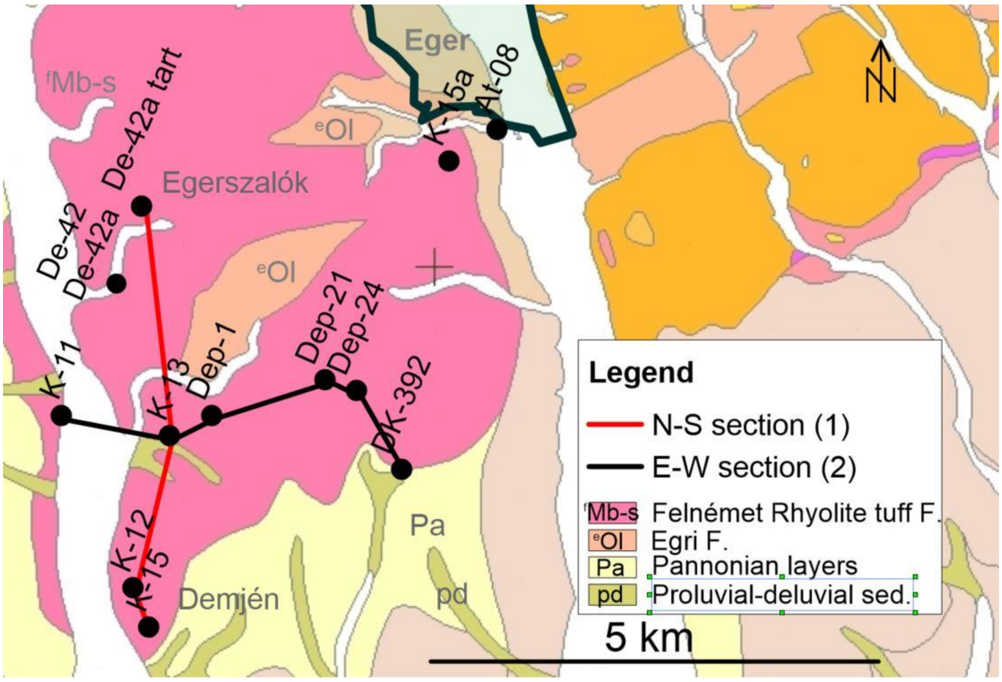

Figure 2. Trails of sections from the Demjén area, covered geological map of the area [based on (Magyar Állami Földtani Intézet, 2005)]

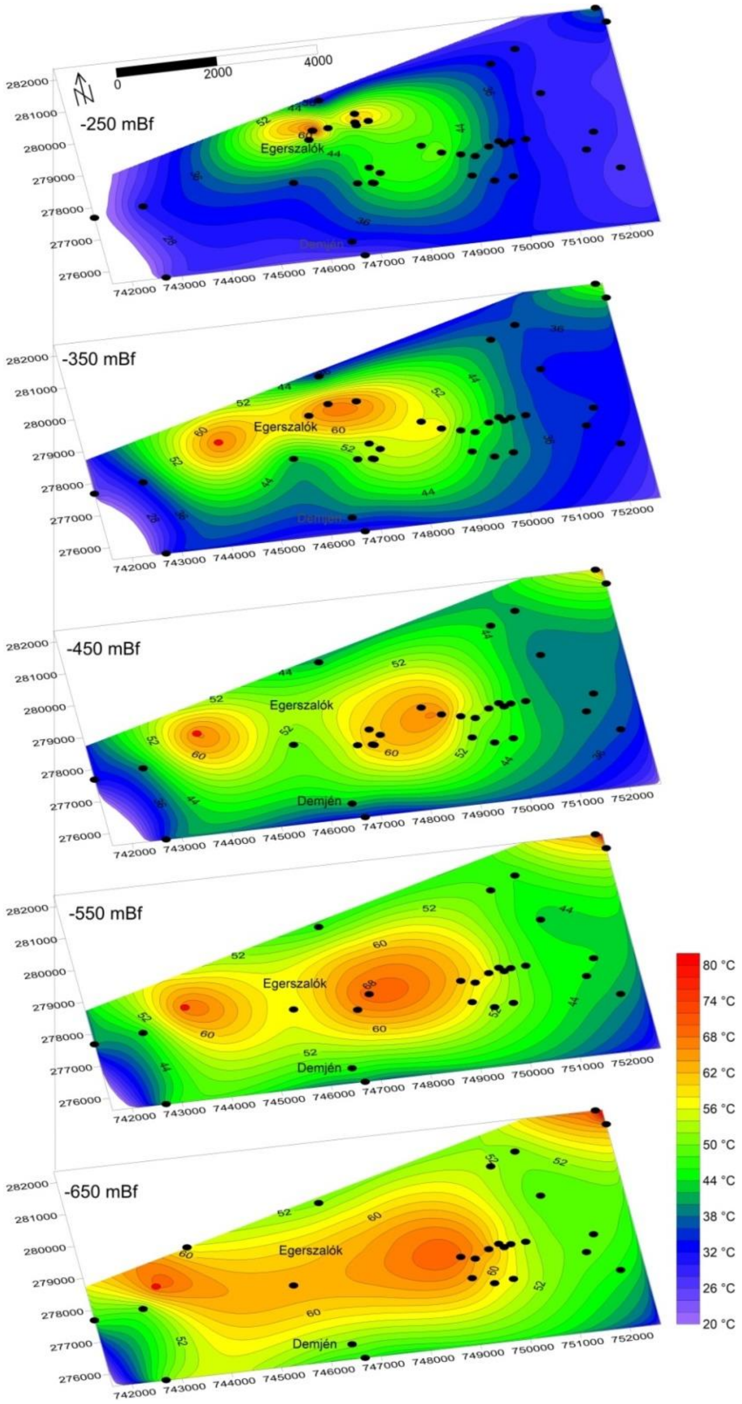

Figure 3. Changes in the temperature distribution at different depth levels in the Egerszalók-Demjén area (red marking: pseudo-well representing the position of the fracture system)

