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Investigation of tidal effects on the karst water level in the Bükk Mountains, Hungary

Summary

As the natural fluctuation of the water level in a well is controlled by the tide, barometric and tectonic effects (Bernard & Delay, 2008), the purpose of the present study was to investigate the water level response to lunisolar gravitational effects of a karstic system located in the Bükk Mountains. In a previous study was mentioned the notorious harmonic pattern measured in the Bükk karstic aquifer, where no ocean or seas have direct influence (Lénárt, 2005). The Sun and the Moon attraction generate a state of stress on the Earth surface which induces a radial deformation of the Earth (Victorine, 2017) and changes gravitational potential depending on the location and phase of their orbit. The aquifer main parameters allow the rock to be an elastic body and to show harmonic periodic fluctuations on the monitored water level in response to Earth Tides. The tidal patterns are classified according to their periodicity (i.e. Spring Tide, Neap Tide and Diurnal, Semidiurnal and Mixed Semidiurnal Tide Cycles).

The Bükk Mountains Water Monitoring System BKWMS provides long-term, high-frequency, and high-resolution water level datasets from the karstic reservoir. Five different measuring points from the BKWMS were selected: a monitoring well in unconfined karst aquifer “Nagyvisnyó, Nv-17”, two thermal production wells screened from deep, buried karst aquifer Zsóry III and MIVÍZ Kertészet, and two springs with gravitational discharge Garadna Spring and Tükör Spring.

Karst water level, Sun distance, Moon distance, Moon phases dataset, and the historical report of the occurrence of were used. The pre-processing, processing and visual interpretation were made by using Excel and MatLab software. Regression methods were applied to extract the main tidal response of each measuring point. By the correlation of two variables (i.e. the water level measurements with the distances and positions of the Moon and the Sun) were calculated and analysed.

The result of this investigation establishes the expression of Mixed-Semidiurnal Cycles on three of the five measuring points. Their enhancement occurs during New Moon and Full Moon when the Sun and Moon are lined up. The borehole geometry (i.e. size) and the aquifer properties (i.e. confinement conditions) are the main characteristics related to the positive response. A certain degree of confinement is confirmed for the thermal well Zsóry III, Tükör Spring, and the Monitoring well Nv-17.

1. Introduction of the investigated area

The investigated place is the Bükk Mountains located in the northern region of Hungary between the latitude 47°44'12.20" and 48°09'35.29" North, and the longitude 20°18'43.81" to 20°59'59.95" East, with an approximate area of 1000 km^2. It covers part of the Bükk National Park (Bükki Nemzeti Park in Hungarian), situated approximately 10 km from the city of

Miskolc, between Szarvaskő and Bükkszentkereszt. The Bükk Mountains represent the second highest mountain range in Hungary with a maximum height of 958.4 m (Istállókő-erőse) (Less, et al., 2005). Figure 1 illustrates the investigated area, the meteorological station Jávorkút, the five selected points (i.e., the monitoring well (*Nagyvisnyó Nv-17*), the two springs (*Garadna* and *Tükör*) and the two thermal wells (*Zsóry III* and *MIVÍZ Kertészet*) and the events of seismic activity provided by the Kövesligethy Radó Seismological Observatory (2017).

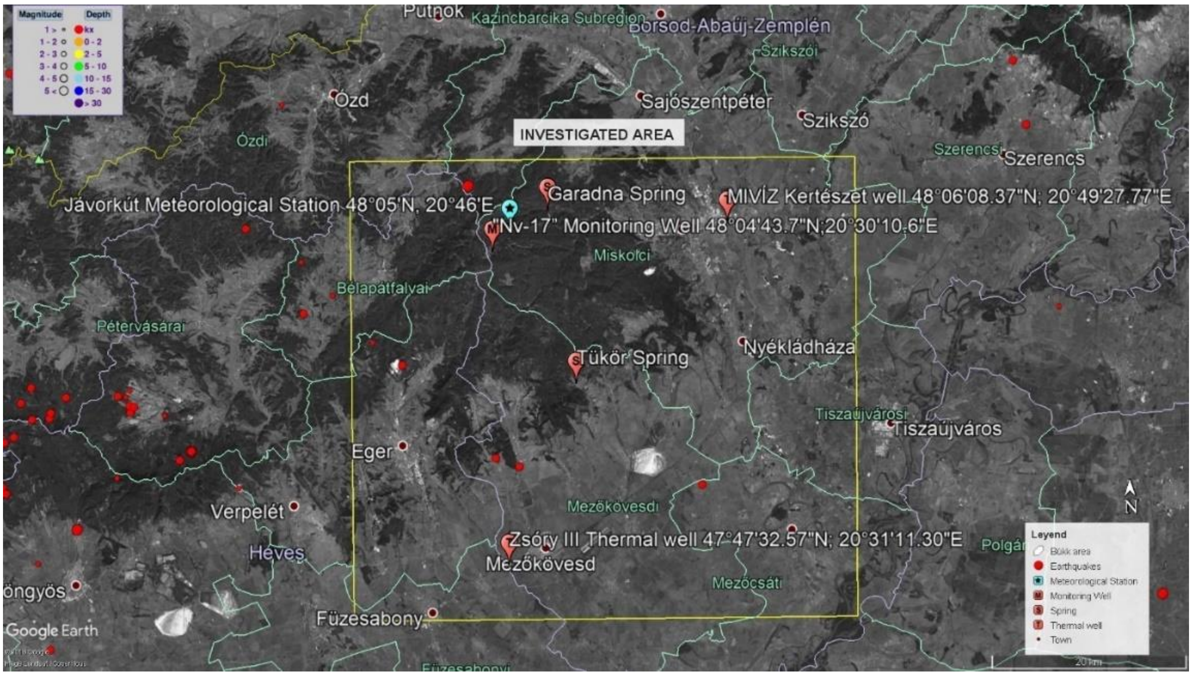


Figure 1. Investigated area, measuring points, meteorological station and earthquakes' magnitude from 1996 until 2016 (author's work based on Google Earth Pro Map)

This region is characterized by karst formations and the occurrence of natural springs, with cold and some with thermal water (with temperatures above 30°C). Springs provide karstic water by gravity drainage and production wells using pumping. From the Bükk Mountains, the city of Miskolc produces karst water at the highest rate. According to Dura, et al. (2010), drinking water consumption of Miskolc is nowadays 35 000 – 42 000 m^3/d for approximately 174 000 residents. The most significant part of exploited karst water covers drinking water demands, but the sector of balneology and balneotherapy is also an essential user (Darabos, 2010).

The Thermal Karst System (TKS) of the Bükk region is about 4300 km^2, but due to its complexity, its boundaries cannot be precisely delineated (Lénárt, et al., 2014). According to Darabos (2010), the central part of the Bükk Mountains significantly includes Cold Karst Systems and should not be divided from the TKS as they form one continuous karst system unit. The primary direction of the seam system is North-South, but the connection of minor fragments of the mountain in the direction of East-West is more unequivocal and closer. To preserve the quality and quantity of karst water, the maximum consideration of the relationship between cold and thermal karst system has been critical (Lénárt, 2010; Darabos, 2010).

The Bükk Karst Water Level Monitoring System (BKWLMS, M.E., 2019) provides qualitative-quantitative parameters (water level, temperature, and in some points measuring conductivity). The operation of the measuring points varies from time to time because of the financial resources' availability. Nowadays, 30 measurement sites are operating in caves, springs, and wells of cold and warm karst-water. In six measurement sites, the data collection has been carried out continuously and automatic since the installation of the dataloggers in 1992 (Lénárt, et al., 2014). The frequency of the measurements varies between five minutes to one hour (but usually are 15-minutes frequency). The density of the data recorded is determined based on the research aims and the importance of specific areas.

As the seismic activity can influence the fluctuation of the karst water level in the wells due to the expansion and contraction of the waves while displacing through the system, reports from 1996 until 2016 were used to identify this disturbance not related to the gravitational effects.

1.1.Climatology of the Bükk Mountains

The Bükk Plateau is situated geographically on a higher position, and the microclimatology slightly differs from the lower areas of the mountain range. The climate is continental, predominantly cool and considered to be wetter than dry. Temperatures vary depending on location and altitude. Springs and autumns are cooler than the national average values with occasional rain (Miklós, 2016). The change in meteorological conditions affects the water balance of the mountains as the more frequent or increasing extremities can be observed nowadays (Darabos, et al., 2016). The apparent increase in the average annual amount of precipitation over the last decades is seen (Darabos, et al., 2016; Darabos, et al., 2012).

