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Transformation of the groundwater system of Mohács Island as a result of landscape change

Main theses of the Ph.D. dissertation

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Introduction

Mohács (or formerly Margitta) Island is a river island of the Danube, located in the southern part of the Great Hungarian Plain, partly extending to Croatia. River regulations in the 19th century and related inland water drainage work reshaped the landscape pattern and farming systems of Mohács Island. First, second, and third military survey maps and a lesser-known detailed survey, the so-called Danube mappation, were utilized for the reconstruction of the landscape in the 18th and 19th centuries. The scanned map-sheets were digitized and converted into a vector landscape map. These results were compared with a landscape map drawn based on the 1952 topographic map. My studies were supplemented with ethnographic data.

Changes in the landscape pattern on the Mohács Island gradually followed the flood and inland water drainage works (HERVAI A. - LÓCZY D. 2009). Since the river regulation, the Danube riverbed has deepened by almost one and a half meters (TAMÁS E. - KALOCSA B. 2003). Unfortunately, this also had a detrimental effect on the floodplain, as groundwater levels also subsided. Floodplain riparian habitats have increasingly lost contact with the river. In the 1980s, bank production wells were installed on the island, allowing a maximum of 33 000 m^3 of water a day (MAJOR V. - SASS J. 2009). There are a total of 25 production wells and three reserve wells in the three well groups located in the vulnerable geological environment.

In my research, I tried to assess the extent of the hydrographic transformation of the former floodplain of Mohács Island as a result of river regulations. My primary goal was to assess the remaining connection between the island's water system and the Danube River. I examined the landscape change of Mohács Island from the 18th century to the present day. Then I displayed the extent of the changes on maps, tables, and charts.

After surveying the change in the landscape, I examined the connection between the Danube and the groundwater wells on the island. I measured the strength of the connection between the Danube and each monitoring wells with cross-correlation. The rate of pressure propagation and the groundwater table rise caused by the flood was calculated. From the results, I made a map and a diagram of the spreading of the impact. Since the groundwater is affected not only by the Danube but also by the production wells and precipitation, I extended the study to measure the effect of these factors using a linear regression model (hereinafter LM). Maps were generated to show the effect of various independent variables (the Danube, water level of production wells, and daily precipitation data). Using literature data, I made an uncovered geological map and a cross-section to show the stratification of the alluvium. I compared the geological map with the maps I interpolated.

I was looking for answers to the following questions:

1) In what areas and to what extent have the riparian and wetland habitats changed since the beginning of river regulation?
2) How is the naturalness of forests changing nowadays?
3) In which areas and to what extent does the Danube still affect the island's alluvial water system?
4) To what extent has a connection remained between the Danube and the Nagybaracskai-Danube and Lake Riha?
5) What are the characteristic speed and spatial distribution of the Danube flood waves in the alluvium of the island?
6) To what extent do the floods of the Danube increase the groundwater system of the island?
7) What additional hydrographic factors (precipitation, production wells) still affect the alluvial water system?
8) What geological factors affect the alluvial water system of Mohács Island?

Materials and Methods

Survey of landscape change

I attempted to quantify the extent of the change at the beginning of my research. The studies were performed using GIS tools (HERVAI, A. et al. 2020b). The GIS software that I used was ArcGIS 10.4.1. The land use data from the maps (the first, second, third military maps, the Danube mapping, the 1952 and the 1987 topographic maps, finally the Corine Land Cover 2012 spatial database) were selected first.

I downloaded the military maps from mapire.eu/hu, the Danube map from maps.hungaricana.hu. The topographic maps I used as a reference were prepared in 1952 and 1987, respectively, and the Corine Land Cover (CLC) spatial database in 2012. The maps were rotated and dragged with the tools of the Georeferencing menu to fit properly on the base maps. The collected spatial databases and maps were transformed into the same (EOV) coordinate system for comparability. First, I had to transform the maps into EOV (HD 72 Unified national projection system) coordinate system for their comparability. After that for raster maps that were already in proper position Define Projection was used to transform to EOV coordinate system. Once the maps were well resized and their appropriate coordinate system was created, the type of land cover had to be identified to observe changes. Thus, raster maps had to be converted into vector maps. Once all the individual areas were marked, their exact areas were determined to be compared with Calculate Geometry function of ArcGIS. The Select by Attribute operation was used to sort the different land cover data. The attribute tables of the different groups were exported to MS Excel. I summarized the total size of the different land cover areas for the different years and made a chart from them.

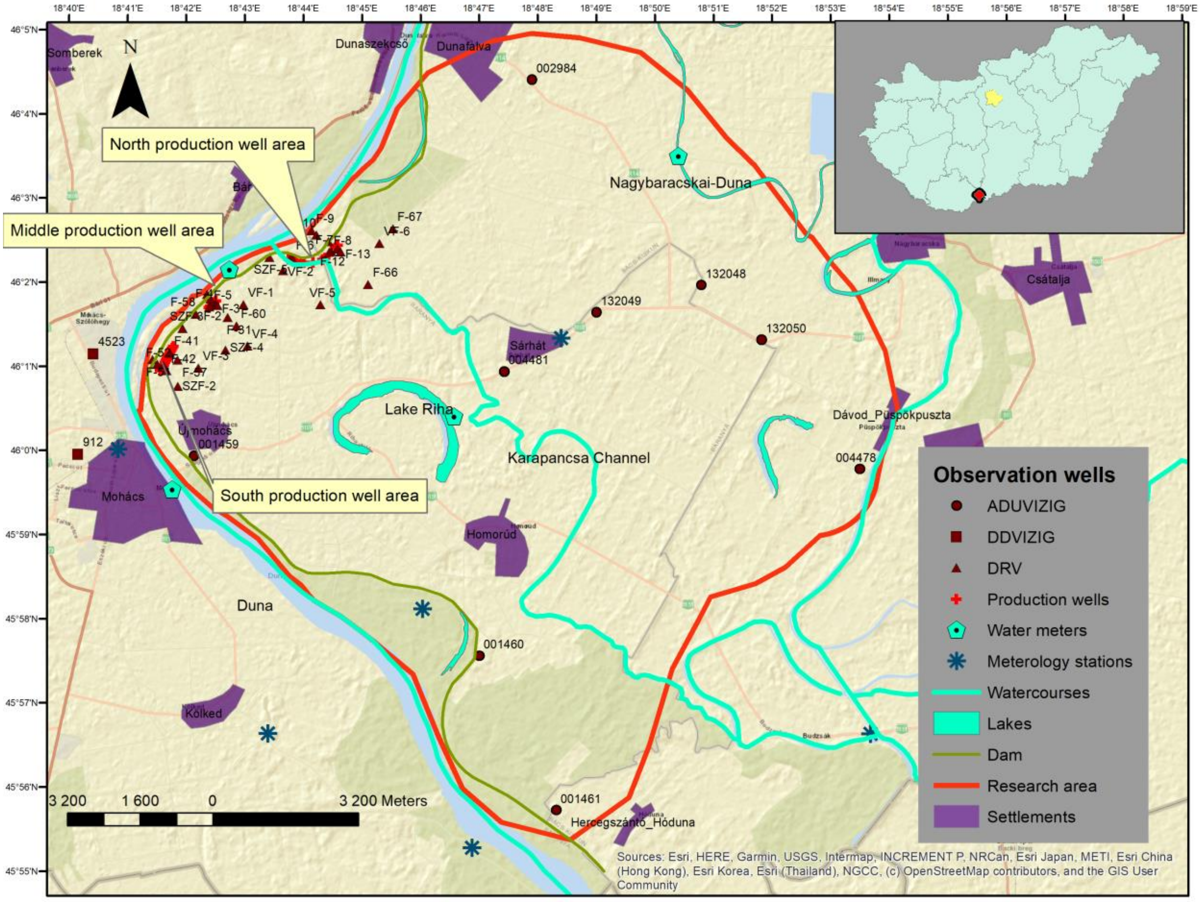
I have reviewed map descriptions for Danube mapping and military maps. The descriptions of Danube mapping were copied from the application received from the Department of Ethnography of the University of Pécs. I used JANKÓ A.'s study (2007) for information on military survey maps and DÓKA K.'s work (2006) to interpret the Danube map.