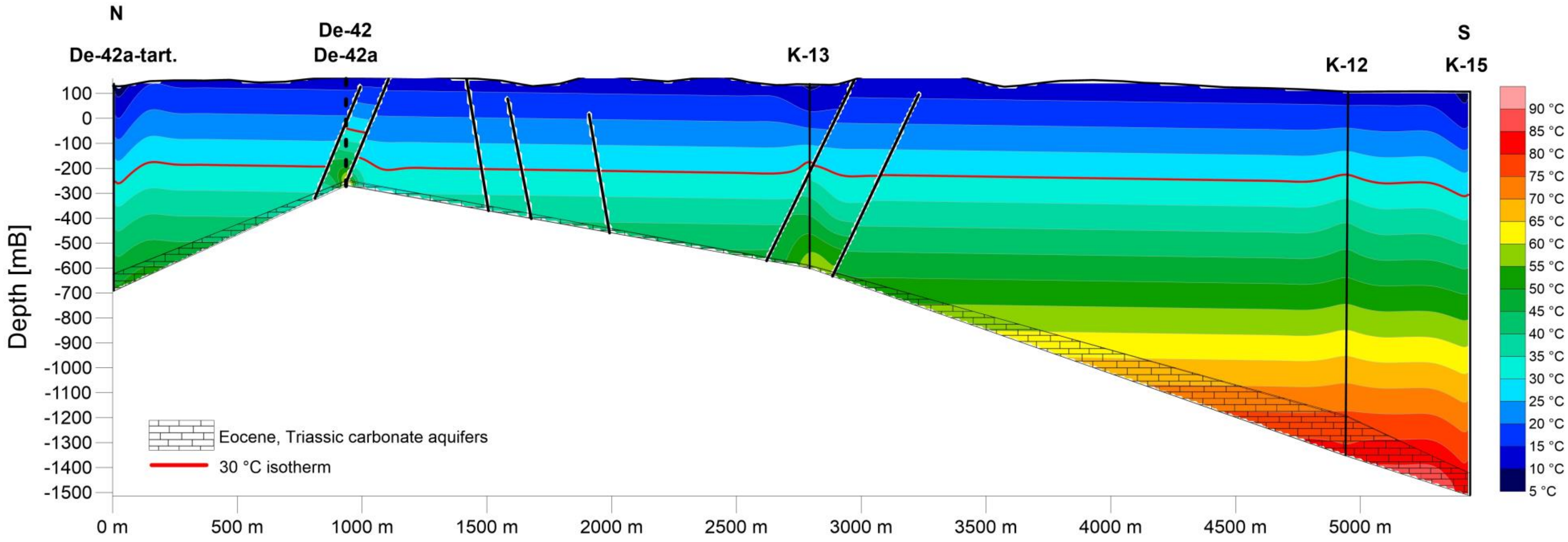

Figure 4. Temperature distribution section in the N-S direction in the Egerszalók-Demjén area, the 30 °C isotherm marked, the envelope curve of the Eocene, Triassic carbonate aquifers, and the layer thicknesses excavated by the boreholes [faults given by the work of Csiky, 1961, 1966)

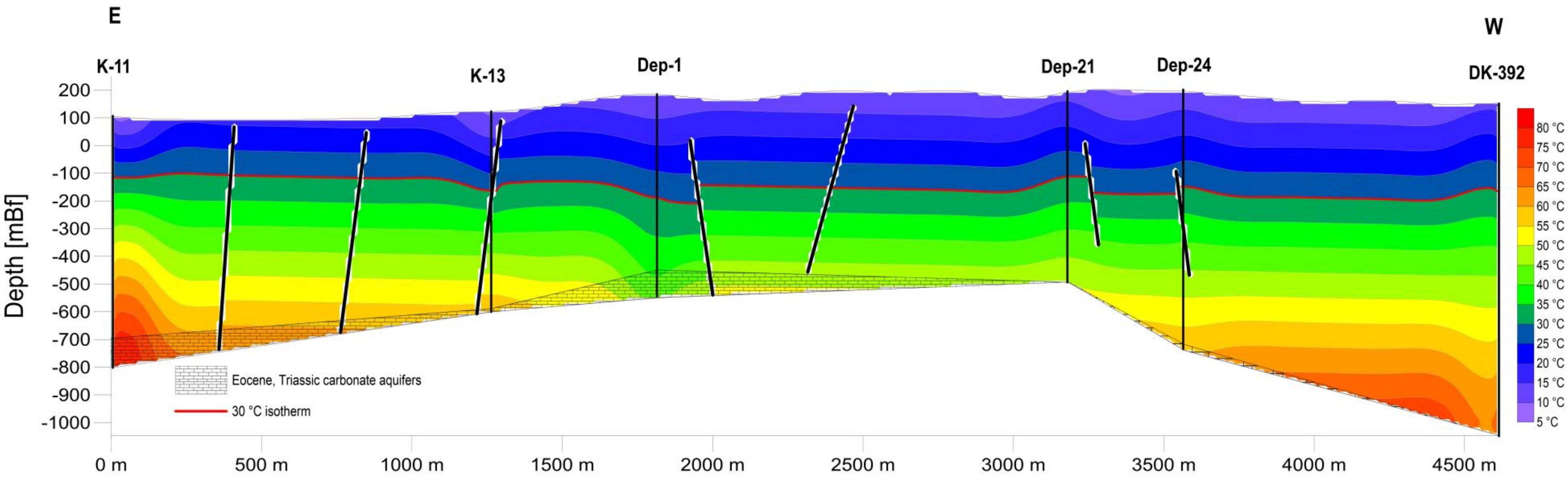

Figure 5. Temperature distribution section in the E-W direction in the Egerszalók-Demjén area, the 30 °C isotherm marked, the envelope curve of the Eocene, Triassic carbonate aquifers, and the layer thicknesses excavated by the boreholes [faults given by the work of Csiky, 1961, 1966)

Using the data of the previously and after 2010 established wells which are reaching the thermal karst aquifer in Miskolc and its surrounding, as well as geological information, I refined the pretercier age bed map of the area (Fig. 6).