Records between 2005 and 2018 show the North-Western prevailing wind direction with an average wind speed of 4.3 m/s (Raspisaniye Pogodi Ltd, 2018). The lowest irradiation values (less than 4300 MJ/m^2), occur around the northern parts of the mountains. The highest rate of radiation is received in July, where there is less amount of cloud cover. The cloudiest weather and the shortest days make December the month with the lowest irradiation during the year (OMSZ, 2013). In the Northern and North-Eastern of Hungary, and around the western borders, the sunshine is less than 1800 hours per year (OMSZ, 2013). In winter, the highest mountains receive one and a half times as much sunshine as the plains, and in summer they have 10% less sunshine as the lower regions, because of the cloudier and wetter weather (OMSZ, 2013).

1.2.Geological characteristics of the area

The Bükk Mountains are built up mostly by karst rocks, characterized by karst formations on the surface to a great extent and also buried with thick non-karstic sediments. As a result of the karst special features, the lack of surface stream network is notorious. Several karst springs can be found in the area; many of them are thermal (providing temperatures above 30°C) (Lénárt & Darabos, 2013). Small but numerous springs with more significant discharge are situated in lower regions. Permanent, temporary, and periodic springs can also be found around the mountain edges. In the central region, the number of springs and creeks is lower. Garadna and Szinva creeks are notable. Dolines and karrenfields are the most typical forms of the karst terrain. There are a high number of sinkholes and active caves associated with a few avenues (shaft caves) that are of uncertain origin (Less, et al., 2005). Figure 2 shows the topographic map of the Bükk Mountains and the city of Miskolc as a reference point.

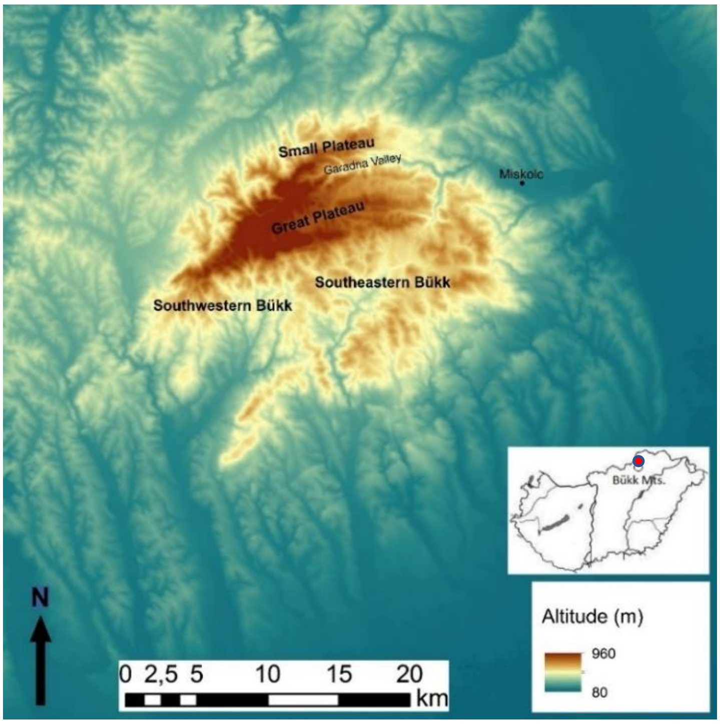


Figure 2. Topography map of the Bükk Mountains (European Environmental Agency, 2017)

The Bükk Mountains is classified into three broad, almost self-contained hydrogeological units, which are further subdivided into smaller components, a fact that makes them not to form a uniform karst water system. The Northern Unit-Észak Bükki egység in Hungarian is built up by a series of carbon-perm-Triassic-Jura sediments from the northern wing of the northern Bükk-anticlinal. The Middle Unit-Középső-egység is the southern, perpendicular wing of the North Bükk Anticline, which is usually a steep layered carbon-top-triad rock series. The Southern Unit-Déli egység (in the geological sense used in the South-beech) middle-triad-upper-Jura layer (Less, et al., 2005). The boundary of the hydrogeological Units is not always the same as the boundary of the geological ones, as the latter geological structures are permeable in the case of contact with rock bodies with similar hydrogeological properties.

The recharge area of the karstic aquifers in the Bükk Mountains is found to be open to the atmosphere (Hertelendi, et al., 1995), classified as an inhomogeneous and fully karstified area. The karst landscape in the Bükk Mountains is characterized by a thin layer of soil on the bedrock, through which precipitation can pass wholly and immediately. This natural replenishment can also quickly influence the water temperature and conductivity values also in the cold-water karstic springs (Darabos, et al., 2012). The vulnerability partly stems from the geological structure itself, since karst is an excellent water conduit and has excellent reservoir properties (Dura, et al., 2010). The average depth of the vertical karstification in some of the mountain caves and the actual amount of cold karst water in the karst reservoir have been determined using monitoring system datasets, speleological excursions, tracer test and other related methods (Darabos, 2010).

1.3.Description of the investigated points

i. Monitoring Well Nagyvisnyó, Nv-17

The monitoring well Nv-17 is located in the coordinates 48°04'43.69" North and 20°30'10.63" East with an elevation of 778.9 maBsl. It is the highest well and most crucial monitoring points of the BKWMS because it provides the best description of the system by not being directly influenced by any production well in the area (Lénárt, 2005). The well measures the top of the karst water level relief, but in the case of no precipitation periods, the production rate from lower wells can generate the decrease of its water level in a long-term period. It was constructed in 1979 with a drilling depth of 350 m from the surface with a water temperature of 9.8°C. It is cased in full length with two screens, one from 310 m to 317 m deep and the second screen from 325 m to 331.5 m deep. The static water level is found to be at 238.1 m deep.

ii. Garadna Spring

Garadna Spring is a cold karst spring situated in the Garadna Valley of the Bükk in the coordinates 48°07'01.8" North and 20°33'23.1" East. It is a gravitational spring where the water flows out naturally. Therefore, no pumps are installed. The spring itself does not connect to the water supply system. A horizontally, inclined drilling produces drinking water near the Spring and connects to the drinking water supply of the settlement of Ómassa.

The majority of the water catchment area (7.4 km^2) of the spring can be found on the Triassic age Fehérkő Limestone formation on the Great Plateau, which is an excellently karstifiable formation. The Garadna water catchment area presents 35 sinkholes and dolines. A large number of tracer tests showed that five of them are in direct contact with the Spring and transport their water to it (i.e. Bánkút Sinkhole, Bánkút Sinkhole - Diabáz Cave, Jávor III Sinkhole, Jávorkút Sinkhole, Bolhás Sinkhole) (Less, et al., 2005). However, the spring itself enters surface water from the Hámori Dolomite Formation, which is built up by moderately karstified dolomite, classified to have a functional water storage capacity (Miklós, 2013).

iii. Tükör Spring

Tükör Spring is located in the town of Kács considered a mixing zone where the Cold System and the Thermal System of the Mountains converge. As the relationship between the systems is not clearly defined, the confinement condition of the Spring involves uncertainty. Tükör Spring is also a gravitational spring but with tepid karst water.

iv. Thermal well Zsóry III

Zsóry III Thermal well is located in the coordinates 47°47'32.57" North and 20°31'11.30" East with an elevation of 119.55 maBsl. It is situated near Mezőkövesd city, in the Zsóry Thermal Spa and is currently not operating, because the spa pumps water from nearby installed wells. The well was constructed in 1969 with a drilling depth of 971.9 m, cased until 957.6 m deep where is located a quartzite layer. It has six screens, the first one was jet perforated and is found in 863 m deep with a total length of 12.5 m. The following four screens were perforated, and their length varies from 7 m to 12.3 m. The sixth screen is found at a depth between 957.6 and 971.9 m and corresponds to an open filter of 14.4 m length. The water temperature corresponds to 74°C in 773 m deep, and the possible exploited water temperature is approximate 64°C, coming from all the six screens. The static water level is found to be in 121.1 maBsl.

v. *Thermal well MIVÍZ Kertészet*

The MIVÍZ Kertészet well is located in the coordinates 48°06'08.37" North and 20°49'27.77" East with an elevation of 111.9 maBSl. It is an operating thermal well in the site of MIVÍZ waterworks company of the city of Miskolc. Its exploited water is used for the heating of the buildings. The measured parameter is the hydraulic pressure (bar), unlike the other measuring points, measured in units of length. The well was constructed in 1986 with a drilling depth of 466 m where the water temperature corresponds to 45°C. It is cased until 464 m deep and has one screen from 447.2 m deep until the bottom of the casing. The static water level is found to be at 126.1 maBsl, corresponding to a hydraulic head pressure of 0.98 bar.