The forest patches database available from Mohács Island was provided by the Forestry Directorate of the Baranya County Government Agency. The vector spatial forest member data table also included an additional tree species row table detailing the percentage of trees in different forest patches that accounted for the given polygons. Based on the descriptions of literature references (KIRÁLY G. et al. 2011, KEVEY B. et al. 2011 and KOVÁCS GY. - DEME T. 2008), I classified the tree species into natural, alien, and aggressive types. Then with the help of ArcGIS 10.4.1. software I reclassified the forest details into four classes using the Reclassify operation. I created "aggressive", "alien", "slightly aggressive" and "natural" classes. I renamed the class called "landscape alien2" (KOVÁCS GY. - DEME T. 2008) to “slightly aggressive”. Then I generated a table and a map from the result. I placed the map made with Digiterra software (KOVÁCS GY. - DEME T. 2008) and the map I made together in a common figure so that they could be compared.

Investigation of the groundwater system of Mohács Island

Investigation of the connection of groundwater with the Danube

I examined the effect of larger flood waves on the groundwater level in 47 groundwater wells (Figure 1). I received data for the period from January 1996 to December 2018 from several organizations. Data on the water level of the Danube and three groundwater wells on the right bank were obtained from DDVIZIG (South Transdanubia Water Directorate), on the left bank (Mohács Island) from ADUVIZIG (Lower Danube Valley Water Directorate), and DRV (Transdanubian Regional Waterworks). Precipitation data were obtained from the National Meteorological Service (OMSz), DDVIZIG, and ADUVIZIG.



1. Figure – The research area (HERVAI A. et al. 2020a)

I had about 270,000 daily groundwater level and Danube water level data, 115,000 daily production well water level data, and 50,000 daily rainfall data. The obtained time series data were filled into database tables (HERVAI A. et al. 2017) using the software ArcGIS 10.4.1. I decided to build my application (C # .net) because I examined 31 flood events at all 49 groundwater piezometers at the same time.

When comparing floods, the selected periods were 40-day time intervals, the middle of each was always the peak of the given flood wave. I set a 5% significance threshold for the acceptability of the results. I also converted the water level data into altitude data above sea level.

The lag-time and the strength of the relationship between groundwater levels and the Danube flood waves were investigated with a cross-correlation function (CCF) of the R statistical software package. I intended to find the proper lagtime and the largest relationship between the Danube and groundwater wells. Therefore I always compared the entire flood wave characteristics at the Danube water level and the given groundwater wells (HERVAI A. et al. 2019). My code called the Cross Correlation Function (CCF) function of the R software in the background with the selected time interval. From the return value of the function, the largest correlation value was selected and the corresponding lagtime (HERVAI A. et al. 2019).

I plotted these values on both a chart and a map. Using the ArcGIS API, I constructed the GIS model and calculated the distance between groundwater wells and the Danube (HERVAI A. et al. 2017).

Linear model tests

For the linear regression model, the five largest flood events of the Danube were selected. The threshold water level was 700 cm to classify an event as a major flood wave (HERVAI A. et al. 2020a). The selected floods had independent, well-prominent peaks. The length of time was chosen according to the hydrograph characteristics of the Danube and it covered complete flood events in all of the five selected cases.

Using the linear regression model function (LM) of the R software package, I calculated the regression between groundwater well water level (m a.s.l.) as a dependent variable, respectively Danube water level (m a.s.l.), production well water level (m a.s.l.), and precipitation value (m) as independent variables.

The dependent variable of the linear regression model was always the time series of the given observation well. However, two independent variables were included in the final model. The first independent variable was a combination of the Danube time series and the averaged time series of nearby production wells. The production wells' water level values are not independent of the Danube water level values. Therefore, they must not be inserted separately into the model. It had also to be taken into account that when there was no production in a given production well, it practically functioned as an observation well. Thus, if I had inserted them one by one into the LM, it would have ruined the explanation. For this reason, I combined the water level values of the Danube with the water level values of the production well with a multistage mathematical sequence of operations (HERVAI A. et al. 2020a).

$$S_r = \frac{S_{max} - S_{min}}{D_{max} - D_{min}} \quad (1)$$

In the first step, I tried to find the strongest effect of the Danube. I shifted and transformed the water level curve of the Danube in time (Equations 1, 2) to get the real impact of the Danube on groundwater.

$$D_{x\ lag} = (D_{x-\ lag}) \quad (2)$$

Then I called the LM function with this transformed Danube time series (D_t, Equation 3). As a result, I obtained the optimal coefficient of determination of the Danube. Then I selected the production wells close to the examined observation well, and I also looked for the optimal coefficient of determination and the optimal delay times for them.

$$D_t = (D_{x\ lag} - D_{max}) * S_r + S_{max} \quad (3)$$

Thus, only operating production wells were included in the statistical study, and non-significant wells were excluded from the final equation. After a few iterations, the lagtime with the strongest relationship was usually found (Pavg, Equation 4).

$$P_{avg} = \frac{P_{x1\ lag1} + P_{x2\ lag2} + \cdots + P_{xn\ lagn}}{\mathrm{n}} \quad (4)$$

The effect of production wells (Pavg, Equation 4) time series, as well as the transformed Danube time series (Davg, Equation 5), was averaged again. Finally, I re-inserted the combined time series into the LM (via the software and the R API). With this method, the effect of production wells was superimposed on the influence of Danube. In the next phase, precipitation was added to the LM, which was the second independent variable in this sense (HERVAI A. et al. 2020a). However, the vector of precipitation time series was only included in very few monitoring wells and had little effect on the final LMs.

$$D_{avg} = \frac{D_t + P_{avg}}{2} \quad (5)$$

I also calculated the optimal delay time of precipitation. As in the case of cross-correlation studies, charts and interpolated maps were generated from the aggregated data. Kriging interpolated maps (HERVAI A. et al. 2017) were generated to present strengths of Danube impact, production well impacts, and inferred geological impact by ArcGIS software.

Geological and geomorphological researches

Geological data, a topographic model, and for a significant part of the bank area, soil drilling data were available for study. Geological maps (DRASKOVITS P. - JÓSA E. 1981, DRASKOVITS P. - JÓSA E. 1986) were taken from the screen and inserted into ArcGIS 10.4.1 (HERVAI A. et al. 2017). Using the Georeferencing and Advanced Editing menu tools, I fitted the map to the appropriate position using the rubber sheet stretching method and aligned the EOV coordinate system to it using the Define Projection operation. The base map of the alignment was the raster ESRI World Street Map and vector maps of surface water bodies. I created a line type vector feature class from the contour lines (HERVAI A. et al. 2020a), which contained the bottom of the alluvia, the Pannonian contour lines. In cases where the value of the deterministic coefficient was too low or too high relative to their distance from the Danube, I tried to find a geological or geomorphological explanation.

