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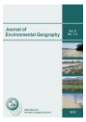

STATISTICAL ANALYSIS OF THE HYDROLOGICAL AND HYDROMETEOROLOGICAL CHARACTERISTICS OF THE UPPER TISZA BASIN

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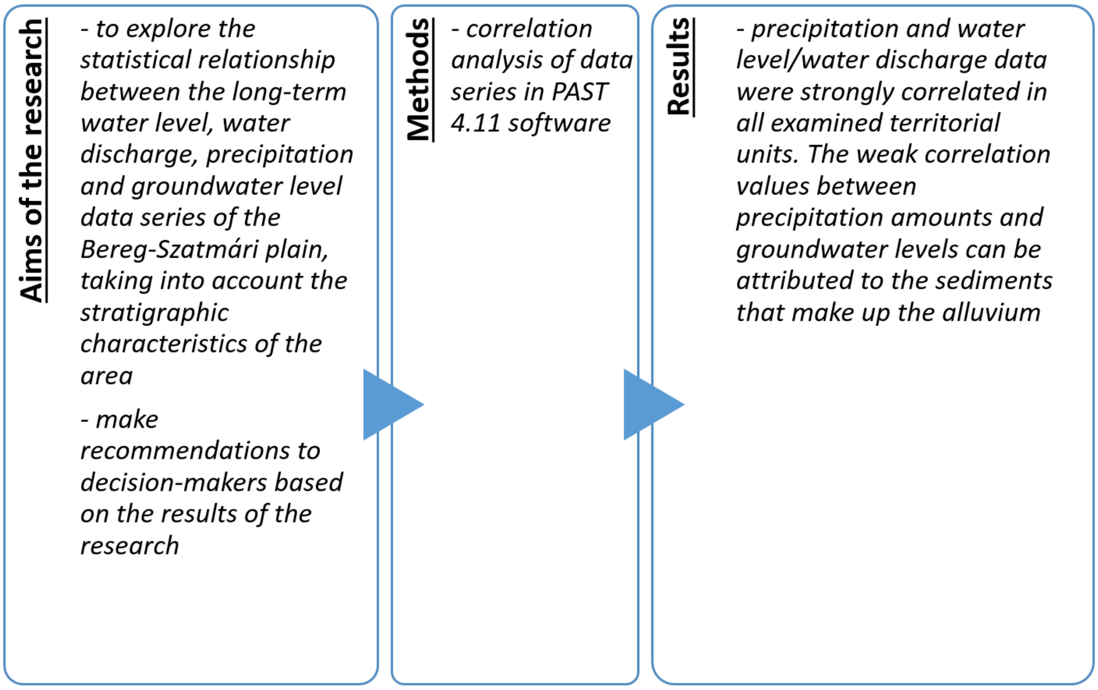
Abstract

Tisza is the largest water base in the eastern part of Szabolcs-Szatmár-Bereg County, in north-eastern Hungary, and its indirect use is mainly associated with agriculture. Our work investigates the hypothesis that decrease in water levels and water discharges of the Upper Tisza in recent decades, together with the incision of the riverbed and the precipitation falling in the area, have an impact on the groundwater level of the Szatmár-Bereg Plain. In our study, data from three water gauges located between the settlements of Tiszaújlak and Vásárosnamény and data from groundwater level monitoring wells (MW) and Hydrometeorological (HMS) stations on the Szatmár-Bereg Plain were compared using statistical methods in Past 4.11 software. The aim of the current study was to identify the strategic steps that need to be taken by the organisations responsible for water management in the Upper Tisza basin in the light of the changes in hydrological, hydrometeorological, and meteorological factors. To ensure that the region has sufficient water supplies for the next decade, appropriate water management and agricultural strategies could be the solution.

Keywords: Upper-Tisza, hydrology, PAST, statistics, groundwater

Graphical Abstract



Aims of the research

- to explore the statistical relationship between the long-term water level, water discharge, precipitation and groundwater level data series of the Bereg-Szatmári plain, taking into account the stratigraphic characteristics of the area

- make recommendations to decision-makers based on the results of the research

Methods

- correlation analysis of data series in PAST 4.11 software

Results

- precipitation and water level/water discharge data were strongly correlated in all examined territorial units. The weak correlation values between precipitation amounts and groundwater levels can be attributed to the sediments that make up the alluvium

INTRODUCTION

The relationship between surface water and groundwater determines whether water drains or feeds the aquifer. The potential difference between the two determines whether surface water receives water from the aquifer or transfers water to the aquifer (Brunner et al., 2009a, 2009b). When the groundwater level is higher than the water level of the river, groundwater will flow into the river, i.e. the river is tapped, creating the base flow during periods without any or with very little rainfall. When the groundwater level is lower than that of the river, the river feeds the groundwater (Grafton and Hussey, 2011; Putarich, 2006; Winter et al., 1998). The interaction can be highly variable in space and time (Grafton and Hussey, 2011), but the interconnected surface and groundwater should be treated as a single water resource (Winter et al. 1998).