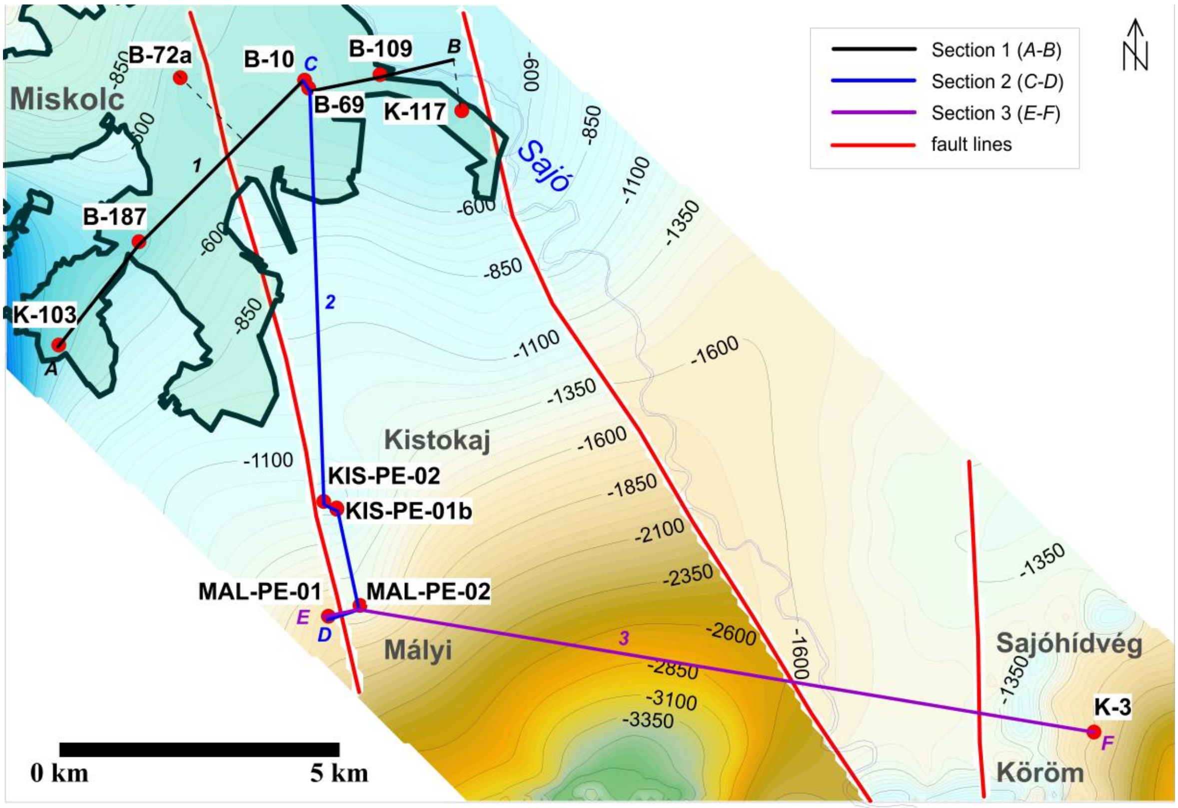

Figure 6. Pretercier basement map of the Miskolc and surroundings study area; the main fault lines as well as the traces of the examined three sections [based on (BTIX Kft., 2010; Lexa, et al., 2000)]

I have given the relation for the geothermal step for the city of Miskolc. Using this calculated temperature data as well as modeled temperature data, I gave the temperature distribution along the three sections in the area.

I have performed water samplings in four thermal karst wells in and around Miskolc, and I determined the chemical composition of the samples with the help of laboratory tests. Using these, I determined the hydrochemical facies of the wells, and for the other wells I used the hydrochemical data in the hydrogeological logs for this purpose. Taking into account the geological, temperature, hydrochemical conditions and ^{14}C measurement results along the two sections, I gave conceptual karst water flow conditions of the area (Fig. 7-8).

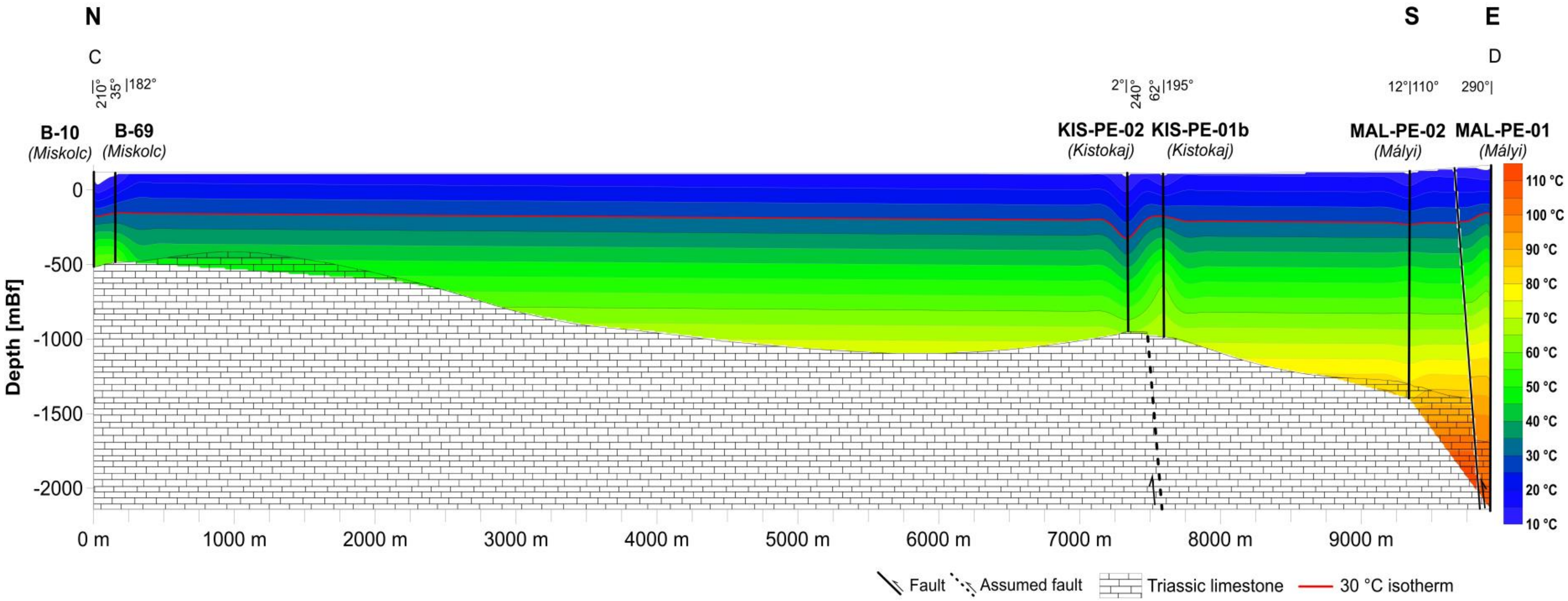

Figure 7. The N-S conceptual temperature distribution profile (2) made in Miskolc and its surroundings, marking the 30 °C isotherm and the Triassic limestone top [based on (BTIX Kft., 2010; Lexa, et al., 2000)]