2. Factors affecting groundwater levels

Figure 3 shows the schematic classification of the identified factors affecting the hydraulic head of the aquifer, one influenced by natural forces and the other one generated by human activities. These mentioned factors were taken into consideration for the present investigation to establish the evident lunisolar gravitational effect on the hydraulic head of the BKWMS.

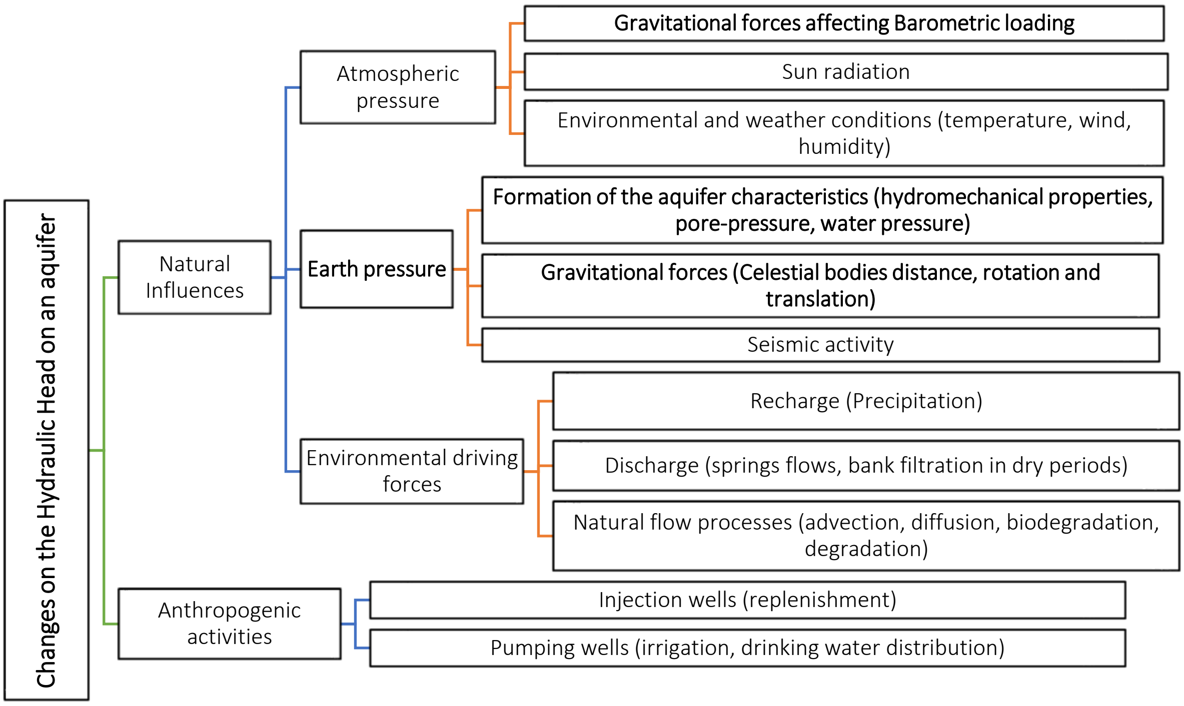


Figure 3. Influencing factors on the hydraulic head fluctuation (Author's work)

Generally, fluctuations on the water level in a well are related to changes in the matrix pressure, recharge, and discharge, infiltration, and percolation rates. Other minor processes stated by Glynn & Plummer (2005) relate sedimentation, compaction/subsidence, diagenesis, erosion, glacial (or ice sheet) advance-retreat, sea-level rise/decline, fracturing or plastic deformation, heat flow, the growth/dormancy/decay of microbial populations, geochemical and/or fluid advection, biogeochemically mediated reactions, gas generation and transport, solute diffusion and advection, radioactive decay chains and many others. However, as most of the chemical and biological processes are slower than gravitational effects, their effect in the system can be neglected.

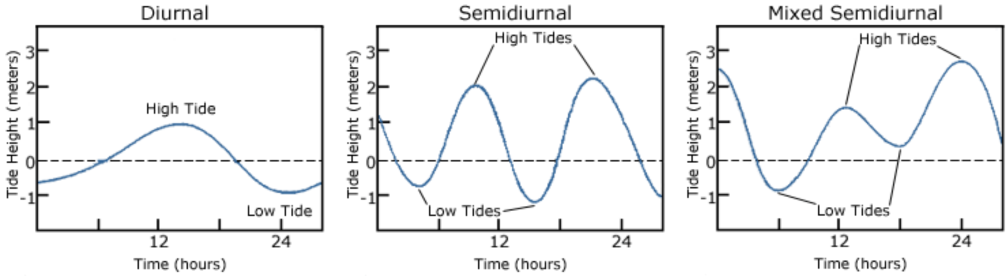
The Department of Natural Resources of Missouri (2007) established the effect on the groundwater levels fluctuation with a clear sinusoidal pattern in porous aquifers with no influence from ocean or seas, or by more significant factors such as nearby pumping according to the Moon's phase. In a previous study in 2004 on the Bükk Mountains (Lénárt, 2005) was identified the notorious harmonic pattern in the karst water level of the Bükk karstic aquifer with no ocean or seas influence.

Tides generation are related to the gravitational forces by the six factors: 1. the rotation of the Earth, 2. the revolution of the Moon around the Earth, 3. the revolution of the Earth around the Sun, 4. the position of the perigee (related with the variation in time of the orbit of the Moon around the earth) and 5. its nodes. Moreover, 6. the position of the perihelion (related to the variation in time of the revolution of the earth around the Sun) (Doan & Brodsky, 2006). These factors can be described by the position of the celestial bodies in their orbits (alignment based on the Moon's phases) and the distance between them.

The process induced by gravitational influences due to the tidal strain occurs in two phases: (1) the poroelastic phase, in which the tidal strain induces a change in a pressure in the equilibrium and (2) the hydraulic phase in which the change in pressure in the medium induces a change in water level in the well (Doan & Brodsky, 2006). The growth in a tidal force causes deformations associated with the expansion of the medium (increase in porosity and permeability) and a decrease in a tidal force causes the medium to compress. Faults and large fractures, zones with reduced strength of the medium are essential factors for the occurrence of these effects (Adushkin, et al., 2017).

Earth Tides ET have direct influence on the hydraulic head fluctuation in the area due to the compression and expansion of the rock matrix as a result of a solid viscous-elastic deformation of the Earth's crust due to the varying gravitational pull of the celestial bodies (mainly influenced by the Moon and the Sun) (Davidson & Wilson, 2011; Maréchal, et al., 2002). The effect of ET near the surface of the Earth consists mostly in tiny horizontal strains as the 'tidal bulge' passes by. The gravity changes from ET squeezes the sediment and changes the pressure of the water in the pores (Rau, et al., 2017). Therefore, the elastic response and the water level fluctuations due to ET effects can only be seen in wells open in confined aquifers and semiconfined aquifers (Bollimunta, 2013; McMillan, et al., 2019). Tides are caused by reflecting the response in non-drained conditions of the formation known as a theoretical confined-static response (Fuentes-Arreazola & Vázquez-González, 2016).

Other daily gravitational effects generate three types of tides classified as Diurnal, Semidiurnal, and Mixed Semidiurnal Tide Cycles (Graph 1). The Diurnal Tide cycle is the experience of one high and one low tide every lunar day, the time it takes for a specific site on the Earth to rotate from an exact point under the Moon to the same point under the Moon. Semidiurnal Tide Cycle refers to the experience of two high and two low tides of approximately equal size every lunar day. Moreover, the Mixed Semidiurnal Tide Cycle refers to two high and two low tides of different size every lunar day (NOAA, 2013).



Graph 1. Diurnal, Semidiurnal and Mixed Semidiurnal tide cycles (NOAA, 2013)

The effects of the ocean pressure over the lithosphere were neglected by assuming that aquifer is far enough (approximately 650 km away from the shoreline) to have no contact with the near seas or oceans. Diurnal patterns due to thermal excitation by solar radiation cause effects in the atmospheric tides; therefore, this factor was also neglected because it is directly influenced by local environmental conditions. The meteorological noise (radiation, air temperature, wind, humidity, among others) can be partially excluded by the use of vented sensors. Vented devices have a sensor which subtracts the atmospheric pressure changes from the total measured pressure and gives a direct value of the water level (in meters or bar) without the significant influence of the barometric pressure.