Rónai (1961) found in his investigations on the "Kraszna–Szamos–Tisza-köz" that the Tisza and Szamos rivers were accompanied by a deep (5–8 m) groundwater table, while in areas further from the rivers, the groundwater level was higher, 2–3 meters closer to the surface. Since the Tisza has a low water level for most of the year, it has a continuous draining effect on the groundwater base. Along the rivers of the Bereg-Szatmár Plain, the fluctuation of the groundwater level is large, up to 5-6 meters within a year (Rónai, 1961). When the groundwater surveys were conducted along the Tisza, the depth of the groundwater in the Bodrogköz was 6 to 8 meters. (Kuti, 1988). The research carried out in the Danube-Tisza Midland Ridge and Hajdúság showed that groundwater levels rise during or after periods of increased precipitation. (Csordás and Lóki 1989, Négyesi 2006). In recent years, the eastern part of Hungary has been affected by several extreme weather events, including droughts and floods, which have had a significant impact on the Upper Tisza region and local agriculture. In our work, we seek to answer questions about the impact of extremely low water levels associated with the extremely dry summers of recent years on the groundwater resources of the area, and the extent to which direct water recharge in the form of precipitation affects water levels and water discharge in the study area.

Based on these variables, our research also investigates whether small water events (Tímár, 2003), which result in a more pronounced incision of the basin morphology, have an impact on groundwater levels in the Bereg-Szatmári Plain through recurrent processes, as climate change is expected to have an increasing impact on the hydrometeorology of the region. Precipitation, surface water and groundwater systems are strongly influenced by the sediments that build up the alluvial plain. Within these flow regimes, the rate of water flow is determined by the relative position of surface water and groundwater levels, the geometry and position of the riverbed, and the conductivity of the medium material of the aquifer (Woessner, 2000).

STUDY AREA

The catchment area of the upper reaches of the Tisza river from Raho to the mouth of the Szamos river is 13 173 km^2, with the largest volume of water coming from the North-eastern Carpathians in the south and from the Radna Hills and the western parts of the Eastern Carpathians (Gutin, Avas Mountains) in the north.

The two source rivers of the Tisza merge at the village of Rahó. It enters the lowland through the Huszt Gate. Its major left-bank tributaries are the Visó and Iza, which originate from the Radna Hills while the right-bank tributaries include the Gyertyános, Tarac, Talabor and Nagyág. Only two major tributaries join the Tisza between Királyháza and the mouth of the Szamos: the Borsa on the right and the Túr on the left (Fig. 1)