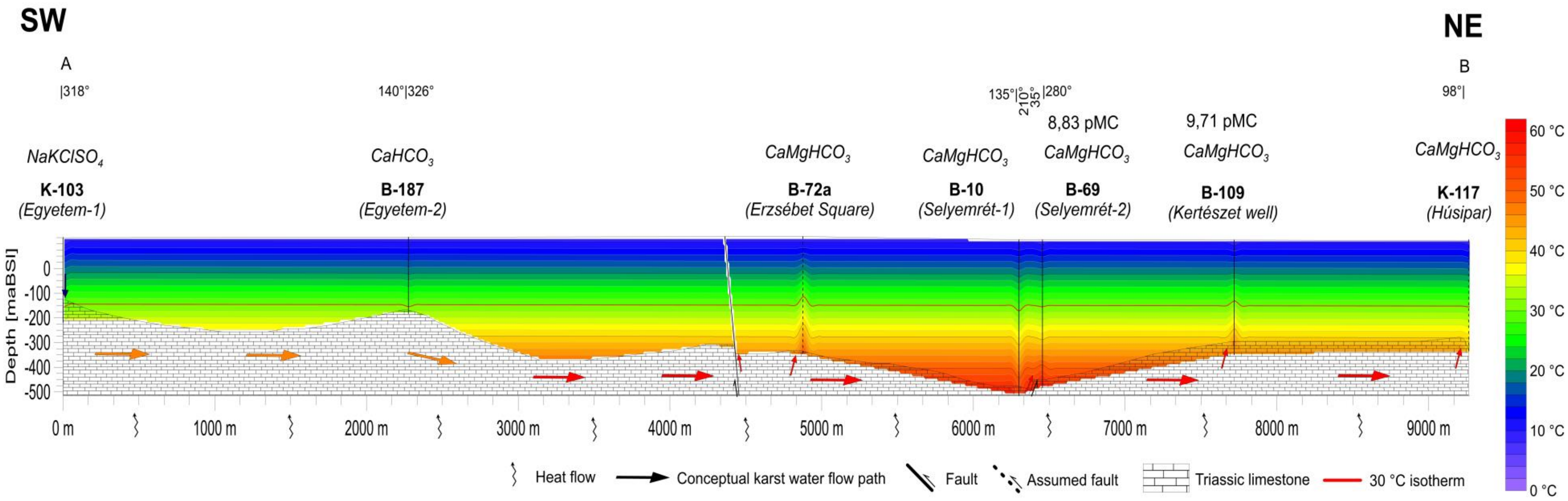

Figure 8. Conceptual temperature distribution profile (1) for the SW-NE area around Miskolc and its surroundings, denoting the 30 °C isotherm and the Triassic limestone top, the content of pMC (percent Modern Carbon) of three wells, and the conceptual flow system of thermal karst water [based on (BTIX Kft., 2010; Lexa, et al., 2000; mbfsz.gov.hu, 2021)]

As both studied areas are of strategic importance for the production of thermal karst water in the Bükkalja area, my new research results help to understand the temperature, flow and structural conditions of the areas and support the research, construction and operation of thermal karst water with greater safety in the future.

3. Applied methods, results – Time series analysis

In my work, I used the long-term data series of the Bükk Karst Water Level Monitoring System operated by the University of Miskolc and performed various types of time series analyzes on them. By performing the analyzes, my aim was to examine the connection between the cold and the thermal karst system in Bükk, the existence of hydraulic continuity between the two systems, and the strength of the connection. During the investigation, the input parameter was the water level dataset of the Nv-17 karst water monitoring well in the central part of the Mountains. Several previous studies have shown that this monitoring point is in a roof position in terms of the cold karst water topography of Bükk, so this well is considered to be a benchmark in my research. To perform the calculations, I selected 6 thermal karst monitoring points as output points. Two of these springs (Miskolctapolca, Termál Spring and Kács, Tükör Spring) and four wells (Miskolc, Selyemrét-2; Miskolc, Kertészet Well; Mezőkövesd, Zsóry-III observation well, Demjén, K-11). The well in Mezőkövesd functions as an observation well, and the other wells are free-flowing, positive, non-pumped wells. The spatial location of the examined measuring points is shown in Figure 9.