Changes of regional or local tectonic stress in the earth crust and loading on the ground due to the occurrence of earthquakes are natural affectations on the subsurface systems. Seismic waves can be easily distinguished on the groundwater level because these respond instantaneously to the earthquake (Survey, U.S. Geological, 1993). Wells relatively close to a major earthquake may experience permanent water level changes but typically the earthquake causes the water level in a well to fluctuates for perhaps a few minutes and then return to a normal level (Department of Natural Resources, Missouri, 2007).

2.2.Tidal effects in wells

A monitoring well is designed to measure water level changes, which can also be related to tidal strain because the porous medium supplies water to it. If the permeability of the medium is too small, then the well responds with delay. The amplitude of the water level oscillations also drops as the aquifer cannot supply enough fluid for the well to match the pressure (Doan & Brodsky, 2006).

The tidal strain is a dilatational strain applied uniformly assuming a homogeneous isotropic reservoir. It induces a change in hydraulic head related to the poroelastic properties of the formation. The rigid casing makes the well not open to the formation and thus is not intrinsically disturbed by the tidal waves for uniform pressure. However, if the well is open or screened, the water level in the well (h_w) has to fit the hydraulic head in the formation. In practice, the change in pressure is provided by the water volume stored in the formation. If the formation is impermeable, the well will not experience any water level change, like a fully cased well. However, if the formation is poorly permeable, the water level in the well is out of equilibrium and would not match the far field hydraulic head in the formation, and fluid flow occurs in the formation near the well (Doan & Brodsky, 2006).

3. Methodology

A previous study in the Bükk Mountains related to the effect of the gravitational forces with the periodic oscillations contained in karst water level records (Lénárt, 2005). For the purpose of this investigation, periods during 2000, 2011 and 2015 from the five different measuring points were selected according to the presence of a very long decreasing/increasing tendency section of karst water level. Precipitation events from the meteorological station Jávorkút were compared, so no considerable amount of precipitation could affect the water level, and the rain effect could not have a considerable encroachment on the karst water level. A steady-state flow system with no considerable flow was assumed. The examined periods are relatively short (within one year), and karst water levels show an almost constant tendency, so there are no much disturbing factors (i.e. evapotranspiration or infiltration).

All datasets were used in a standard time reference (UTC) so that the phase difference between the tidal relation was accurately determined. The datasets of the Moon and Sun distances were converted from daily to frequencies of 5, 15, and 30 minutes according to the frequency of the measuring point datasets by using interpolation. This process was made by using MATLAB® in its version R2017b with the fillmissing-spline method. The datasets of the karstic water level and the Moon phases (Miskolc, Hungary as the point of reference) were also interpolated to ensure the same length and the right concordance between the dataset’s frequency. The highest frequency of each dataset corresponds to 5-minutes in MIVÍZ Kertészet well, 15-minutes in “Nagyvisnyó, Nv-17” Monitoring Well, Garadna Spring, Zsóry III Thermal karst well and MIVÍZ Kertészet well, and 30-minutes in Tükör Spring.

The application of linear, quadratic, and cubic regressions allowed to eliminate the tendency from the natural flow and determine the net fluctuation of the water level. Therefore, the tendency was eliminated, and the residuals values used as the net, smaller oscillation of the karst water level. Then, by using Excel tools - Data Analysis, the Moon and Sun Distance and their residuals were correlated with the karst water level and its regression residuals. The correlation was applied to the most extended period scenario (more than 5 months period).

The quantitative cyclic pattern of the Moons phases was established from the qualitative data of the Moon phases (its position in orbit to the Sun and the Earth). The values were given to each phase according to the degree of possible affectation. Quarter-Moon’s phases were classified as 3 as the minor effect possibility due to the partial cancellation generated by the 90° angle in space. Full Moon Phase was denoted by 2,5 and New Moon phase by 2, due to the Sun lineament and thus an expected gravitational power enhancement. Figure 4 illustrates the quantitative interpretation in 43 days of the Moons phases.

The occurrence of monthly tides (Spring and Neap tides) and daily tides (Diurnal, Semidiurnal, and Mixed Semidiurnal tides) were graphically analysed during specific periods. Their occurrence was examined according to their relation with the Moon phases (Moon translation around the Earth, approximately 29 days, Earth-Moon-Sun lineament, and Earth rotation). The second power of the water level was applied to create a visible effect of the fluctuation. Diurnal, Semidiurnal and Mixed Semidiurnal tide cycles require water level measurements with shorter periods and high frequency (1 day with minimum 24 records).

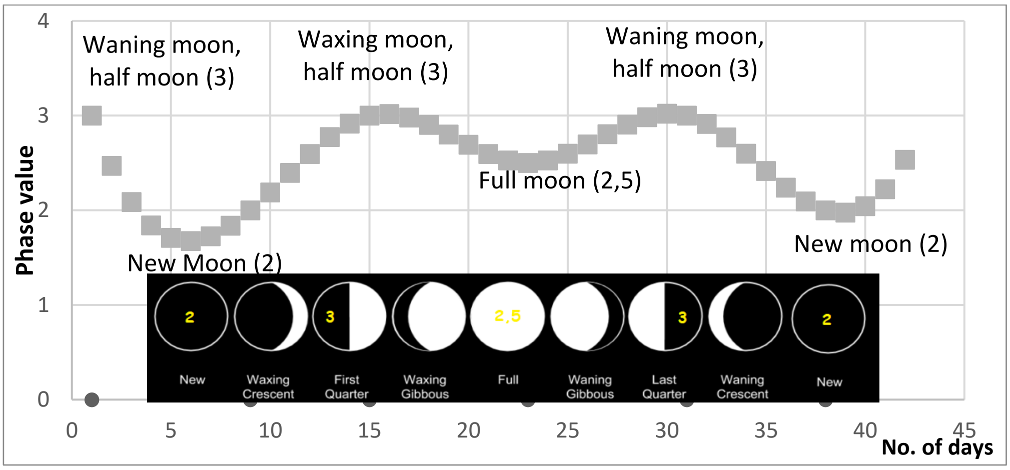


Figure 4. Moon Phases cycle and cycle pattern from April 26th to June 6th of 2000. 2 - New Moon phase, 2.5 - Full Moon and 3 - half-Moon's phases. (modified from starinastar.com (Cummings, 2019))

The reports of earthquakes provided by the Hungarian Kövesligethy Radó Seismological Observatory (2017) from 1996 until 2006 were used to determine their possible influence in the measurements or their relationship with the occurrence of errors during the recordings. For the random peaks and the lower points compared to the average values were further analysed with the occurrence of earthquakes reported in 32 km radius. These periods were also carefully excluded as part of the pre-processing stage and avoid their selection during analysis.

4. Analysis of the gravitational forces in the Bükk karstic aquifers

4.1.Analysis of the Monitoring Well Nagyvisnyó, Nv-17

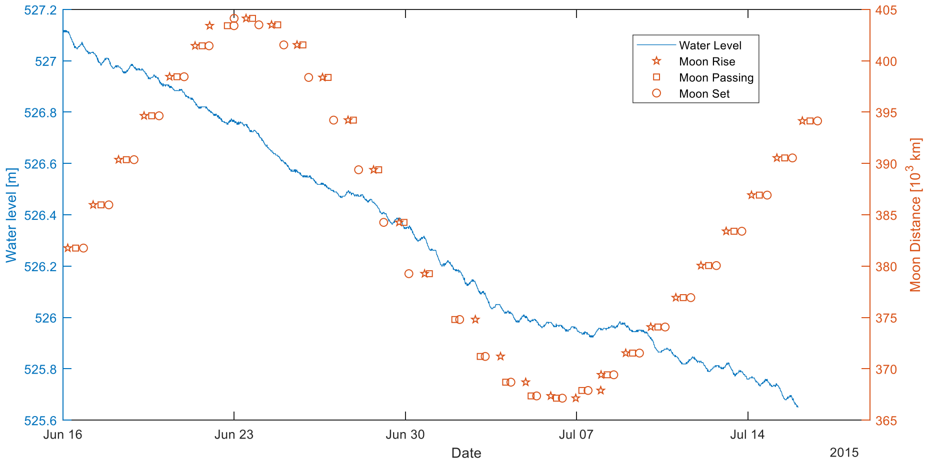
Table 1 resumes the highest correlation values between the water level fluctuation and the studied parameters in a long-term period. The positive and negative correlation results are considered as the natural recession tendency in the aquifer due to the dry period occurrence rather than caused to the proximity of the Sun and the Moon. Therefore, the water level and Sun distances have no direct relation.