Presentation and evaluation of results

Territorial change of riverine and wetland habitats on Mohács Island since the beginning of river regulation

In the first part of my research, I summarized the transformations of the landscape pattern of Mohács Island as a result of river regulations. Based on my results, it can be stated that Mohács Island was fully exposed to floods and the surface reshape the activity of the river before the regulation of the Danube (HERVAI A. et al. 2020b). Regarding the process of landscape transformation, I found that in the first stage of the regulation, curves were cut, dams were built and partly canals were created (HERVAI A. - LÓCZY D. 2009). As a result of the regulations, the proportion of flooded areas decreased from 90% to 50% by 1825 (HERVAI A. - LÓCZY D. 2009). Later, the island became swampy by the end of the 19th century. From the 20th century onwards, drainage played a primary role (second stage) in shaping the landscape. By the middle of the twentieth century, the proportion of flooded areas had further decreased (HERVAI A. et al. 2020b) to 10% (real floodplains within embankments). Since 1956, the surface has not been flooded, beyond the embankments, but under the surface, groundwater transmits pressure waves of floods.

Based on the evaluation of the first military survey map made in the 1780s, at the end of the 18th century, most of the island, 92%, was dominated by natural habitats (forests, swamps) (HERVAI A. et al. 2020b). Between 1823 and 1845, the Danube was surveyed, for the mapping, which is the second map I digitized. I pointed out that the proportion of wetlands decreased from 33 to 26%, but their proportion was still significant.

The prolonged second military survey reached the island of Mohács in 1858 when the Danube branch of Baracska was still a living, natural watercourse. My results suggest that scrub areas accounted for a quarter of the island at that time (HERVAI A. et al. 2020b), which appeared around the farmsteds (gardesn with winter accomodations). Despite the transformations, the proportion of wetlands was still significant (from 26% to 25%), and the proportion of forests changed little (slightly increased from 44% to 45%).

The third military survey reached the island in 1884. The „fok", oxbow, and lake system around Lake Földvár still existed. The eastern half of the island was occupied by marshes, swamps, and grove forests (HERVAI A. et al. 2020b). The proportion of wetlands increased from an initial 25–30% to 40% by the end of the 19th century (Table 1). The island was getting swampy from the accumulated waters (BUZETZKY GY. 2002). Further water management regimes have therefore focused on draining inland waters rather than building new cutoffs and dams.

In 1904, the pumping station in Karapancsa was built, which was already designed for the drainage of inland water. The drainage of inland water was completed between 1905 and 1910 (HERVAI A. - LÓCZY D. 2009). Almost 1,800 ha of the 20,000-hectare island were pumped (BUZETZKY GY. 2002).

Consequently, and as a result of the work, the landscape pattern of the island changed radically, as can be seen from the 1952 topographic map. According to my GIS studies (Table 1, Figure 5, and Figure 6), by the 1950s, agricultural land had grown from the previous 3% to 71% (HERVAI A. et al. 2020b). By the beginning of the 21st century, the proportion of arable land had changed by a few percent, but their proportion remained at around 70%.

1. table – Distribution of different surface shapes on the examined maps (HERVAI A. et al. 2020b)

Cseréld pontokra a vesszőket!

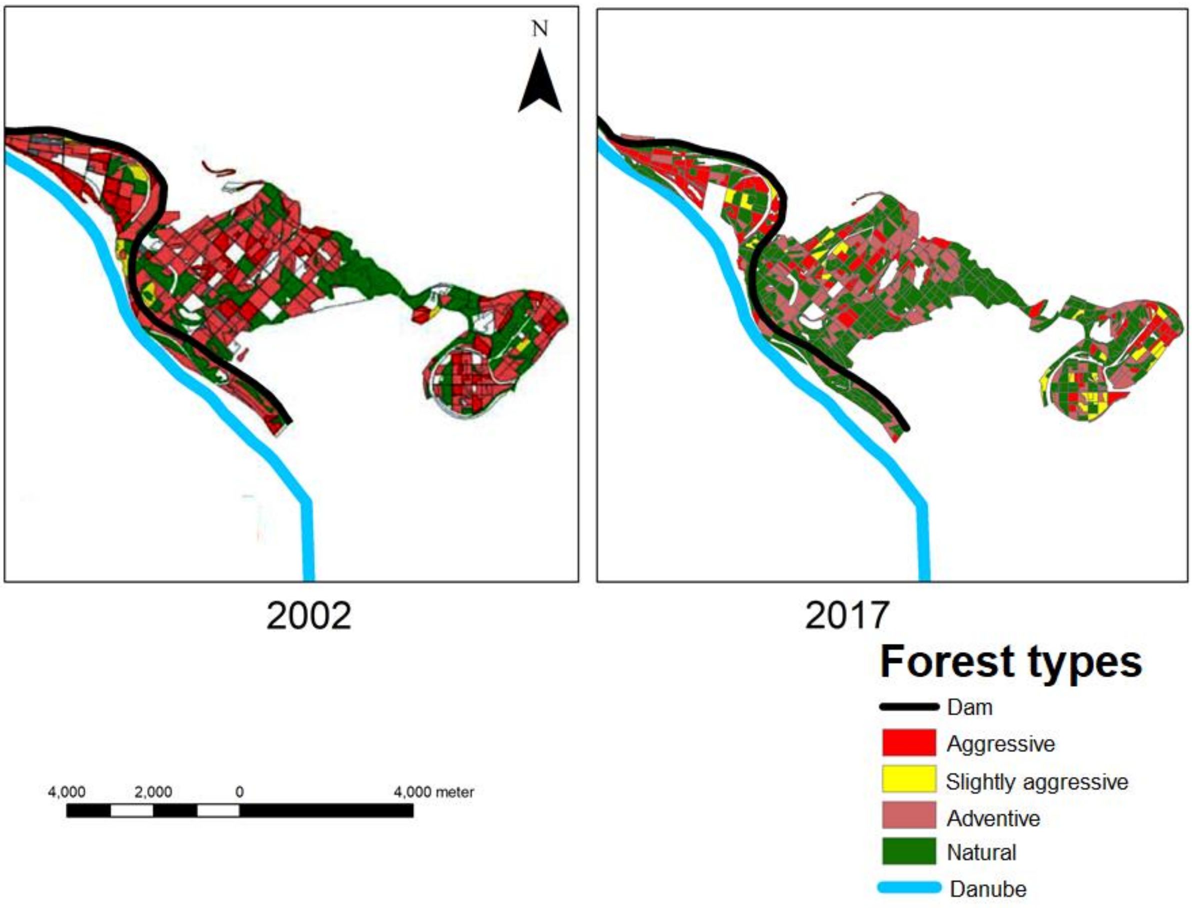
	Forests	Bog forests	Swamps	Meadows and scrums	Croplands	Waterbodies	Settlements
1784	58,93%	0,00%	32,73%	5,45%	0,00%	2,72%	0,13%
1825	44,07%	14,46%	11,71%	22,25%	0,00%	2,74%	4,71%
1858	45,42%	8,56%	16,53%	21,41%	1,63%	2,48%	3,96%
1884	19,59%	23,88%	15,71%	26,32%	3,03%	8,95%	2,77%
1952	19,74%	0,00%	3,33%	2,09%	71,09%	1,68%	1,58%
1987	23,56%	0,00%	2,07%	2,25%	65,56%	2,44%	4,12%

2012	16,82%	0,00%	1,61%	3,45%	71,80%	1,54%	4,78%

It can also be seen that the proportion of forests has decreased from almost 60% to less than 20% of the original (HERVAI A. et al. 2020b). Wetlands almost disappeared by the middle of the 20th century (now 1-2%). Based on GIS studies, it can be stated that the almost completely natural floodplain landscape around 1800 (BIRÓ M. 2008) was taken over by a man in 150 years.