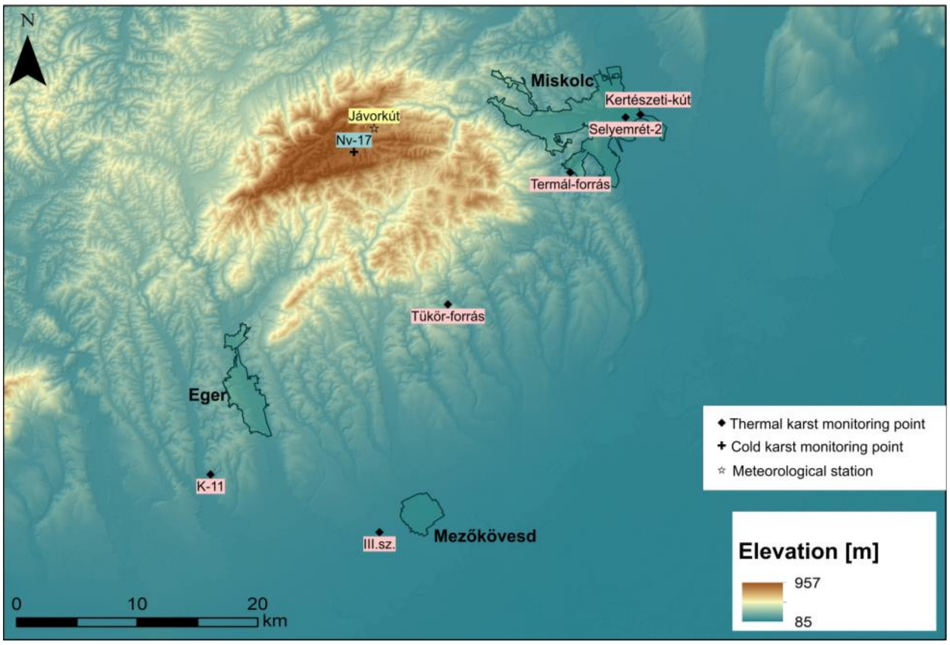

Figure 9. Location of test site, monitoring points

In the first step, I compared the water level/pressure curves of the measuring points graphically. In the light of the evaluation and the results, it could be concluded that the effects of the changes in the cold karst have a certain delay, but also occur in the thermal karst measuring sites. Based on these, I considered it justified to perform higher-level time series analyzes and to numerically prove the relationship between the cold and thermal karst system. As an example, I present a comparison of the self-normalized data sets of Nv-17 and Kertészet Well (Fig. 10).

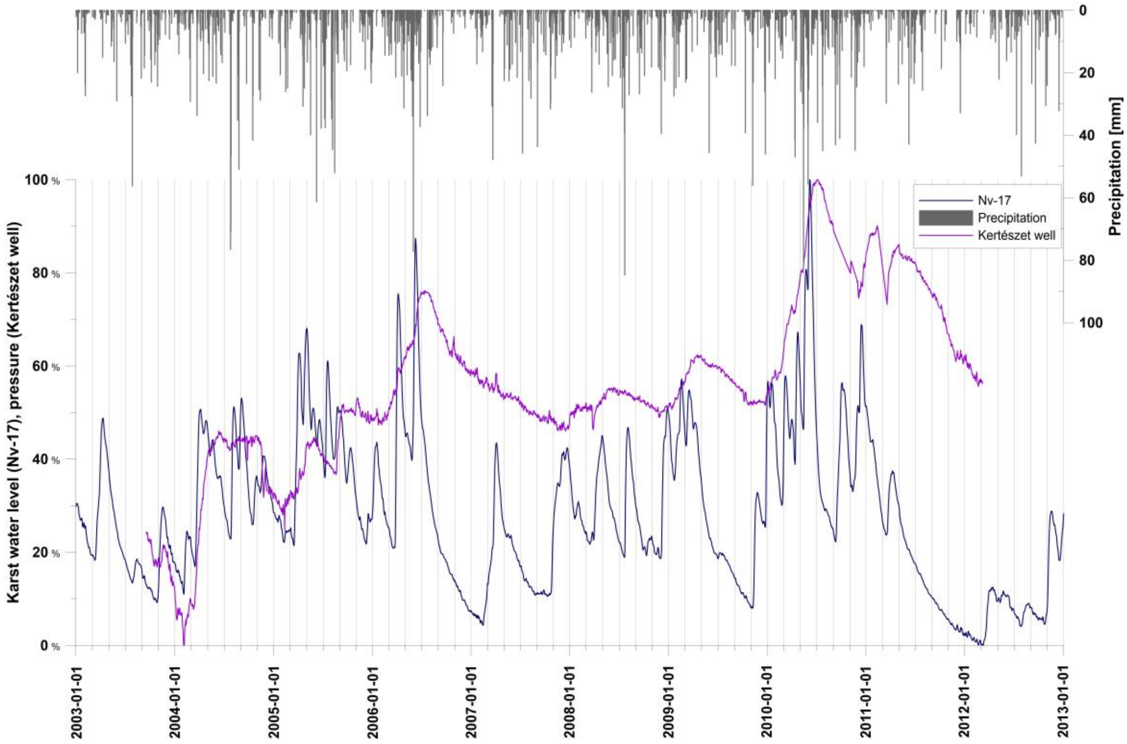

Figure 10. Comparison of the self-normalized data sets of Nv-17 and the Kertészet well, supplemented with the precipitation dataset of Jávorkút between 2003 and 2013

By performing cross-correlation studies, I demonstrated that there is a relationship between Nv-17 and each measurement site and determined the degree of delay (Fig. 11). This delay specifies the time after which changes at the input point occur at the output measurement points. Based on the results, the delay is 35 days for the Selyemrét-2 well, 41 days for the Kertészet well, 112 days for the K-11 measuring point, 163 days for the Zsóry-III well, and 178 days for the Tükör Spring.