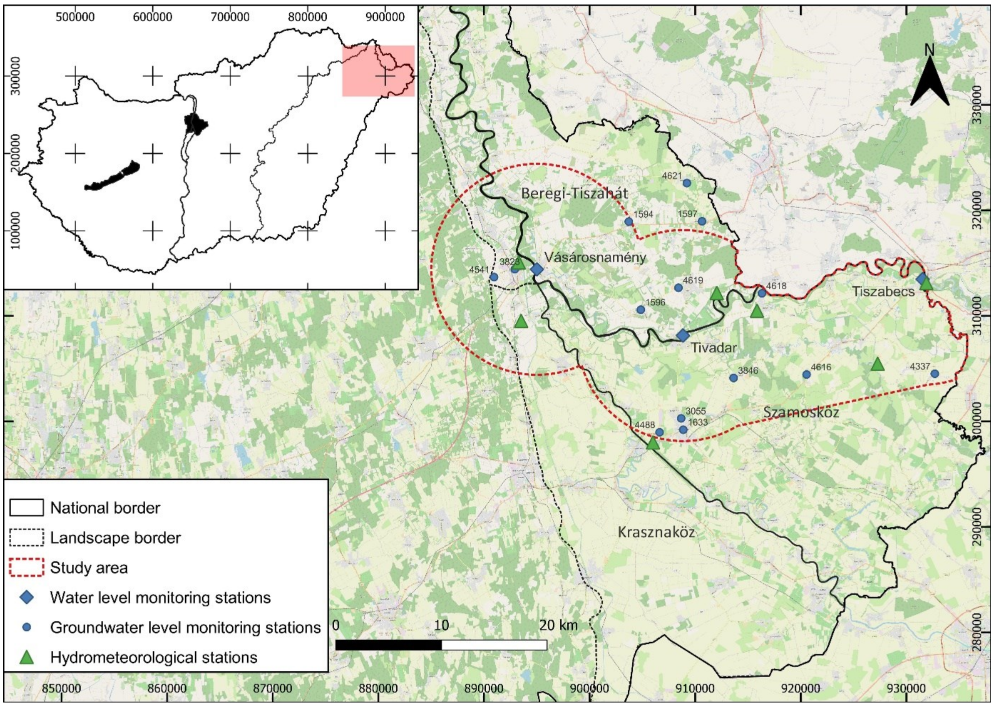


Fig.1 Location of the study area

The study area is an alluvium composed of Holocene sediments and, in some places, Pleistocene gravel, and formed by the dense network of the Tisza and its tributaries. The rivers flowing from the Carpathians have built an alluvium composed mainly of gravel on the eastern edge of the Bereg-Szatmár Plain. Then the slowing and meandering rivers left behind a mainly clayey-silty alluvium, while on the eastern margin of the Nyírség, the alluvial plain of the Krasznaköz was composed of fluvial sediments mixed with blown sand. On these alluvial fans, clayey, silty alluvial soils predominantly developed on the Beregi-Tiszahát and along the western margin of the Krasznaköz, while in the Szamosköz the surface is mainly characterized by brown earth alternating with alluvial soils (Pécsi 1969). The former uniform alluvial fan was fragmented by tectonic movements at the end of the Pleistocene. The outcrops of the Nyírség were fossilized, while the alluvium covering the surface of the depressions was eroded during fluvial tillage. These surfaces were later colonized by a silty-clayey alluvium.

Following river regulations in the 19th and 20th centuries, the supply of these sediments has almost completely ceased in the saved floodplain areas. The sediment transported by the rivers accumulates in the floodplain within the dams during flood flows.

Today, the area is rich in surface waters. Waterways, like River Tisza, have frequently shifted their channel and flooded the area during the Holocene leaving behind a braided channel pattern.

In the Upper Tisza basin, annual discharges show considerable fluctuations, mainly over spring and summer, due to high precipitation totals in May and June, from Mediterranean cyclones in autumn, and from snowmelt in early spring.

In terms of precipitation, the area is in a very favorable position compared with the lower-lying parts of the Plain. This is largely influenced by orographic factors along the eastern border of the country. The average annual precipitation in the Upper Tisza region is 605 mm (Virág et al., 2014), whereas in the catchment area, it may reach up to 700 mm. (Tarnóy, 1992)

The Bereg-Szatmár plain is one of the richest areas of the country in terms of groundwater (VKKI, 2010).

The present-day landscape of the Upper Tisza Basin has been strongly influenced by river regulation works starting in the mid-19th century. With the cutting of overdeveloped meanders and the construction of river embankments, the Tisza and its tributaries were forced into narrow floodplains, which increased the river's gradient and accelerated its incision (Károlyi, 1960).

The Upper Tisza section between the villages of Tiszabecs and Gergelyiugornya divides the Bereg-Szatmári Plain into the Bereg-Tisza Plain and the Szamos Plain, while the Szamos River further divides the landscape as a sharp borderline on the edge of the Nyírség. On the right bank of the Tisza in a north-eastern direction is the Beregi-Tiszahát, while in the south-eastern part is the Szamosköz, surrounded by the Ukranian-Hungarian border and the Krasznaköz. (Csorba, 2021).

METHODS

For the current research, we processed the data sets of three stream gauges, 14 groundwater level measuring wells and 8 hydrometeorological stations along the river section (Table 1). When sorting the data series, we primarily considered the groundwater table depth and hydrometeorological stations that were located within a 10-kilometer radius of a water gauge of the section. Two wells and one hydrometeorological station fell outside these circles. Their data series were separately compared with the water level and water flow data due to their spatial distance in the statistical tests. We processed the raw data provided by the Upper Tisza Water Directorate in MS Excel. We analyzed water level data series from 1901 to 2021 for the Tivadar and Vásárosnamény water gauges, and only from 1924 to 2021 for Tiszabecs.