Graph 2 shows the harmonic oscillations presented by the water level in the monitoring well in 2015, associated to the Moon distance and its rising, passing and setting over the City of Miskolc (reference point). The lunisolar effect is examined in more detailed with mathematical methods in the following steps due to the evidence of the cyclic periodicity on the raw water level dataset during a lunar month period.

Table 1. Highest correlation results of "Nagyvisnyó, Nv-17" monitoring well.

Year	Frequency	Relation	Regression	Correlation [%]
2000	Hourly	Water level of the well and Sun distance	Linear	-83.92
		Water level of the well and Sun distance	Cubic	85.31
	Daily	Water level of the well and Sun distance	Linear	-86.31
		Water level of the well and Sun distance	Cubic	86.33
2011	Daily	Water level of the well and Sun distance	Linear	-92.55
2015	Daily	Water level of the well and Sun distance	None	83.48
		Water level of the well and Sun distance	Linear	-90.08
		Water level of the well and Sun distance	Quadratic	91.50
	15 minutes	Water level of the well and Sun distance	None	-97.02
		Water level of the well and Sun distance	Linear	-91.09

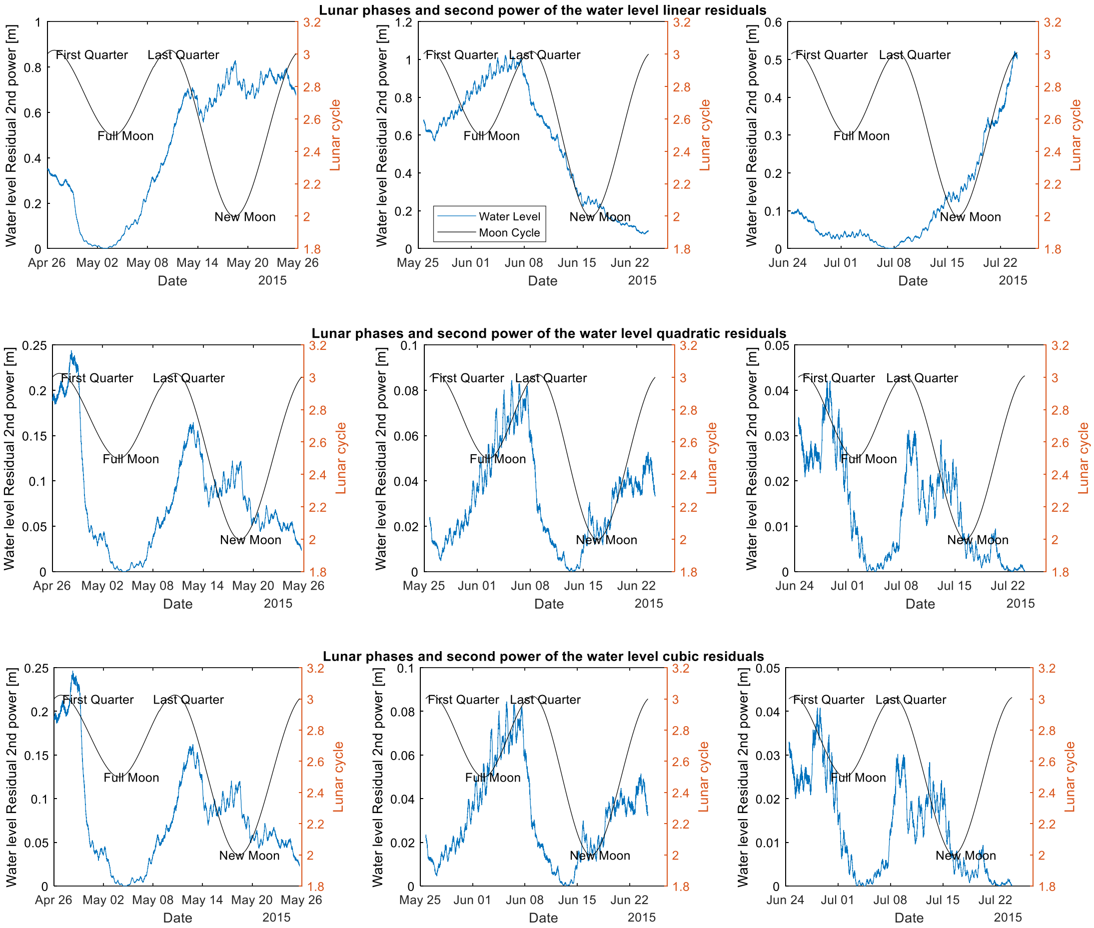
(Author's own work)



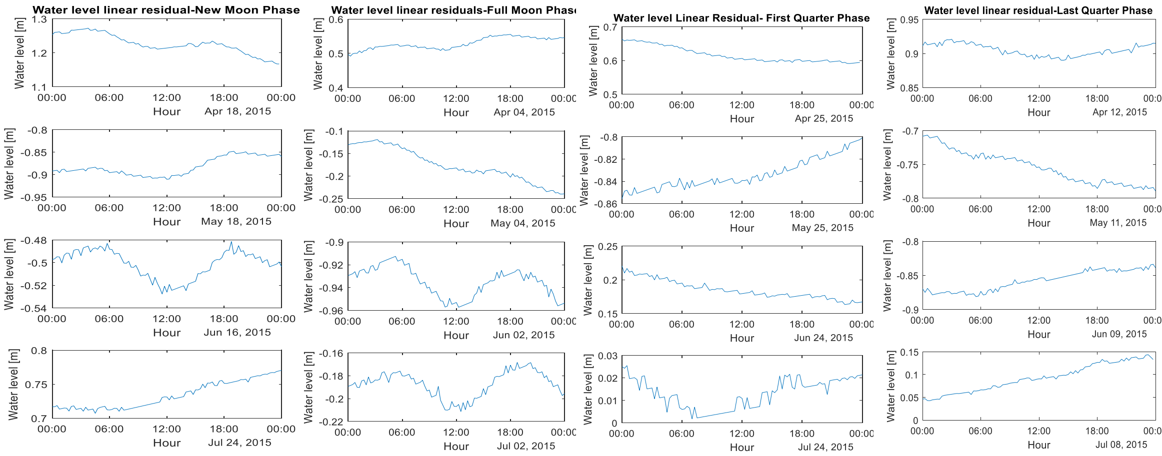
Graph 2. Karst water level fluctuations of the "Nagyvisnyó, Nv-17" monitoring well according to the Moonrise, Moon passing and Moonset during a Lunar Month (Author's work)

Graph 3 shows the relation between the Moon phases and the second power of the karst water level fluctuation. In a complete year period analysis, the fluctuation pattern of the water level expresses maximum points but not related to the Moon Phases.

Graph 4 shows the examined days of New Moon, First Quarter, Full Moon and Last Quarter, along 2015 and the water level response to Diurnal, Semidiurnal, and Mixed-Semidiurnal tidal cycles. During Full Moon and New Moon days in 2015, an apparent response to the Mixed-Semidiurnal tidal cycle is expressed in most of the examined periods with two high and two low peaks. In contrast, during the days occurring First Quarter and Last Quarter phases, the karst water level does not show evident sinusoidal fluctuation. Therefore, the enhancement of Mixed Semidiurnal tides is occurring only during the New Moon and Full Moon periods and the attenuation is presented during the First and Last Quarter lunar phases.