The change of the forests of Mohács Island according to their naturalness in the 21st century

KOVÁCS GY. and DEME T. (2008) examined the forests of the Béda-Karapancsa Region in a ten-year study looking for old oak-ash-elm hardwood groves (Fraxino pannonicae-Ulmetum). According to their studies, the area of habitats is not covered even one-tenth of the total. In many cases, the place was occupied by monocultures of alien tree species. Floodplain oak-ash-elm hardwood groves have been found to occur in only half of their potential habitat. They drew a map (Figure 2), the equivalent of which I also made as described in the methodology, and compared it with their map.



2. figure – Changes in the naturalness of forest areas in the Homorúdi forest in the 21st century (edited: HERVAI A.)

To present the change on a map, I chose the largest contiguous landscape element or ecotope, the Homorúdi, and Karapancsa forests. My study did not cover the forests of Béda, nevertheless, their structure is very similar to the forests of Karapancsa. Comparing the two periods (Figure 2 and Table 2), it can be seen that the proportion of natural forests has increased from 32% to 52%, thanks to forest protection and WWF and DDNPI activities. As the proportion of forest members made up of aggressive tree species decreased (from 21% to 18%), the proportion of forest members made up of slightly aggressive tree species increased.

Cseréld pontokra

2. table – Changes in the group proportions of Béda-Karapancsai forest members

	Natural	Adventive	Slightly aggressive	Aggressive
2002	32,71%	44,44%	1,35%	21,50%
2017	52,60%	23,89%	4,76%	18,75%

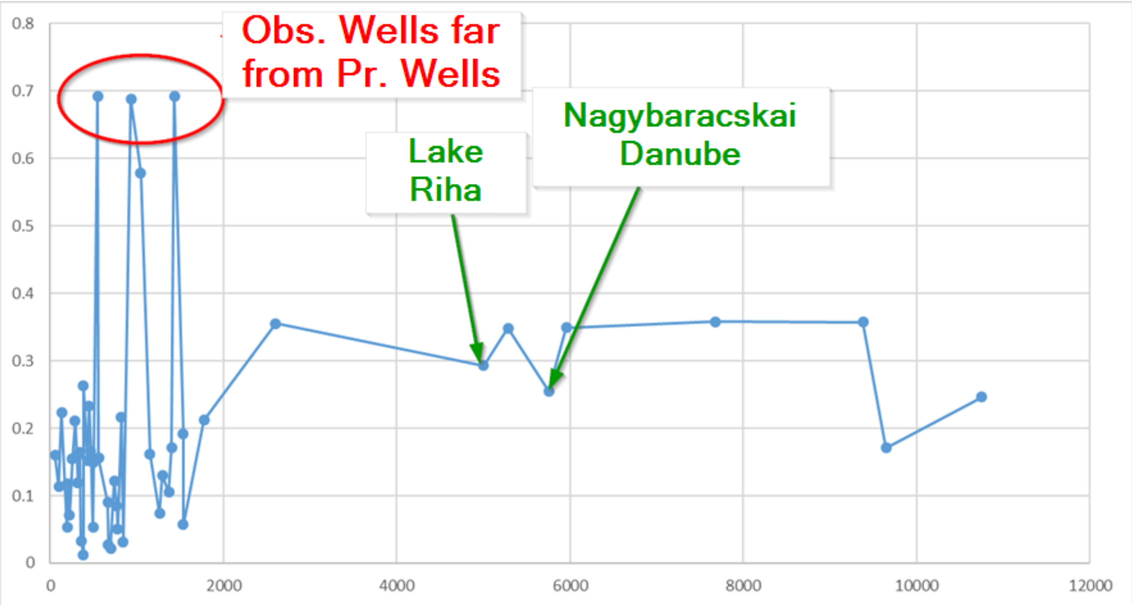
The impact of the Danube on the alluvial water system of Mohács Island

Correlation of complete time series

I compared the time series of the groundwater well with the preceding days' time series of Danube. With the support of my application, it was possible to measure these relationships between the time series of the Danube and groundwater wells for the entire period by calling the CCF (Cross-correlation function) function of the R API (HERVAI A. et al. 2019). On Mohács Island, I was able to obtain time series of different lengths for 47 groundwater wells.

When comparing the whole timeseries, the cross-correlations have a very weak relationship even at the maximum correlation lagtime even near the Danube (Figure 3). The highest correlation values are, naturally, relatively close to the bank (r-value 0.7), but strangely not directly next to the bank.

These outstanding values suddenly jump to an almost explanatory correlation value of 0.7, compared to an average near-bank correlation value of 0.1 to 0.2. Examining the mentioned wells (Fig. 3), we can see that they are located far from the production wells. After two kilometers, the strength of the connection nowhere exceeds the average correlation value of 0.4, but these values are still higher than those I measured near the bank for the entire period.



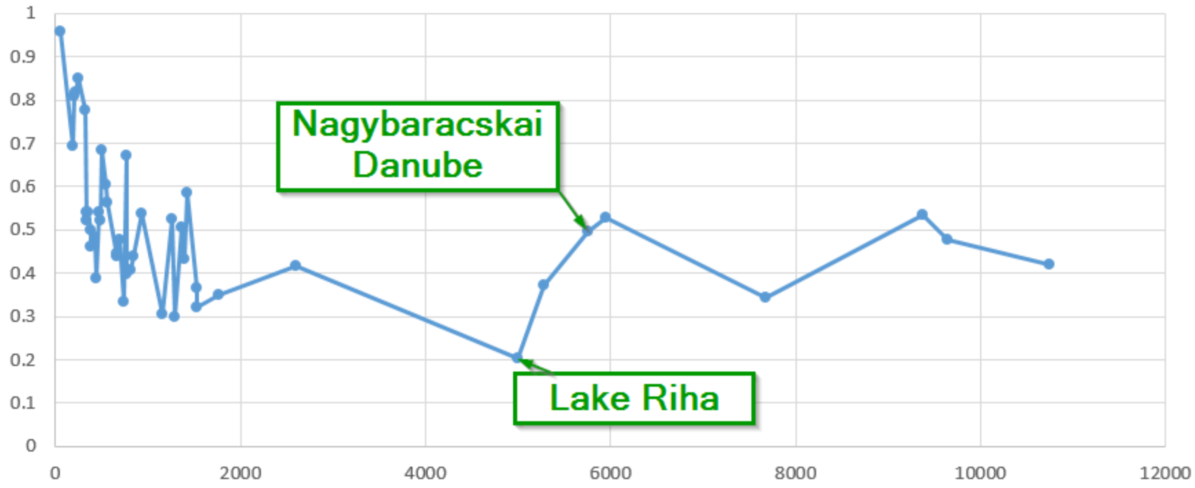
3. Figure – Strength of cross-correlations (r) between the Danube and groundwater wells moving away from the Danube (m) for complete time series (edited: HERVAI A.)