We analyzed the discharge data for Tiszabecs and Vásárosnamény from 1950, and the discharge at Tivadar from 1956 until 2021. Water level, water flow, groundwater level and precipitation data series were analyzed from 2002 at Tiszabecs, 2006 at Tivadar, and 2004 at Vásárosnamény until 2021.

For the statistical procedures, the open access version 4.11 of PAST (PAleontological STatistics) (Hammer et al., 2001) was used.

Pearson correlation was used for data analysis, which compares two variables (e.g., water yield and precipitation, water level, and groundwater level). The Pearson correlation shows the extent of the linear relationship between the two data sets. The degree of correlation can be quantified using the following formula,

$$r = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{[n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2][n\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2]}}$$

where *n:* number of points; x_i and y_i are pairs of points belonging to each other.

The degree of existing correlation, the Pearson correlation index (r), can take values between -1 and +1. The closer it is to 1 in absolute value, the greater is the linear relationship between the two variables. Its sign shows the direction of the relationship, i.e., positive or negative.

Based on the above classification, the results obtained in the correlation analysis were those with an index of 0.2 or less and those with an index of 0.6 or more.

RESULTS

Analysis of long-term rainfall and groundwater level data series

The averages of annual precipitation at the hydrometeorological stations in our study area show very different trends. In addition, we examined the data from stations located separately around each hydrometeorological station, which allowed the division of precipitation trends into three classes:

- rising and stagnating
- stagnating
- stagnating and decreasing

Table 1 Data from water level monitoring stations (WLS), groundwater monitoring wells (GW), and hydrometeorological stations (HMS)

Types	ID	Station name	Water level zero-point (m a.s.l.)			Start of detection
WLS	1	Tiszabecs	114.340			1924
WLS	2	Tivadar	105.400			1901
WLS	3	Vásárosnamény	101.980			1901
Types	ID	Station name	Terrian height (m a.s.l.)	Rim height (m a.s.l.)	Well depth (cm)	Start of detection
GW	4621	Beregdaróc	110.89	111.30	730.00	2006
GW	1597	Beregsurány	111.80	112.14	920.00	1956
GW	1594	Csaroda	109.44	109.00	650.00	1937
GW	1633	Fehérgyarmat	112.35	112.00	611.00	1937
GW	3055	Fehérgyarmat	110.93	111.00	750.00	1986
GW	4488	Fehérgyarmat	110.64	111.00	750.00	2003
GW	4616	Fülesd	112.62	113.00	710.00	2006
GW	1596	Gulács	110.35	110.00	900.00	1955
GW	4337	Kispalád	117.25	117.00	650.00	2002
GW	3846	Kömörő	112.64	113.00	800.00	1996
GW	4618	Szatmárcseke embankment	111.92	112.00	800.00	2006
GW	4619	Tarpa	110.42	110.00	800.00	2006
GW	3823	Vásárosnamény	111.12	111.00	870.00	1995
GW	4541	Vásárosnamény	112.97	113.00	730.00	2004
Types	ID	Station name	Terrian height (m a.s.l.)			Start of detection
HMS	1	Tiszabecs	117			1950
HMS	2	Sonkád	115			1950
HMS	3	Kispalád	120			2005
HMS	4	Tarpa	114			1950
HMS	5	Szatmárcseke	113			1950
HMS	6	Fehérgyarmat	111			1950
HMS	7	Olcsva	112			1950
HMS	8	Vásárosnamény	114			1950

The stations in Vásárosnamény and Olcsva, based on their long-term series data, were classified into the rising and stagnating categories, while the stations in Tarpa, Szatmárcseke and Fehérgyarmat were classified into the stagnating category, and the stations in Sonkád and Tiszabecs were classified into the stagnating and falling categories. (Fig. 2)

Groundwater levels showed a more consistent decreasing trend for most wells. Of the 14 analyzed time series, eleven wells showed decreasing trends, two were stagnating and one was increasing. (Fig. 3)

Relationships between water level, water yield, groundwater level and precipitation data

Tiszabecs

In the Pearson correlation test, only the mean water levels and discharge of the water gauges at Tiszabecs were correlated above the minimum value of r = 0.6 (the correlation between the data series was r = 0.89). In addition, the data series from both Hydrometeorological stations and the groundwater level monitoring wells in the area were also strongly correlated with the mean water level averages (r = 0.60; 0.62; 0.64). Apart from the mean water averages, the groundwater level data series showed a strong positive relationship with the discharge data series (r = 0.62). The relationship between precipitation and water levels was correlated with the mean high water levels for both precipitation data series. The correlation was almost perfectly positive in the groundwater level well data series, with an r-value of 0.95 (Fig. 4A).