Graph 3. Karst water level fluctuations of the "Nagyvisnyó, Nv-17" monitoring well according to the Moon phases (Author's own work)



Graph 4. Response of the karst water level in the "Nagyvisnyó, Nv-17" monitoring well to Mixed Semidiurnal tides during in a period of Full and New Moon, First and Last Quarter phases (Author's work)

4.2. Analysis of Garadna Spring

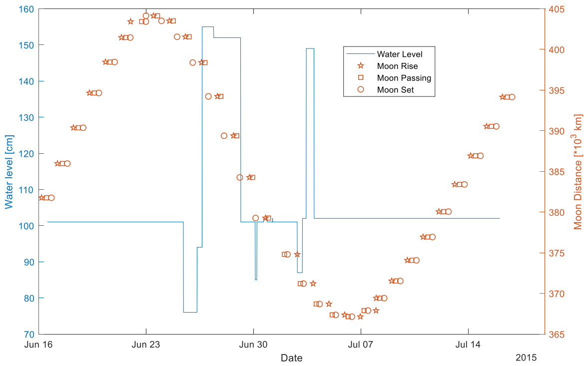
In 2011 and 2015 with an optimal frequency of 15 minutes, Garadna Spring presented no correlation between the water level and the Sun and Moon distance datasets. During 2015, the dataset has several gaps of where the sensor did not record and required interpolation. It also expressed single peaks, interpreted as measuring errors. Therefore, it did not provide relievable results for further analysis. The possibility of earthquakes effects within a radius of 32 km influence was further investigated. Table 2 describes the three possible water level peaks related to the coincidence of earthquakes reported in a radius of 32 km during 2011. Due to the not reliable dataset of 2015, a clear relationship between the occurrence of earthquakes was not possible to be determined.

Table 2. Possible related earthquake events to the Garadna Spring water level fluctuation.

Date	**Time**	**Mag.**	**Lat. North**	**Lon. East**	**Depth [km]**	**Region**
06/06/2011	21:55:08	1.4	48°12’77”	20°35’92”	10.0	Czech and Slovak republics
07/07/2011	12:05:53	1.6	48°22’82”	21°27’35”	0.0	Hungary
27/07/2011	5:42:36	1.7	48°19’90”	21°18’95”	0.4	Hungary

(Author’s work)

Graph 5 shows the water level fluctuations in Garadna Spring associated with the Moon distance and its rising, passing and setting over the City of Miskolc (reference point). The raw water level dataset during a Lunar month period do not show evidence of the cyclic periodicity due to the lunisolar effect.



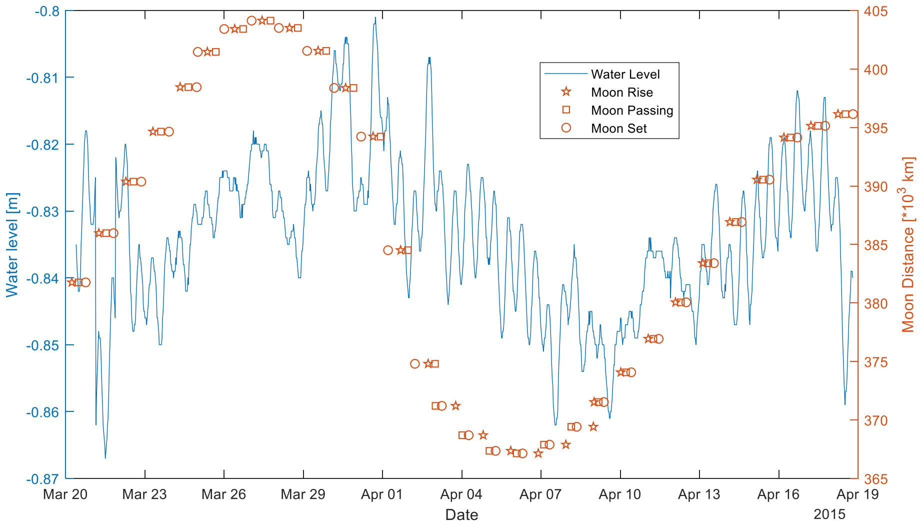
Graph 5. Karst water level fluctuations of Garadna Spring according to the Moonrise, Moon passing and Moonset during a Lunar Month (Author’s work)

The water level oscillations were monthly and daily compared with Lunar phases for all the three possible scenarios (linear, quadratic, and cubic). The relationship between New Moon and Full Moon periods was not be clearly defined, and the fluctuation patterns do not correspond to any tidal cycles. The water level fluctuation in 2011 is higher than in 2015. During 2015, the karst water level was found to have an almost stable hydraulic head with no visible relationship with the gravitational effects. Therefore, the Spring is not affected by the gravitational influences due to its hydromechanical characteristics, and the fluctuations correspond to its response to other external factors.

4.3.Analysis of Tükör Spring

In 2011, a correlation of 81.4% was found between the water level of the Spring and the Sun distance datasets. During 2015 no correlation was found between the parameters; therefore, the behaviour of the water level tendency could be defined as decreasing natural flow due to the aquifer processes, and not directly related to the Sun and Moon distances.

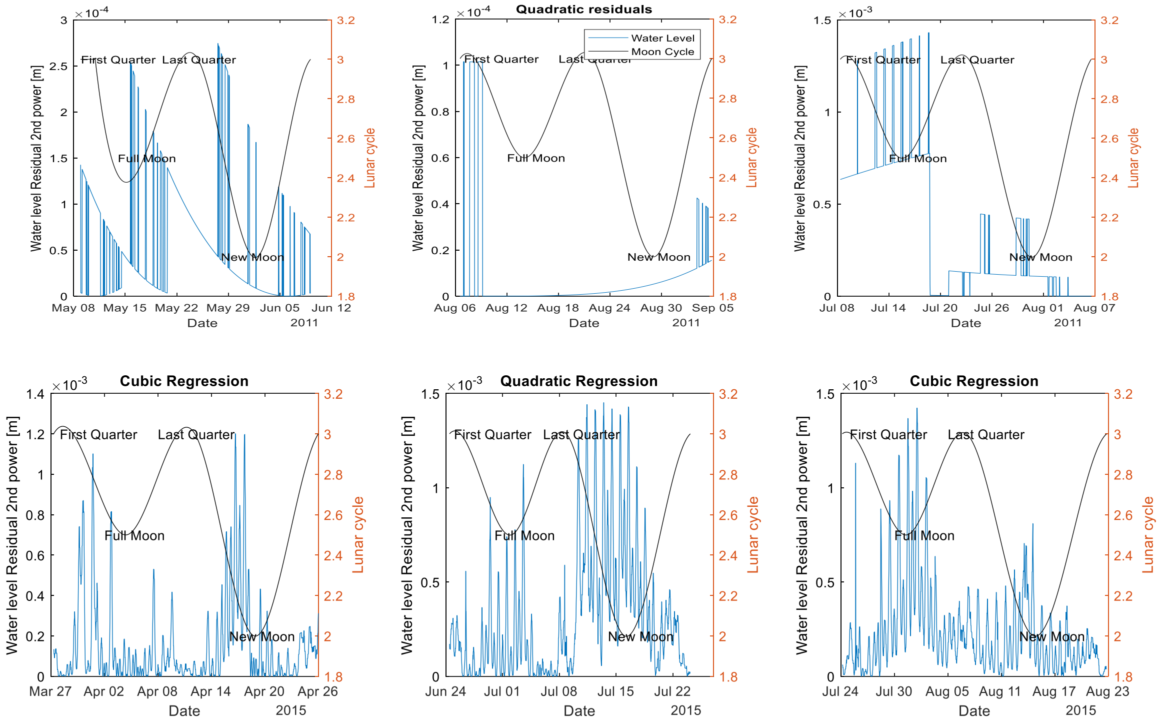
Graph 6 shows the harmonic oscillations presented by Tükör Spring during 2015, associated with the Moon distance and its rising, passing and setting over the City of Miskolc (reference point). Therefore, the lunisolar effect is examined in more detailed in the following steps.