For the entire period, as the result shows (Figure 3), there is a low connection between the Danube and the groundwater wells. However, in my research, I intended to assess the relationship between the floods of the Danube, thus I examined the entire period only for the sake of comparability. Based on the results presented for the whole period, it is quite strange that the connection of the wells close to the bank with the Danube is generally weaker than that of the wells in a longer distance.

The average correlation of flood events

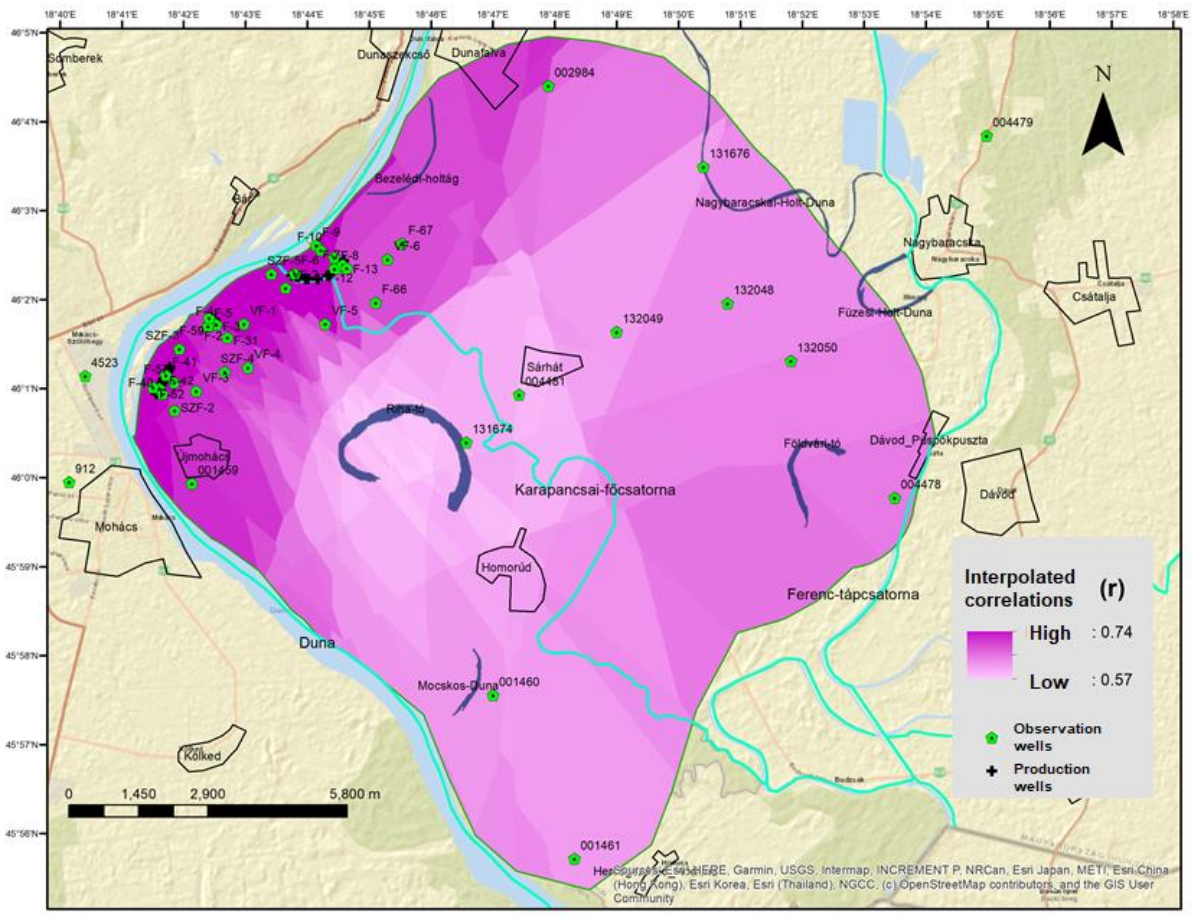
To protect the fragmented landscape elements, micro-topography, and soil that still preserve the surface of the former floodplain, it is necessary to map the impact of flood events. From the previous results, it can be seen that the correlation between the Danube and the groundwater wells is relatively low throughout the year. From 31 flood events, I tried to deduce how long and to what extent the vegetation, at the remaining habitats on the island, receives water from the Danube throughout the aquifer and the soil. For all floods, I collected all the characteristic correlation values (VEKERDY Z. - MEIJERINK, A.M.J. 1998), and the associated delay and the groundwater uplift values for each groundwater well using my software (HERVAI A. et al. 2019).

The cross-correlation relationship with the Danube (Figure 4) proved to be strong (with r values between 0.7 and 0.9) only at a 2-300 m distance from the bank. Thereafter, this initial strong relationship, fluctuating within the first two kilometers, decreases to a correlation value of around 0.6. Despite that, this value presents only a weak-to-medium relationship, still much stronger than looking at the entire period. The strength of the relationship, to such an extent, is maintained almost throughout the island. However, there is an upward and a downward outlier.



4. Figure – Strength of cross-correlations (r) between the Danube and groundwater wells moving away from the Danube (m) in flood periods (HERVAI A. et al. 2019)

I generated maps from the correlation values by kriging interpolation (HERVAI A. et al. 2017) (Figure 5). Values weaken away from the river, but not completely uniformly. Along the bank, until the village of Bár, a stronger connection can be observed, relatively uniformly. A significant connection can only be seen at the curve from Bár to Mohács, even though there are plenty of production wells there (HERVAI A. et al. 2019). After the curve, this value decreases significantly. We can also find a depressed area in the correlation map behind the middle production wells and around Lake Riha.