Tivadar

Within a 10 km radius of the Tivadar gauging station, data from 3 hydrometeorological stations and 10 groundwater monitoring wells have been analyzed. Three of the ten studied wells, Beregsurány, Beregdaróc and Fülesd, were outside the circle with a 10 km radius, but these data series were also analyzed as they were the closest to the Tivadar water level monitoring station.

Similar to the data from the stations selected at Tiszabecs, the index value of the correlation between the data collected in the groundwater level monitoring wells showed a very strong positive relationship, with an r-value of $r \geqslant 0.83$, except for the Beregsurány data series. The strength of the relationship between the rainfall data series was similar, with r values of 0.89, 0.92 and 0.94 respectively. The water level and discharge data in the water balance showed a much stronger relationship compared to the Tiszabecs data. The discharge data for both small and large water bodies were very strongly correlated (r = 0.82; 0.85), while the medium water body

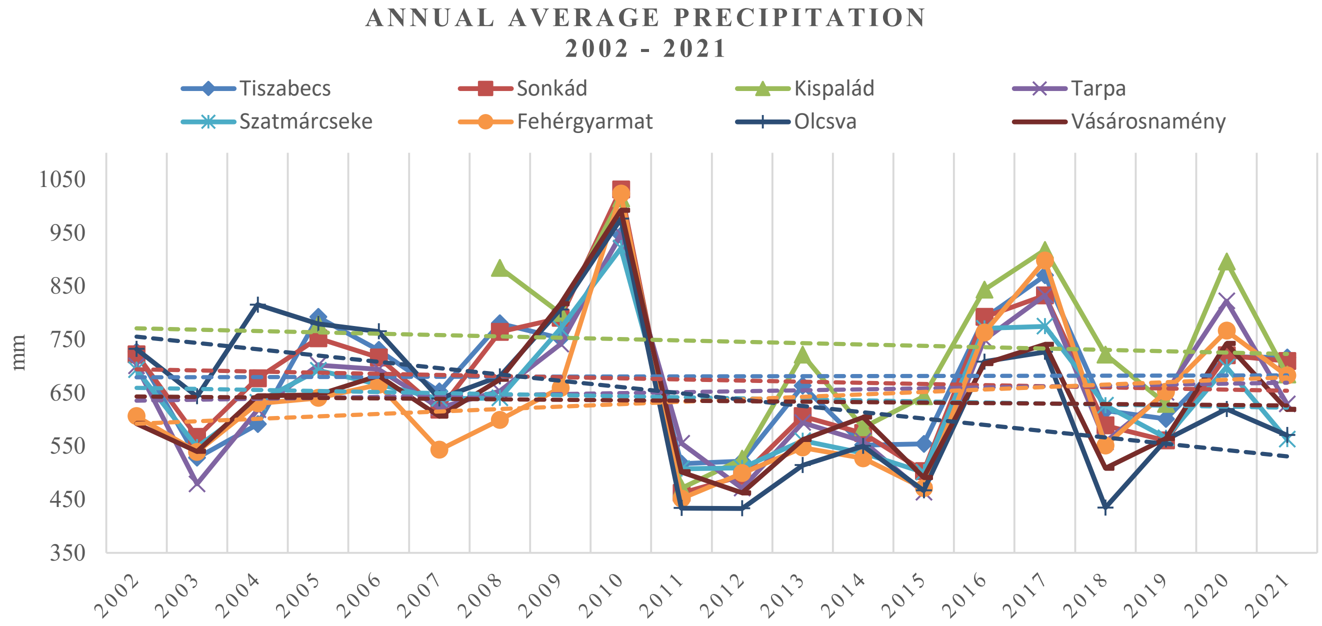


Fig.2 Annual average precipitation

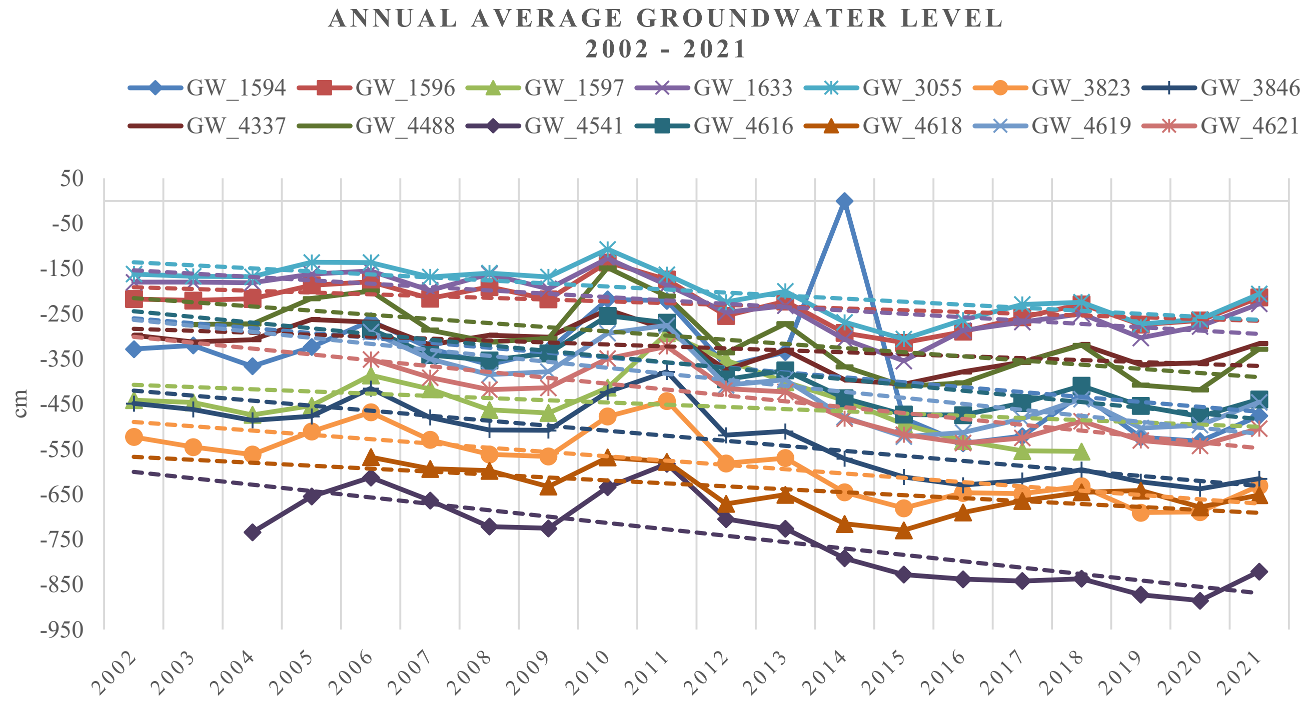


Fig.3 Annual average groundwater level

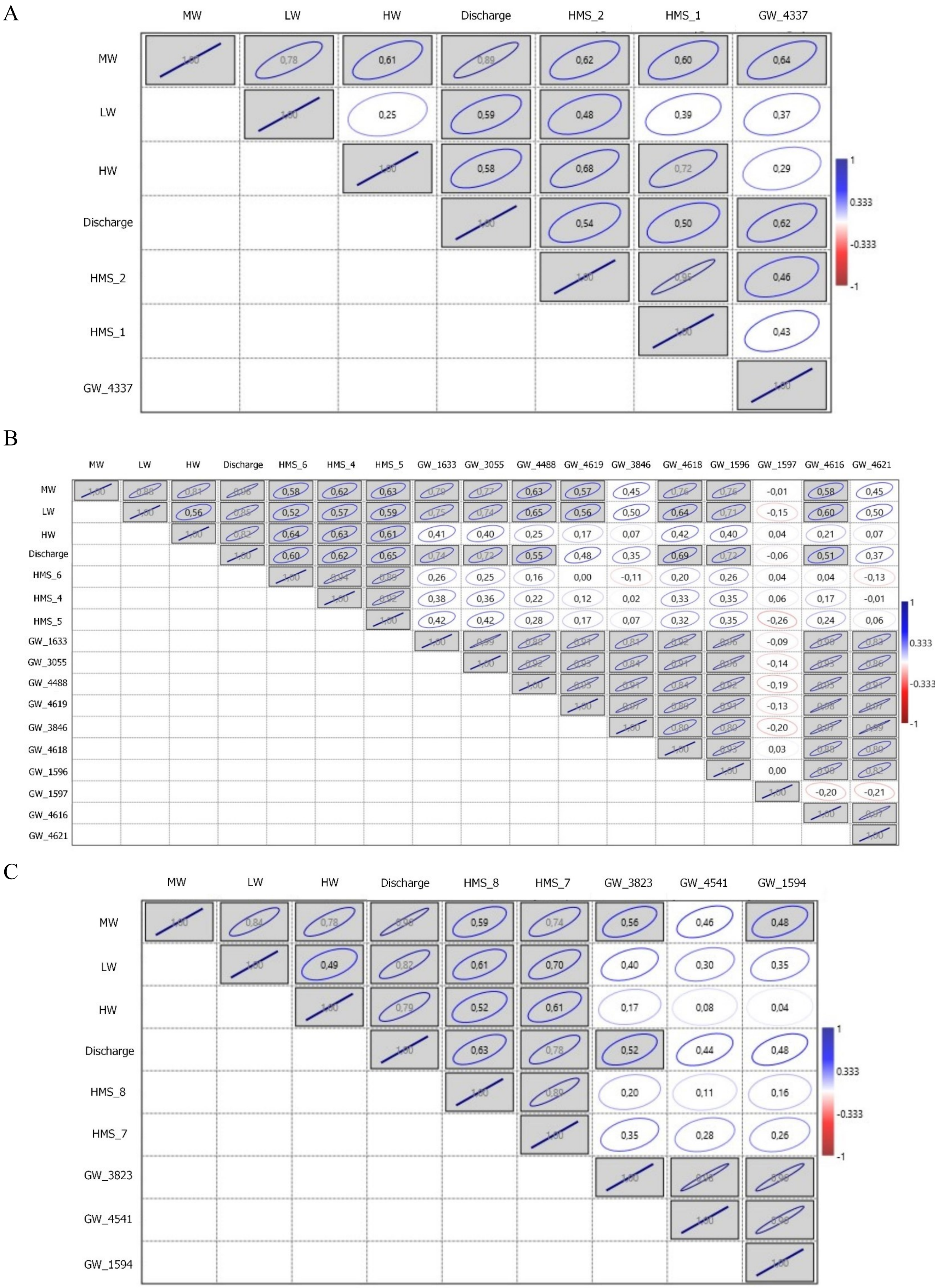
data were almost perfectly matched ($r = 0.96$). A strong positive correlation between the annual rainfall and water levels was obtained only for medium and large water bodies, in these cases, r values ranged between 0.61 and 0.64. The correlation values between water yield and precipitation data were roughly similar, with data from the three stations correlating with annual averages of discharges with $r = 0.60$; 0.62; 0.65.

For the rainfall - groundwater level variable pairs, the correlation did not exceed the value of a stronger than medium relationship in any case, and negative r values were obtained when several variables were examined.

Between groundwater levels and water levels, only the mean and low water levels showed a strong relationship, but this was not detected for all wells. A negative correlation value was obtained for the Beregsurány well (Fig. 4B).

Vásárosnamény

In all three cases, the correlation between the averages of water levels and discharge measured at the cross-section of the Vásárosnamény gauging station was very strong, with the averages of the mean water and discharge data series showing an almost perfect positive correlation



A

	MW	LW	HW	Discharge	HMS_2	HMS_1	GW_4337
MW	1,00	0,78	0,61	0,89	0,62	0,60	0,64
LW		1,00	0,25	0,59	0,48	0,39	0,37
HW			1,00	0,58	0,68	0,72	0,29
Discharge				1,00	0,54	0,50	0,62
HMS_2					1,00	0,95	0,46
HMS_1						1,00	0,43
GW_4337							1,00