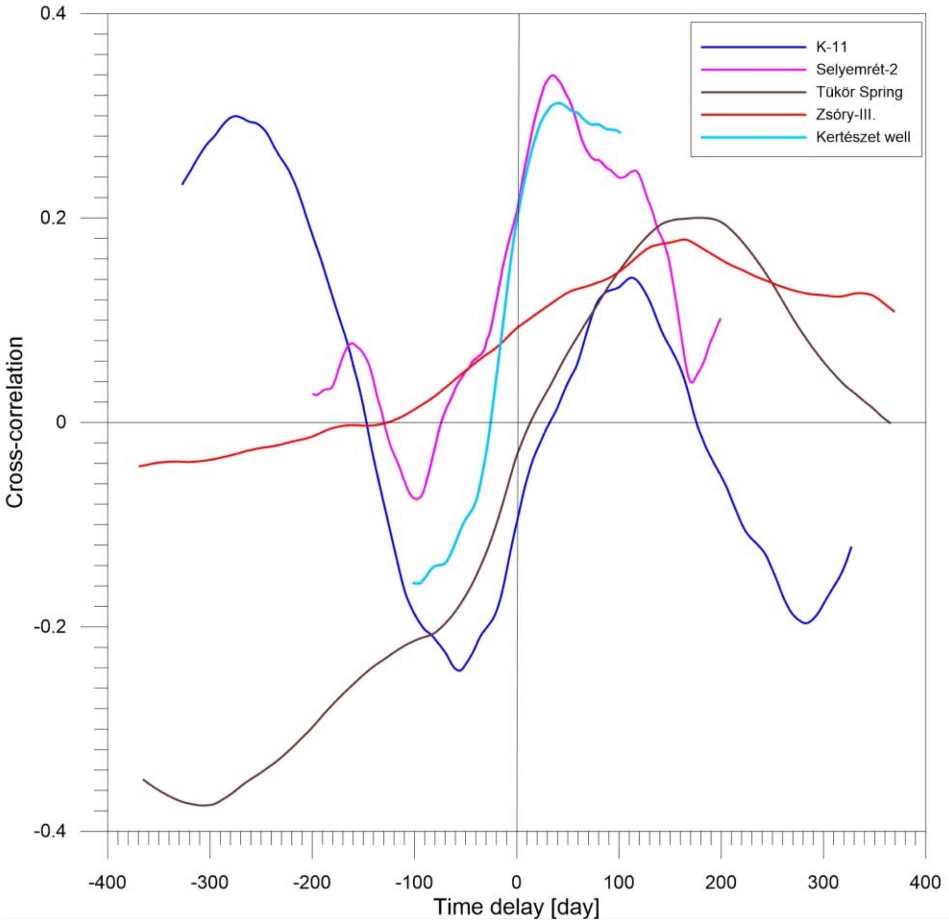

Figure 11. Cross-correlation between Nv-17 and thermal karst measurement sites

Using the delay times, I determined the average hydraulic pressure propagation velocity for the space between the Nv-17 and the investigated measuring sites (Fig. 12). Based on the results, it can be stated that the best hydraulic connection from the central areas of Bükk was towards to the East, followed by the Southwest and then the Southeast directions.

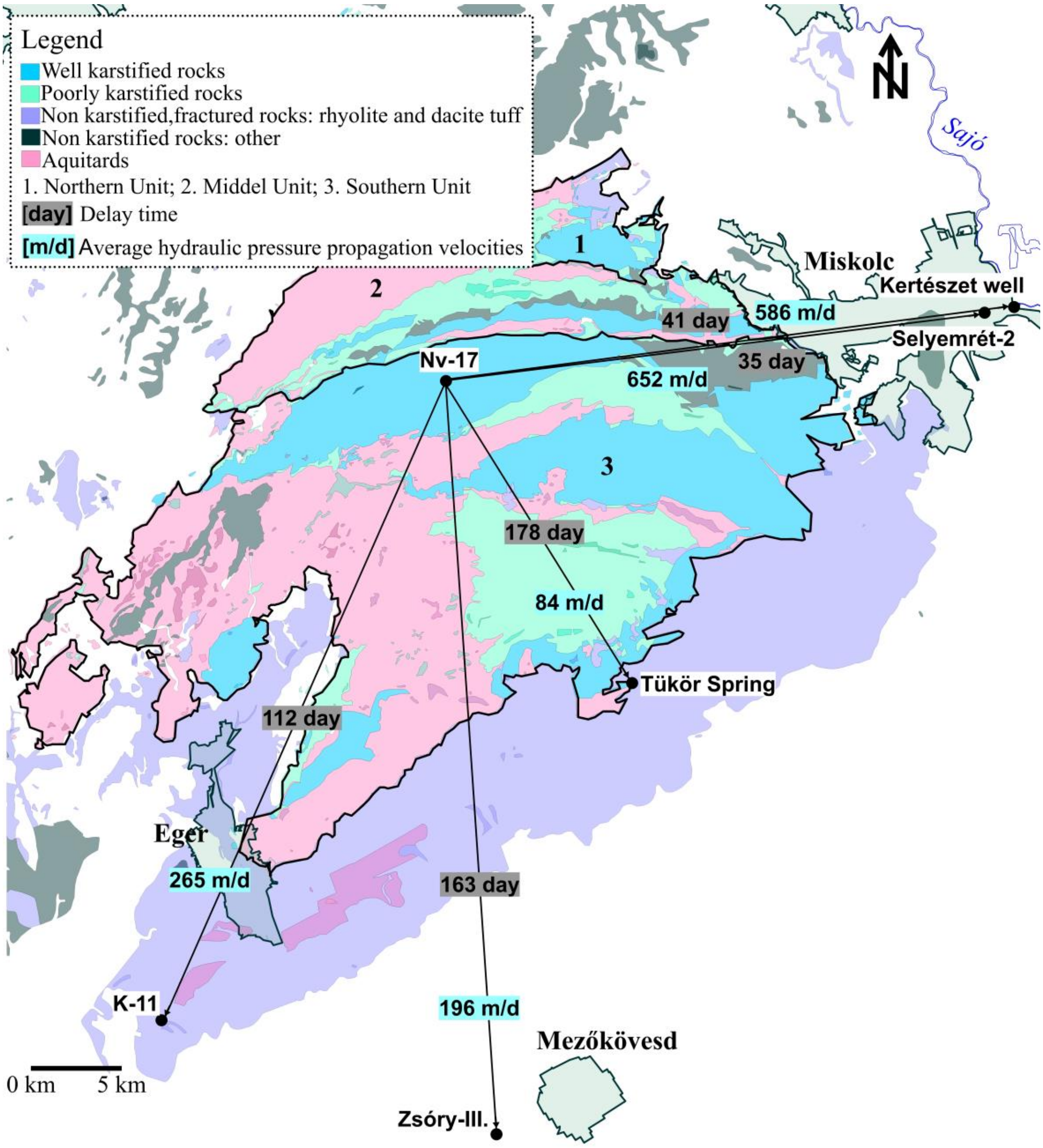

Figure 12. The delay times [days] determined from the cross-correlation calculations and the average hydraulic pressure propagation velocities [m/day] between the cold and thermal karst system between the Nv-17 and the investigated thermal karst monitoring sites [base map(Darabos, 2017)]

In the coherence study, I examined the strength of the relationship between Nv-17 and each thermal karst monitoring site. Period times determined from frequencies characterized by a high coherence value are acceptable. Based on this study, I found that the high coherence values of the regionally related (cold and thermal karst system), large system with significant hydraulic resistance, appear at low frequencies and at high periodic times between the data sets of cold and thermal karst measurement sites. Eligible periods for Selyemrét-2 are 199, 44, 36, 27 days; 101, 40 days for the Kertészet well; for K-11, 327, 82, 50, 41 days; the Zsóry-III. for 148, 74, 46, 35, 22 days; 365, 183, 61, 49 days for the Tükör Spring; in the case of the Termál Spring, they occurred for 222, 89, 44, 30 days.