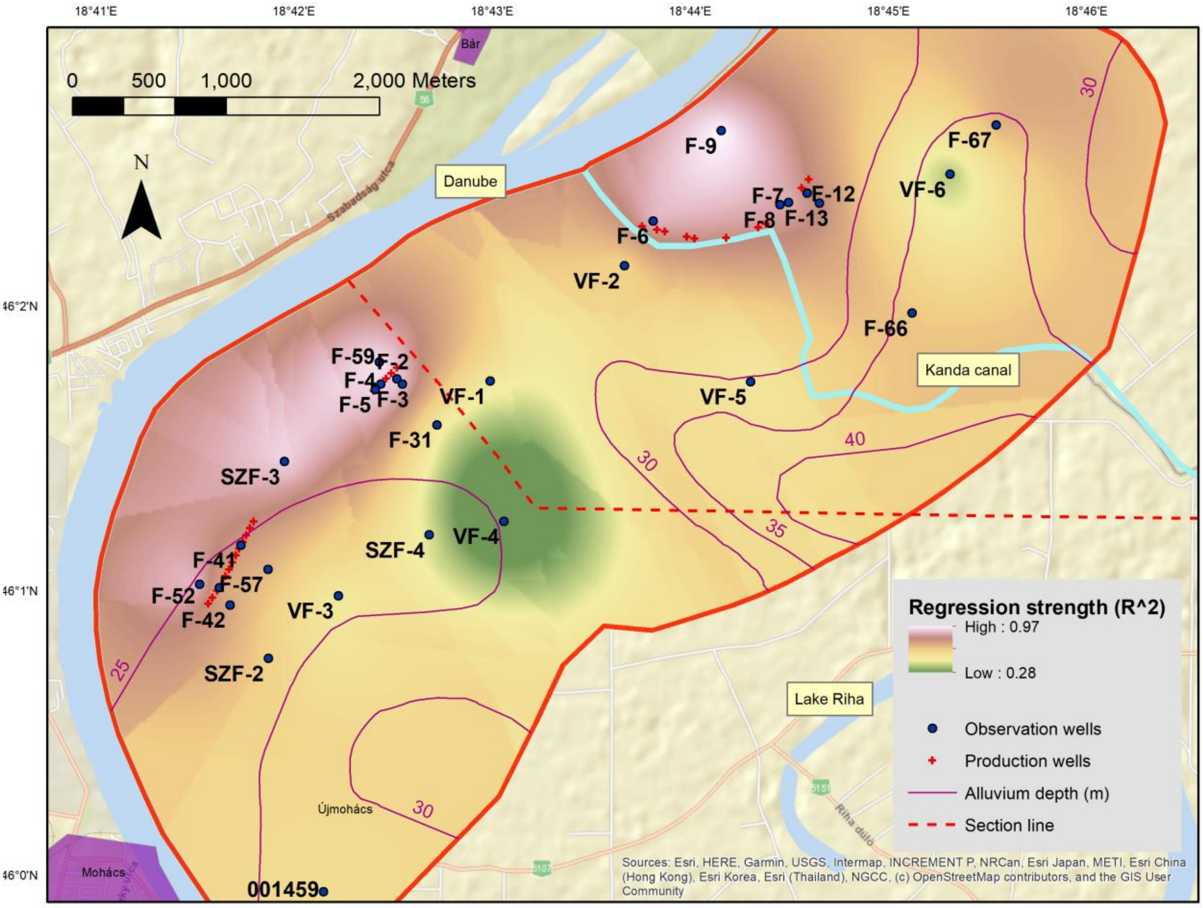


5. Figure – Strength (r) of correlations with the Danube based on interpolated values of groundwater wells (HERVAI A. et al. 2019)

Linear regression model studies to estimate the impact of the Danube, production wells, and precipitation on groundwater

SGW levels are influenced not only by the Danube but also by production wells (MAJOR V. - SASS J. 2009) and precipitation (RAINS, M.C. - MOUNT, J.F. 2002). The water levels of the Danube and production wells were inserted into the LM (HERVAI A. et al. 2020a) in a combined manner as described in Methods. I examined only wells close to the bank, and only for the year 2007 and the period from 2009 to 2018. It was only during that period that I had such an amount of water level and precipitation time series that I could perform the LM tests with sufficient accuracy. Kriging interpolation was made from the data measured and summarized on the observation well point network (HERVAI A. et al. 2017). It was only in this near-bank area that I had enough points for a network of gravity, a geological map, and drilling log data where, after interpolating the groundwater data, I could conclude geological determination.

Based on the selected five flood events, it can be stated that the coefficient of determination, lagtime, and the raising effect of the Danube water level show mainly the effect of the Danube flood wave on groundwater pressure waves (HERVAI A. et al. 2020a). The result of the LM calculation more accurately describes the effect of the Danube, at least in this near-bank area, than the correlation. The LM calculation was more precise also due to the denser point network, therefore, the regional differences in the effect of the Danube could be better observed on the maps prepared for the LM.



6. Figure – Interpolated map of the effect of Danube floods with regression value (R2) (HERVAI A. et al. 2020a)

Based on the kriging interpolated average deterministic coefficient map it is proved that close to the bank (between the first 500 meters) the connection between the Danube and the groundwater is very strong during large flood events. Close to the area of the southern production wells regression values are lower than for the northern ones. The lowest regression is measured on the southernmost section of the bank where the K001459 well is situated. Moving away from the bank, the effect of the Danube decreases everywhere, but not uniformly. The lowest effect is behind the middle production well series, just where the thickness of the confining layer is shown zero (Figure 6).

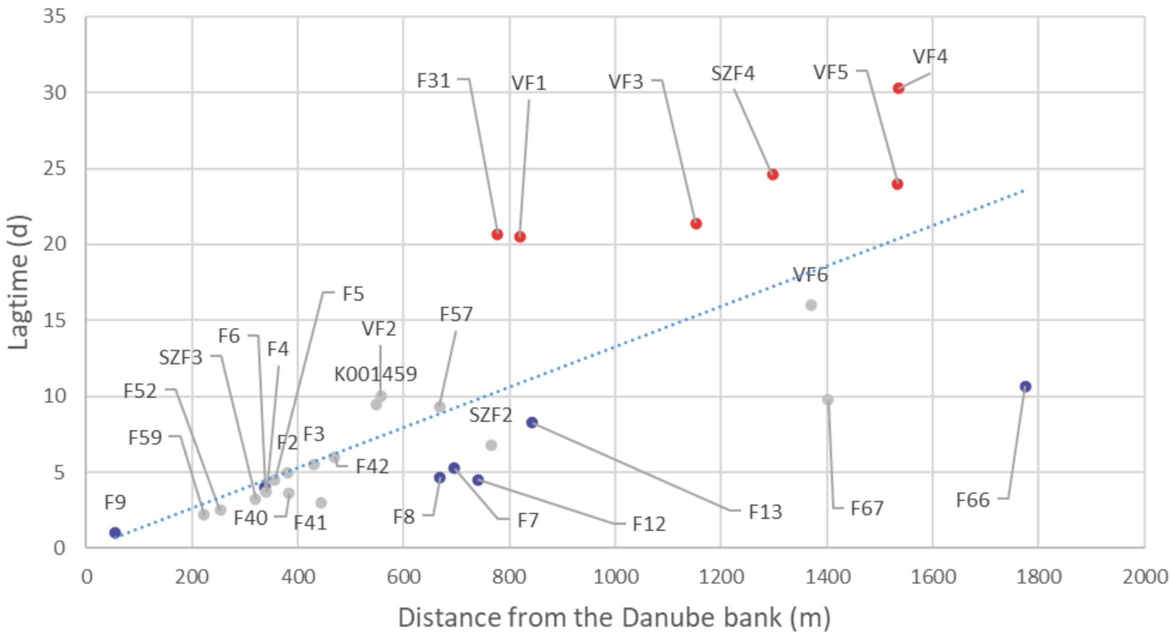
To what extent has there been a connection between the Danube and the Nagybaracskai-Danube and Lake Riha?

If we look at the strength of the correlations for the entire period together with the surface watercourses (Figure 3), it can be seen that Lake Riha and the Nagybaracskai-Danube have a stronger connection with the Danube than the groundwater levels near the bank, but slightly weaker than its surroundings. So these surface water bodies do not behave exactly like groundwater, but show similar trends.