B

	MW	LW	HW	Discharge	HMS_6	HMS_4	HMS_5	GW_1633	GW_3055	GW_4488	GW_4619	GW_3846	GW_4618	GW_1596	GW_1597	GW_4616	GW_4621
MW	1,00	0,88	0,81	0,96	0,58	0,62	0,63	0,79	0,77	0,63	0,57	0,45	0,76	0,76	-0,01	0,58	0,45
LW		1,00	0,56	0,85	0,52	0,57	0,59	0,75	0,74	0,65	0,56	0,50	0,64	0,71	-0,15	0,60	0,50
HW			1,00	0,82	0,64	0,63	0,61	0,41	0,40	0,25	0,17	0,07	0,42	0,40	0,04	0,21	0,07
Discharge				1,00	0,60	0,62	0,65	0,74	0,72	0,55	0,48	0,35	0,69	0,72	-0,06	0,51	0,37
HMS_6					1,00	0,94	0,89	0,26	0,25	0,16	0,00	-0,11	0,20	0,26	0,04	0,04	-0,13
HMS_4						1,00	0,92	0,38	0,36	0,22	0,12	0,02	0,33	0,35	0,06	0,17	-0,01
HMS_5							1,00	0,42	0,42	0,28	0,17	0,07	0,32	0,35	-0,26	0,24	0,06
GW_1633								1,00	0,99	0,88	0,91	0,81	0,92	0,96	-0,09	0,90	0,83
GW_3055									1,00	0,92	0,93	0,84	0,91	0,96	-0,14	0,93	0,86
GW_4488										1,00	0,95	0,91	0,84	0,92	-0,19	0,95	0,91
GW_4619											1,00	0,97	0,89	0,91	-0,13	0,98	0,97
GW_3846												1,00	0,80	0,80	-0,20	0,97	0,99
GW_4618													1,00	0,93	0,03	0,88	0,80
GW_1596														1,00	0,00	0,90	0,82
GW_1597															1,00	-0,20	-0,21
GW_4616																1,00	0,97
GW_4621																	1,00

C

	MW	LW	HW	Discharge	HMS_8	HMS_7	GW_3823	GW_4541	GW_1594
MW	1,00	0,84	0,78	0,96	0,59	0,74	0,56	0,46	0,48
LW		1,00	0,49	0,82	0,61	0,70	0,40	0,30	0,35
HW			1,00	0,79	0,52	0,61	0,17	0,08	0,04
Discharge				1,00	0,63	0,78	0,52	0,44	0,48
HMS_8					1,00	0,89	0,20	0,11	0,16
HMS_7						1,00	0,35	0,28	0,26
GW_3823							1,00	0,96	0,96
GW_4541								1,00	0,98
GW_1594									1,00

Fig.4 Correlation coefficients between water level, discharge and rainfall, and groundwater level data series measured at monitoring stations within a 10 km radius of the (A) Tiszabecs / (B) Tivadar / (C) Vásárosnamény water level monitoring station (MW - mean water, LW - low water, HW - high water, HMS - Hydrometeorological station, GW - groundwater level monitoring well)

($r = 0.96$). Of the two precipitation data series the Vásárosnamény station data series correlated only with the low water averages and the discharge data series ($r = 0.61$ and $r = 0.63$), while the precipitation data series measured at the village of Olcsva showed a strong positive correlation with both the water levels and the discharge data series. The correlation index between the data series of the two hydrometeorological stations was $r = 0.89$. The correlation between the data measured in the groundwater level monitoring wells was $r = 0.96$ and $r = 0.99$. The data series from these wells showed only a weak or medium positive correlation with most of the water level averages in the correlation analysis, and for two variables (high water - groundwater level well, discharge - groundwater level well) the correlation between the data series was very weak (Fig. 4C).

DISCUSSION AND CONCLUSIONS

In the correlation analysis, we found that low and bankfull water levels follow an opposite trend, with low water periods being associated with lower water levels and high water events with higher water levels, except in the case of Tiszabecs, where the river bed is more severely incised due to the slope conditions and the quality of the sediment transported by the river. In parallel, monitoring well data also showed a marked decreasing trend, with some wells showing a drawdown of 1–2 m over the past 70 years.

Based on the strength of the relationships between precipitation and groundwater levels in the study area, we conclude that the spatial distribution of the sediments should influence the groundwater table depths. The gravel sediments deposited in the Carpathian foreland allow precipitation to percolate more into the subsurface and this excess can be reflected in river discharge and water levels through groundwater flow.

Based on the results of similar research conducted in alluvial areas, it was also concluded that rainfall directly affects the groundwater level in these areas (Fistikoglu et al., 2016). If we supplement these data with evaporation and water withdrawal data, we can easily make predictions about short-term changes affecting the water base.

Although we did not include evaporation and groundwater extraction for industrial and agricultural purposes as factors in our study, the utilization and recharge of floodplain and protected floodplain areas for water management and open water surfaces is a topic for future research.

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