I performed cross-spectral analysis on the time series, during which I obtained a Fourier transform of the cross-correlation values calculated between the two measurement sites. Furthermore, I did the same on the data sets of each measurement site, and then I performed a periodicity test to see if the periods attributable to the high coherence values were found on the Fourier-transformed curves. Periods with a high coherence value determined during the coherence study can be considered reliable for the study, and during the cross-spectral analysis, the common periods of the two measurement sites can be determined. This method eliminates any other effects on the results. The period times that can be designated by the three methods were identifiable, with slight variations in some places (Table 1). This result also proves the existence of the relationship between cold and thermal karst in Bükk.

Table 1. Results of periodicity tests using coherence tests, cross-spectral analysis and Fourier transform for the thermal karst measuring sites examined

Monitoring point	**Period times can be assigned based on the coherence function [day]**	**Periodic times can be assigned based on cross-spectral analysis results [day]**	**Period times can be assigned based on the Fourier transform of the studied data sets [day]**
Kertészet well	101, 40	101, 41	102, 42
Selyemrét-2 well	199, 44, 36, 27	200, 44, 36, 27	199, 44, 36, 27
K-11	327, 82, 50, 41	327, 82, 47, 41	327, 84, 50, 42
Zsóry-III.	148, 74, 46, 35, 22	148, 74, 39, 28	142, 47, 22
Tükör Spring	365, 183, 61, 49	366, 183, 61, 49	365, 61, 49
Termál Spring	222, 89, 44, 30	222, 89, 49, 30	222, 89, 45, 30

Based on the summation of the results of the coherence studies, the cross-spectrum analysis and the Fourier transform study, I determined the period times for the Nv-17 and the thermal karst sites (Table 2).

Table 2. Period times determined from the results of coherence studies, cross-spectrum analysis and Fourier transform studies for Nv-17 and thermal karst sites examined

Monitoring point	Period times [day]
Kertészet well	101-102, 40-42
Selyemrét-2 well	199-200, 44, 36, 27
K-11	327, 82-84, 47-50, 41-42
Zsóry-III.	142-148, 39-47, 22-28
Tükör Spring	365-366, 61, 49
Termál Spring	222, 89, 44-49, 30

Furthermore, with the help of spectral analysis, I performed a periodicity study on the data sets of precipitation of the central part of Bükk, Nv-17 water level and thermal karst monitoring sites. In previous research, the main period time for maple precipitation was determined to be 365 days. I determined the main period in the Nv-17 data series, which was 368 days, and then examined whether this period occurs at the thermal karst measurement sites. The 368-day period was detectable for all measuring sites, with a difference of 3 days for the Kertészet well and 30 days for the Selyemrét-2 well, which may be due to the fact that the Selyemrét-2 well receives supplies from several flow pathes.

The results of the cross-correlation studies, the coherence study, the cross-spectrum analysis and spectral analysis support the relationship between the cold and thermal karst systems in the Bükk Mountains. Furthermore, since the cold-hot karst system is controlled from above, the conditions in the thermal karst are influenced by the cold karst system above it, and the pressure conditions in the thermal karst are also affected by meteorological events.

Based on the results, I established that the free-flowing, non-pumped thermal water wells draining the Bükk thermal karst are suitable for long-term monitoring activities, their data sets can be used for hydrogeological research, water resources management and water protection tasks. The result further strengthens the usefulness and legitimacy of the operation of the Bükk Karst Water Level Monitoring System, which has been operating for 30 years, and shows that its maintenance is essential for future sustainable water management.

I performed autocorrelation calculations on the data sets of the investigated thermal karst monitoring sites (Fig 13). Based on the results, it can be concluded that the method cannot be applied effectively in monitoring points which are operating thermal wells.