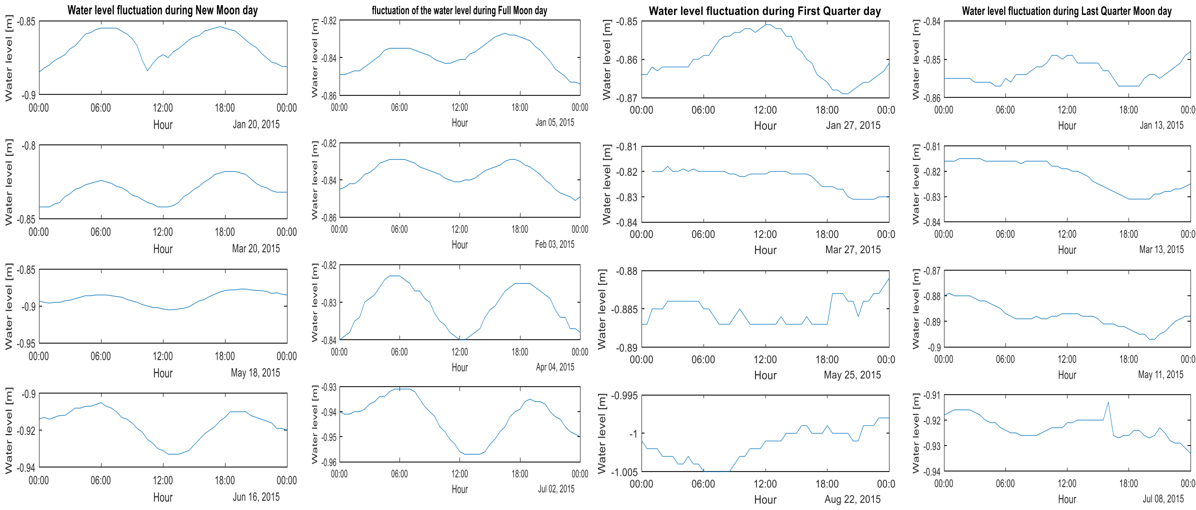
Graph 6. Karst water level fluctuations of Tükör Spring according to the moonrise, moon passing, and moonset during a lunar month (Author’s work)

The relation between the Moon phases and the second power of the water level is shown in Graph 7. During 2011, a clear relationship between them cannot be seen. During 2015, some peaks were found corresponding to the same periods of Full and New Moon by applying quadratic and cubic regressions. The water level and lunar phases presented coincidence, but a persistent delay in the water level rising or decreasing is presented between 5 and 6 days.

Specific days of New Moon, First Quarter, Full Moon and Last Quarter along 2015 were selected with the purpose to examine the response of the water level to Diurnal, Semidiurnal and Mixed Semidiurnal tidal cycles. Graph 8 shows enhanced patterns during the New Moon and Full Moon days in 2015. On the contrary, the Spring shows random fluctuations during First Quarter and Last Quarter phases. The response of the system to the gravitational forces can be interpreted as a certain degree of confinement.



Graph 7. Relation of the water level second power of Tükör Spring with the Moon's phases during 2011 and 2015, respectively (Author's work)



Graph 8. Tidal response of Tükör Spring water levels during New Moon, Full Moon First and Last Quarter days in 2015 (Author's work)

4.4. Analysis of Zsóry III Thermal well

The hydrographs of Zsóry III Thermal well showed peaks which can be related to drawdown and recovery phases due to the production rates of the near operating wells. During 2011, with a daily and hourly frequency, the only high correlation found (above 80%) was 95.3% between the water level and Sun distance. Even there is a high correlation, the direct relationship between these parameters cannot be stated, as it is considered the fact that without any regression, the decreasing tendency is mainly and strongly attached to the natural flow effect. Therefore, the Sun distance changes could not be causing the high decreasing tendency in the aquifer (five meters change).

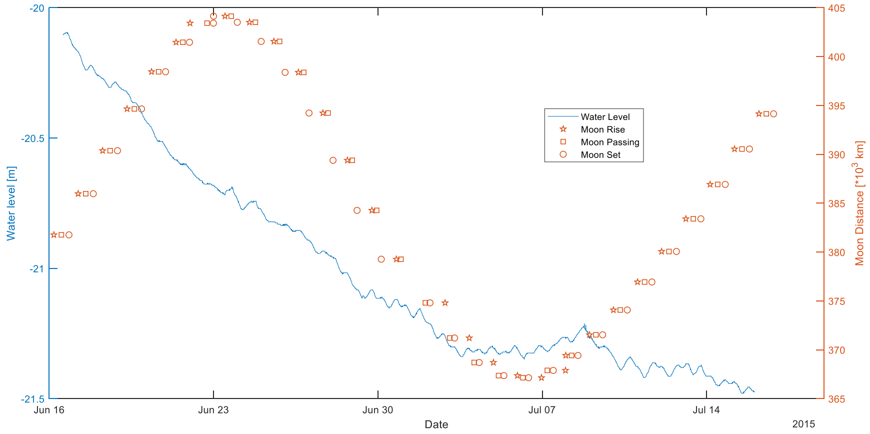
In the periods of 2011 and 2015 with a frequency of 15 minutes, no correlation was found between the water level of the thermal well, the Sun distance, and Moon distance datasets. Therefore, the possibility of the affectation by earthquakes occurrence in 32 km radius influence was further investigated. According to the coincidence of earthquakes with the water level fluctuation, it could be possible to determine a positive impact in the subsurface system. The related events in a radius of 32 km during 2011 and 2015 are described in Table 3.

Table 3. Possible related earthquake events in Zsóry III Thermal well.

Date	Time	Mag.	Lat. North	Lon. East	Depth [km]	Region
27/07/2011	5:42:36	1.7	48°19’90”	21°18’95”	0.4	Hungary
07/09/2011	22:38:20	2.4	47°77’34”	19°67’26”	5.0	Hungary
08/06/2015	6:18:41	1.2	47°92’63”	19°86’61”	0.0	Hungary
11/08/2015	6:33:02	1.6	47°84’60”	20°06’78”	8.4	Hungary
13/08/2015	6:29:55	1.8	47°79’37”	20°03’80”	8.8	Hungary

(Author’s work)

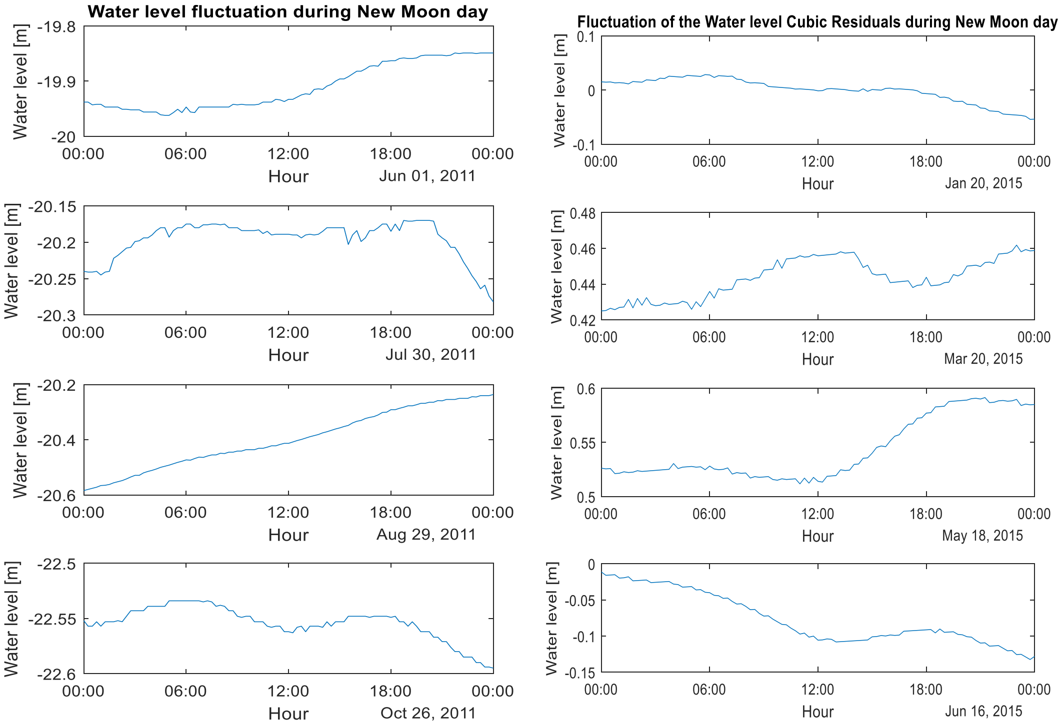
Graph 9 shows the harmonic oscillations presented by the water level in Zsóry III Thermal well, associated with the Moon distance and its rising, passing and setting over the City of Miskolc (point of reference). The lunisolar effect in a lunar and day period is examined in more detailed in the following steps due to the evidence of the cyclic patterns presented by the raw water level dataset during a lunar month period.



Graph 9. Karst water level fluctuations of Zsóry III according to the Moonrise, Moon passing and Moonset during a Lunar Month (Author’s work)

In a complete Moon translation period during 2011 and 2015, the water level shows maximum and minimum inflexion points, but these are not related to the possible tidal effect. In case of the periods from July to August of 2011 and from January to February of 2015, the water level cubic residuals rise the most during the New Moon phase. Other examined periods were found to have a random distribution of the peaks; therefore, external factors are affecting the water level of the Zsóry III, i.e. the operation of nearby production wells.