If we observe the strength of the cross-correlation relationships for all floods, it can be said that the average correlation of Lake Riha with the Danube during floods is even weaker (0.4). In comparison, the connection of the Nagybaracskai Danube with the Danube, measured at floods, has a correlation strength of 0.8, so it is stronger than in its immediate surroundings (Figure 4) and twice that of Lake Riha. In Figure 4, there are two points that contrast with their surroundings. This large difference can also be observed in the kriging map of correlations (Figure 5). So in the vicinity of Lake Riha, the connection between the groundwater and the Danube is the weakest, the flood waves practically do not reach here. In contrast, during large floods, the connection to the channel Nagybaracskai-Danube is still very significant.

Characteristics and spatial distribution of the Danube floods in the alluvium of the island

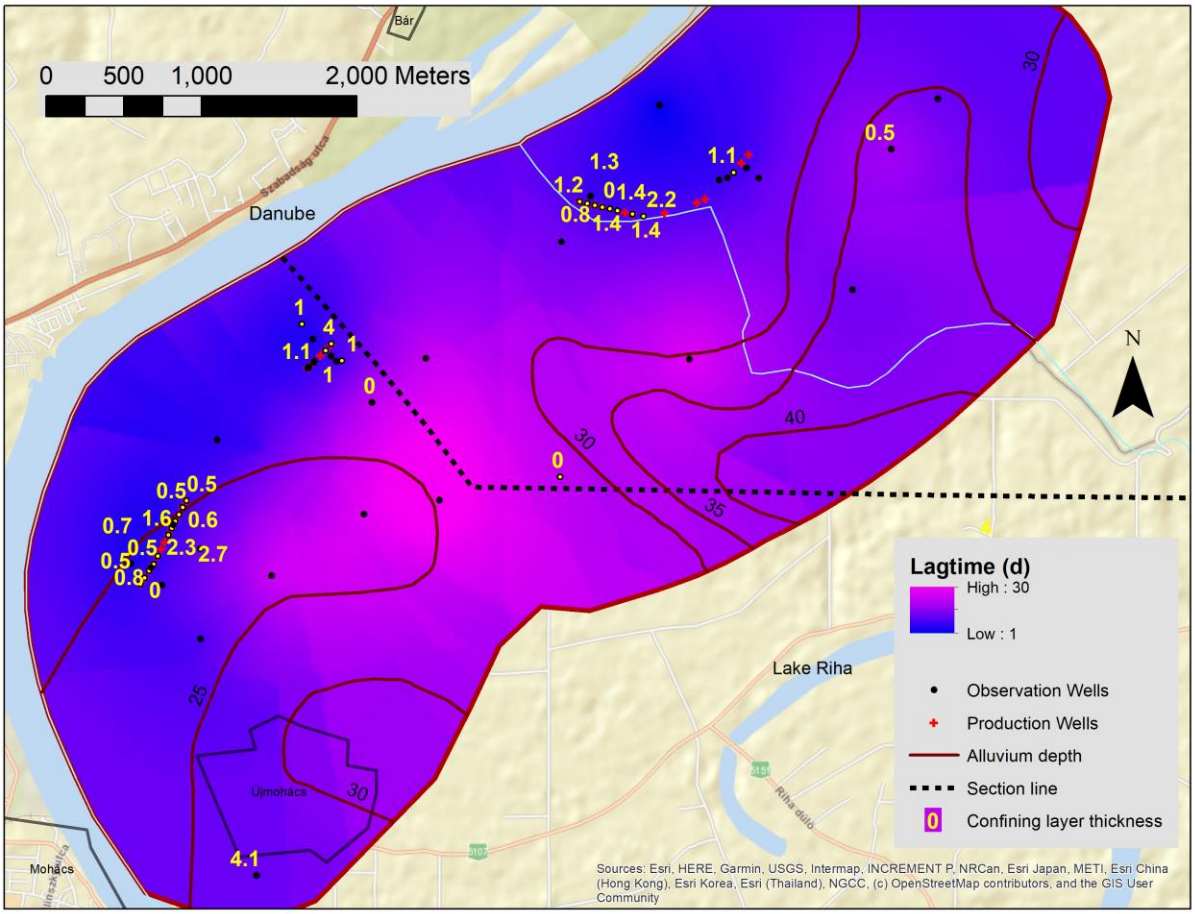
A chart of average pressure head peak lag time (Figure 7.) shows that values are fluctuating with increasing distance from the bank. They fit roughly to a linear trend line, but they are scattered. A group of observation wells below the trendline (blue circle) is the wells that can be found in the neighborhood of the northern production wells. Moving away from the bank, their dispersion increases.



7. Figure – The average groundwater wave delays away from the bank. Red dots: observation wells in the area of the middle well line at a distance of more than 500 meters. Blue dots: observation wells in the area of the northern production well line. Gray dots: all other observation wells (HERVAI A. et al. 2020a)

This means that the flood wave in groundwater in this area traveled faster on average than elsewhere. The wells below the trend line (red circle) are a group of piezometers located at more than 500 meters distance from the Danube, behind the middle and southern producing wells. Thus, it is clear from these wells that not only do they have much lower contact with the Danube, but the flood effects arrive there three to four times slower, even though their distance is only double to the wells near the production well.

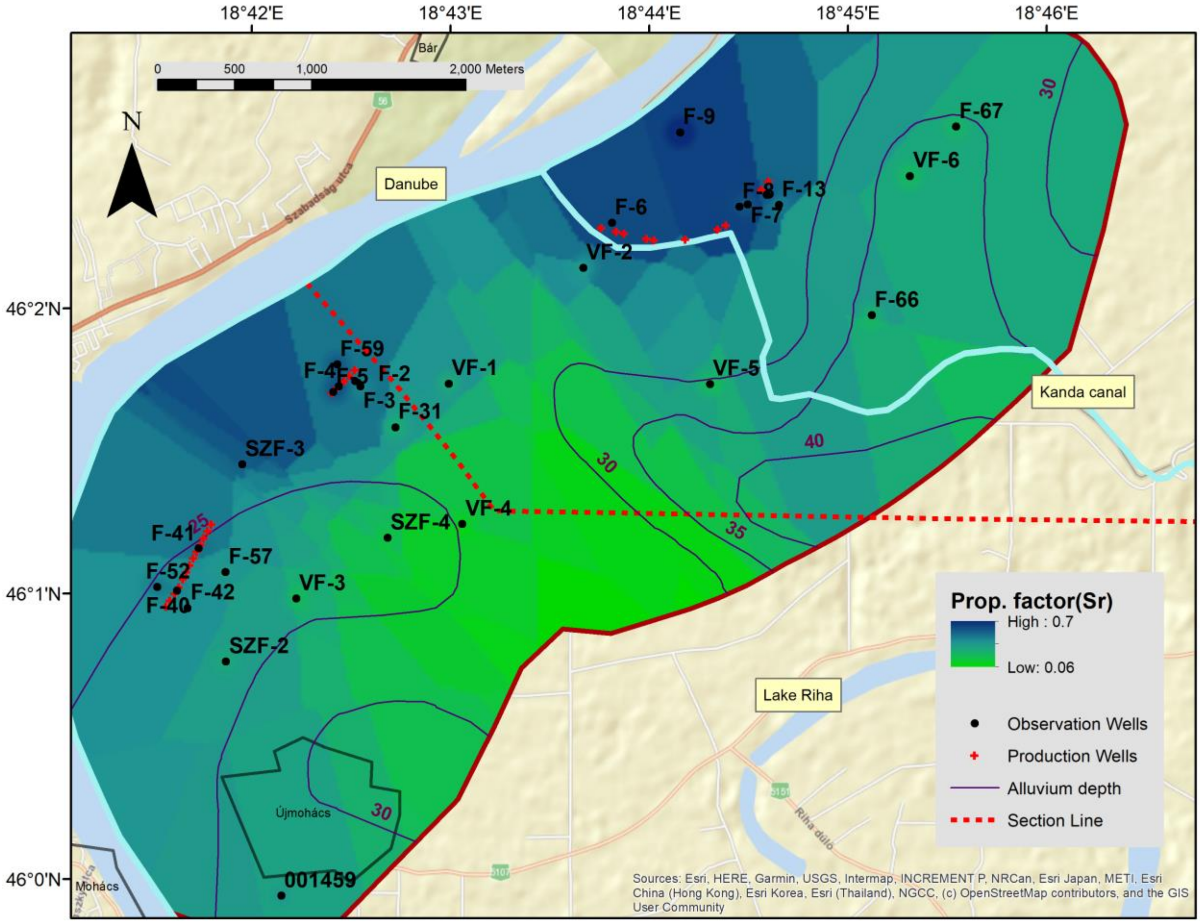
Taking a look at the results of the kriging interpolated map (Figure 10.) of average characteristic lagtime, the spatial distribution of lagtime differences can be seen. The map visually presents the observed deviations. Behind the area of middle and southern production wells, the average pressure heads progress at least two times slower than behind northern production wells.