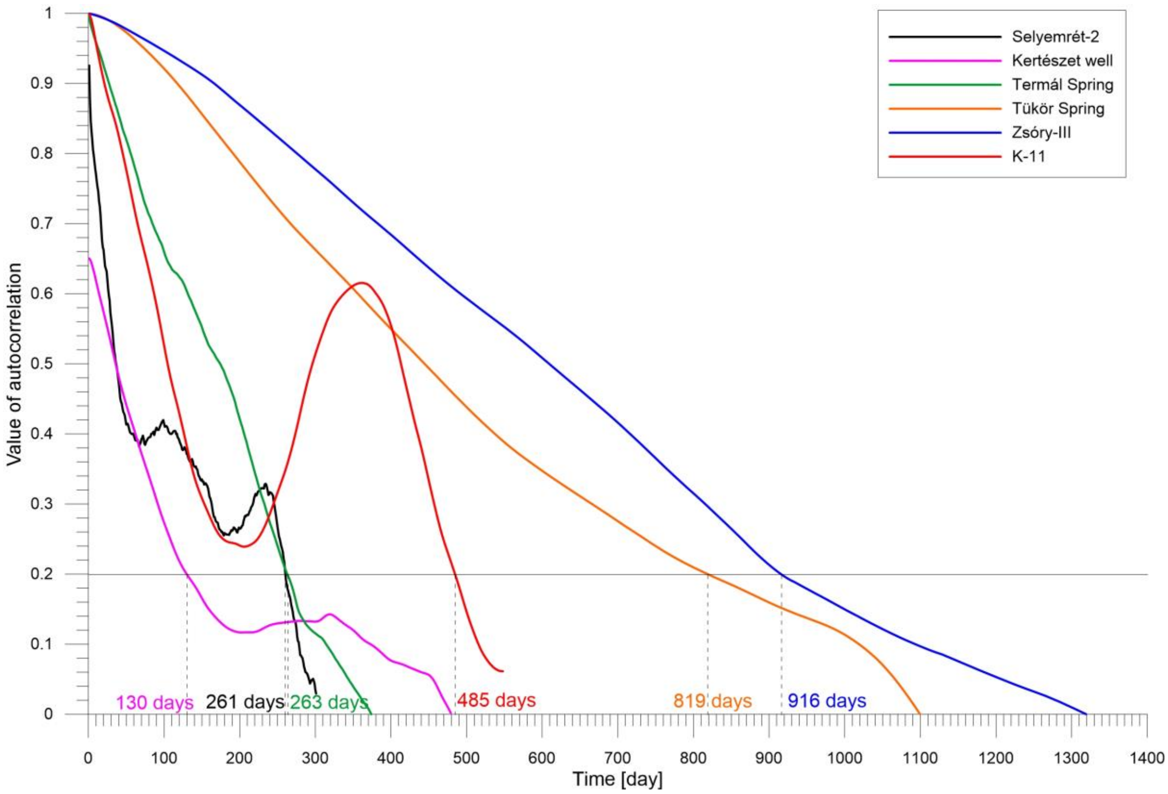

Figure 13. Autocorrelation values for hot water monitoring sites

I gave the memory effect of the system for three monitoring points, 263 days for the Termál Spring, 819 days for the Tükör Spring, and Zsóry-III. and 916 days. From the shape and course of the curves, I established that the Zsóry-III. and the Tükör Spring curves run together for the first 26–27 days and then separate, but up to r_k = 0,2 are very similar. I conclude from this that the waters from the two monitoring points come from flow lines running in the same geological formations.

Based on a thorough review of the existing literature, I believe that no such complex evaluation of the partial results has been carried out so far, therefore I consider the results of the research described in my dissertation to be significant from a scientific and daily water management point of view.

4. Theses

***Thesis 1**: I found that in the Egerszalók-Demjén area, the geothermal step does not change linearly as a function of the depth up to the examined depth of 1647 m. The relationship showing the best fit can be described by a logarithmic relation, which I expressed by the equation $Gl_i=9,6212*ln(z_i)-51,0165$ (where: Gl_i [m/°C] - geothermal step at the examined point, z_i [m] - depth of sole in the same place).*

***Thesis 2**: In the Egerszalók-Demjén and Miskolc and surrounding area, using geological information and geological and temperature data from new drilling data, I achieved the following results:*

- ***A.** In the Egerszalók-Demjén area, I prepared the temperature distribution of the area along two sections. Using information from several hydrocarbon exploration wells as well as modeled temperature data, I provided a tomographic temperature distribution map of the area. Thus, I determined the previously unknown underground temperature conditions at the spatial level in both the horizontal and vertical directions.*
- ***B.** In the area of Miskolc, I refined the existing map of the Triassic basin with drilling data. Based on the modeled and calculated temperature conditions, I made the depth temperature distribution in the area along three sections. Based on the results of hydrochemical, geological and ^{14}C measurements, I determined the conceptual karst water flow conditions of the area along two sections.*

***Thesis 3**: Based on the graphical comparison of the long-term data sets of Nv-17 and the thermal karst monitoring points included in the study, it can be concluded that the large flood peaks in the Nv-17 water level data series also appear in the data series of thermal karst measuring sites with different shifts and extent. Based on this, it can be rightly assumed that the cold and hot karst systems are hydraulically related to each other.*

***Thesis 4**: Based on the results, it can be concluded that in the case of the karst system connected at the regional level (cold and thermal) with a large hydraulic resistance, a strong correlation is shown at low frequency and in high period times between the data sets of cold and thermal karst measurement sites.*

***Thesis 5**: The results of the spectral analysis and cross-spectral analysis carried out on the data series of Nv-17 (Bükk Plateau), Kertészet well (Miskolc), Zsóry-III. well (Mezőkövesd) and K-11 (Demjén) confirm that the cold and thermal karst system is in strong hydraulic contact with each other, and the pressure conditions of the thermal karst* *are basically determined by the amount of precipitation reaching the cold karst in the central part of Bükk. Based on the results of the cross-correlation test, it can be stated that the strongest hydraulic connection can be determined in the eastern direction, followed in descending order by the southwestern and then the southern areas.*

***Thesis 6**: Based on the results of the cross-correlation and periodicity studies (spectral analysis and cross-spectral analysis), it can be stated that the free-flowing, non-pumped thermal water wells draining the Bükk thermal karst system are suitable for long-term monitoring activities, thus, their data sets can be successfully used for research for hydrogeological purposes, for solving water resources management and water protection tasks.*

5. References in the thesis booklet

1. **Darabos, E. (2017)**: Vízkészlet számítás és idősorok elemzése karsztosodottsági jellemzők meghatározása céljából a Bükki Karsztvízszint Észlelő Rendszer adatai alapján. Miskolc, Miskolci Egyetem, PhD értekezés.
2. **Darabos, E., Tóth, M.,Lénárt, L. (2014)**: *Karsztvízkészlet-meghatározás módszertani fejlesztése a Bükk példáján*. XVI. Bányászati, Kohászati és Földtani Konferencia: 16th Mining, Metallurgy and Geology Conference, Székelyudvarhely, Románia, pp. 248-252.
3. **Lénárt, L. (1994)**: *Vízmozgások a Bükk-vidéken*. A Bükk-vidék vízkészletvédelméért, pp. 9-16.
4. **Lénárt, L. (2008)**: *Hideg, langyos és meleg karsztvíz-zónák a Bükkben és környezetében*. Mineral waters in the Carpathian Basin 5th International Scientific Conference. Csíkszereda, pp. 41-50.
5. **Lénárt, L. (2022)**: A 30 éves bükki karsztvízszint észlelő rendszer (BKÉR) leghosszabb adatsorai által dokumentált változások, a változások okai 1992-2021 között. Felszín alatti vizek - láthatóvá tenni a láthatatlant. Az MHT Borsodi Területi Szervezetének 2022. évi Víz Világnapi Ünnepi Kiadványa, pp. 41-52.
6. **McIntosh, R. W., Kozák, M., Plásztán, J. (2011)**: Geológiai értékek a leszálló és termokarszt területek morfotektonikai összehasonlítása tükrében. Calandrella 14, pp. 22-33.
7. **Szilágyi, G., Böcker, T., Schmieder, A. (1980)**: *A Bükk hegység regionális hidrodinamikai képe és karsztvízforgalma*. Hidrológiai Közlöny 60(2), pp. 50-55.