Graph 10 illustrates the water level response during the specific days of New Moon in 2011 and 2015. The occurrence of the tidal cycles cannot be established, but during New Moon days, the well is shown cyclic oscillation with peaks during 6 and 18 hours similar to Mixed-Semidiurnal tidal cycles. The tidal cycles were altered during New Moon of July of 2011 and March of 2015 due to the possible influence of the near operating wells. Although the occurrence of random fluctuations is strongly related to other external factors (i.e. near thermal production wells located in the surroundings), the well is showing a tidal behaviour in its water level corresponding to the effect of the gravitational forces.



Graph 10. Selected days of New Moon during 2011 and 2015 in Zsóry III Thermal well and water level fluctuation during these periods (Author's work)

4.5. Analysis of MIVÍZ Kertészet Thermal well

In 2011 with a daily and hourly frequency, the highest correlation found (above 80%) is 83.8% between the water level and Sun distance, and 86% between the Sun distance quadratic regression. Even having a high correlation, it cannot be established a direct relation of the Sun distance causing a high decreasing tendency in the aquifer (average of 1 m change). Therefore, this fact is mainly attributed to other major external factors. The water level data for the MIVÍZ Kertészet presented three negative peaks during 2015, which can be attributed to measuring errors; therefore, in further analysis, these periods were not taken into consideration.

In 2011 and 2015 with a frequency of 15 minutes, the possible effect of earthquakes in the subsurface system with the occurrence in 32 km radius influence were further investigated. The coincidence of the sudden changes in the karst water level and the occurrence of earthquakes in a radius of 32 km during 2011 and 2015 are described in Table 4. Some of the specific peaks during 2015 associated with earthquakes might also be related to the errors while the measuring device is recording.

Table 4. Possible related earthquake events to the MIVÍZ Kertészet well water level fluctuation

Date	**Time**	**Mag.**	**Lat. North**	**Lon. East**	**Depth [km]**	**Region**
03/06/2011	7:48:32	1.5	48°33’06”	19°86’54”	2.0	Czech and Slovak republics
06/06/2011	21:55:08	1.4	48°12’77”	20°35’92”	10.0	Czech and Slovak republics
01/04/2015	6:08:30	1.7	47°85’01”	20°02’29”	7.7	Hungary
01/06/2015	6:18:41	1.2	47°92’63”	19°86’61”	0.0	Hungary
08/06/2015	11:50:54	2.0	48°17’95”	21°20’61”	5.8	Hungary
16/07/2015	10:09:52	1.6	48°04’95”	20°88’03”	10.0	Czech And Slovak Republics
19/07/2015	13:36:18	2.3	48°03’53”	20°82’10”	2.7	Czech And Slovak Republics
21/07/2015	6:08:30	1.7	47°85’01”	20°02’29”	7.7	Hungary

(Author’s work)

The raw water level dataset of MIVÍZ Kertészet well during a lunar month period during 2011 and 2015 did not show evidence of the cyclic periodicity related to the lunisolar effect. Although the water level showed maximum peaks, the tidal effect was not apparent. Different periods of New Moon days were analysed during 2011 and 2015 to examine the response of the water level to the Diurnal, Semidiurnal and Mixed Semidiurnal tidal cycles. The small fluctuation and the random peaks did not correspond to any tidal cycles. The well is responding to other external influences rather than being affected by the gravitational effects.

5. Conclusions

Pre-processing requires more exhaustive sound removal methods to determine a definite influence in long-term and medium-term tidal effects. The applied regression methods were found to be not very practical to unmask the long-term and medium-term tidal influence.

Three scenarios were evaluated to determine the influence of the gravitational forces in the Karst aquifer, i.e. *Long-term period:* More than five-months period, *Medium-term period:* Lunar monthly periods (Moon completes its translation around the Earth and spring, and neap tides can be generated) and *short-term period*: 24 hours period where Diurnal, Semidiurnal, and Mixed-semidiurnal tides are expressed.

The karst water level fluctuation does not show high response to tidal effects in a long-term period in relation with the Sun distance, the Moon distance, and the Moon phases, during their translation among their orbits. In this case, the karst water level increasing and the decreasing tendency is strongly related to other natural factors (i.e. recession behaviour in the aquifer in dry periods and its replenishment by precipitation).

In a medium-term period of Moon phases, the response is not clear. In some cases, the karst water level is fluctuating by the occurrence of other factors (i.e. replenishment by precipitation, near pumping wells and operation of the wells). In a short-term period (24 hours -period) was found higher fluctuation related to Mixed Semidiurnal Cycles during New Moon and Full Moon days due to the stronger effect in the karst aquifer enhanced by the Sun-Moon lineament. The 90° angle in space produced partial cancellation, and the tidal effect was easily masked during First Quarter and Last Quarter phases.

The **Monitoring well Nv-17** screened for the open karst water level has the smallest diameter and is closest to the surface. Due to its location has less possibility to affected by other processes. The Monitoring Well showed an apparent response to Mixed Semidiurnal Cycles during 2015, but not clear relation in a medium-term period.

Garadna Spring is considered to be screened into the open karst system, and it is confirmed by the negative response to tidal effects. Although the frequency and resolution of the measurement were optimal to determine the tidal effect, its water level fluctuation is somewhat strongly related to other natural and anthropogenic factors in the three periods examined scenarios.

Tükör Spring showed an apparent response to Mixed Semidiurnal Cycles during 2015. It could be associated with its degree of confinement; thus, it is not exclusively related to the open karst system. Based on international literature, it shows the most reliable relationship with the Thermal Karst System as its behaviour is more similar to confined systems. The water level and lunar phases are highly related, but there is a persistent delay between 5 and 6 days in the water level rising and decreasing.

Zsóry III thermal well is significantly influenced by more significant factors (i.e. water extraction from the near operating wells) in a long-term and medium-term period. In the short-term period, the coincidence between Mixed Semidiurnal Cycles and New Moon Phase were found during 2011 and 2015. Cycles with smaller amplitudes and in some cases with random distribution can be attributed to gravitational forces. The harmonic patterns are enhanced during New moon period. These random harmonic fluctuations could be related with the alteration of the degree of confinement, during wet periods the increase of saturation of the of clay layers near the surface changes the confinement state (i.e., reducing the direct connection between the atmosphere and unsaturated zone and thus the instantaneous pressure equilibration at the water table).

MIVÍZ Kertészet Thermal well is significantly influenced by more significant factors (i.e. operation of the well). The thermal well did not show possible relation with the tidal effect in the three examined scenarios.

Based on the literature, the positive response of the karst water level in the wells to tidal effects is associated with the borehole geometry and the aquifer features. The attribution to gravitational forces effects is also supported by the depth of the aquifer, which confirms the confinement of the thermal well Zsóry III, Tükör Spring and the Monitoring well Nv-17. The effect of the solar radiation has no relation with the Semidiurnal and Mixed diurnal harmonic fluctuations because the cycles are potentialized only during New Moon and Full Moon, coinciding with the significant effect due to the lineament of the Moon with respect the Earth and the Sun.

High peaks periods of the karst fluctuation coincided with the occurrence of the seismic movements in 32 km radius influence on the Garadna Spring, Zsóry III Thermal well and MIVÍZ Kertészet well. The occurrence of sudden changes in tectonic stresses could be further investigated according to the results of earthquakes.

6. Further Investigation

For a complex scenario, chemical reactions and interactions can also be considerate. Therefore, the temperature, the conductivity, and the pH datasets can be latter involved in the hydraulic head fluctuation due to the dissolution and the evolution of the karstic system, parameters also provided by the BKWMS.

Atmospheric pressure changes influence the barometric loading related to the Earth deformation over the area and could still affect the aquifer's matrix. Disentangle the Earth Tidal effect from the barometric loading can be possible by applying frequency analysis and can provide more reliable information about the tidal behaviour.

The rotation of the Earth with the coincidence on the occurrence of a lag time effect on the fluctuations was neglected in the case of this investigation. The distance of the Moon and the Sun also varies in time. Therefore, the Moon position (Moon phases) would do not coincide with the most potent effect. Although it is possible to determine where the three parameters coincide, it requires further correlation and complex scenarios models.

The development of tidal investigations on the karst system can clarify the aquifers' parameters due to the hydromechanical response to gravitational forces and related mechanisms which generate the fluctuations in the well water level.

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