8. Figure – Interpolated map of the delay time of the Danube floods (HERVAI A. et al. 2020a)

The raising effect of the Danube floods on the island's groundwater system

The kriging interpolated map of mean groundwater raising effect (Figure 19.) showed similar results to the map of the LM interpolated coefficient of determination considering Danube levels only (HERVAI et al. 2020a). This effect is the strongest close to the bank. In the northern part, beyond the series of production wells, the value of the proportionality factor remained high, even though the production wells extract water from the soil. In the lane behind the central and southern production wells, the Danube raised groundwater at a much lower rate.



9. Figure – Interpolated map of groundwater raising effect or proportionality factor (Sr) (HERVAI A. et al. 2020a)

Impact of production wells and precipitation on the island's groundwater system

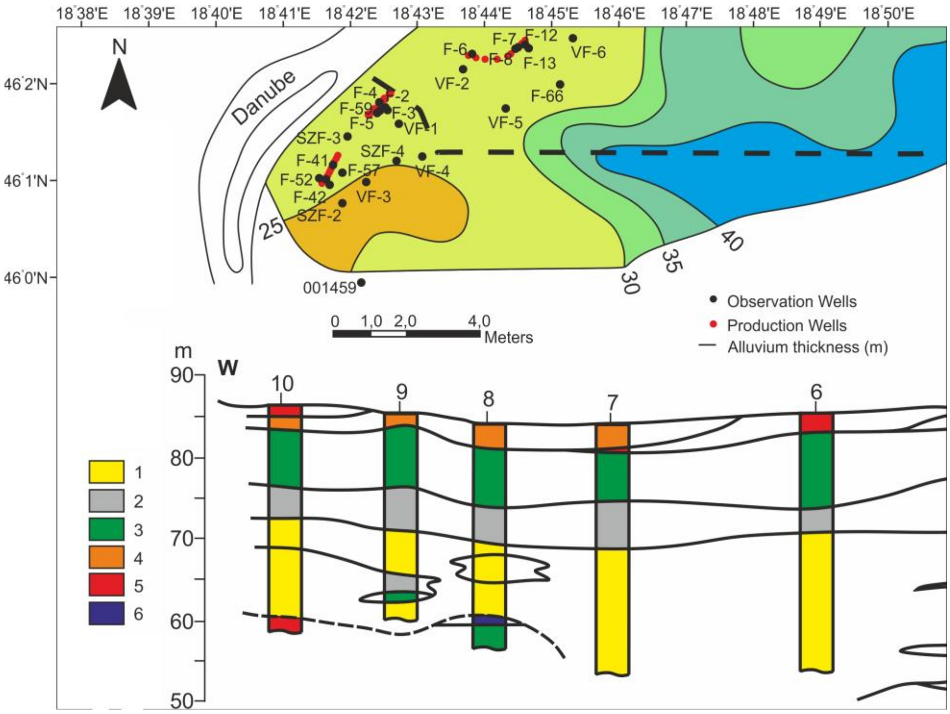
Investigating the effects of production wells was a complex task because several wells can operate simultaneously in one well row during floods (HERVAI et al. 2020a). It was also necessary to observe that the production wells are located at different distances from the observation wells. Theoretically, it was not even certain that they were in operation at all during the flooding, but in reality, there were at least one, but rather more, wells in operation during the selected flooding period. Naturally, only these working wells could be included in the linear regression model (LM).

By summing the time series of the operating production wells and the time series of the transformed Danube, I created a combined result curve. By inserting this result curve into the LM, I showed the full effect of the Danube on each observation well. I revealed by examining the time series of the 2013 flood transformed Danube water and the F-4 groundwater well, the production wells "cut out" only a few percent of the Danube integral. This value is also roughly equal to the change in the value of the coefficient of determination if the production wells were included in the linear model. As a result of my research, I have proved that the direct impact of production wells lasts only up to a few 100 m of distances.

Precipitation time series were included in the LM when their significance level was lower than 0.05. Overall, precipitation vectors had only a very minimal effect on linear regression models of individual groundwater wells (HERVAI A. et al. 2020a). Precipitation vectors had only a very minimal effect on the LMs. On the one hand, the primary reason for it is that it is questionable that there was a significant rainfall event at all. Even if there was, it still provided insignificant amounts of water compared to large floods. On the other hand, most of the area is covered with clay. Rain vectors appeared only in the inner part of the island and only during the July 2009 flood. It improved the deterministic coefficient by 0.03 for well VF-2, 0.15 for well VF-4, and 0.04 for well VF-5. This means that the measured values explained the LM, i.e. groundwater movement, in only a few percent (3-4%). Therefore, in these three observation wells, the groundwater explanatory rate of precipitation for the five flood events was between 0.6% and 3%. In the other cases, I could not demonstrate the effect of precipitation on groundwater, so these were not included in the overall linear regression model.

Impact of geological factors on the island's groundwater system

The interpolated maps (Figures 6, 8, and 9) are very similar in many aspects. The strong influence of the Danube extends up to about 500 meters, gradually decreasing beyond this distance. This effect disappears everywhere around 1500 meters. However, it declines the fastest behind the middle production wells, where it ceases at 1,000 meters. Naturally, this can occur since production wells produce large amounts of water. However, this does not explain the territorial difference between the southern, central, and northern production wells. Based on the transformed and combined (with production wells) Danube and groundwater water level time series in 2013, it is clear that the effect of production wells explains only a maximum of 10% of the variance of groundwater during major flood events (HERVAI A. et al. 2020a). Therefore, at least during these flood periods, the losing connection must be sought elsewhere. Figure 10 shows the depth of the Pannonian clay layer based on geophysical measurements (DRASKOVITS P. - JÓSA E. 1986) and a geological cross-section from the area of the middle production well (DRASKOVITS P. 1982). The surface projection of the cross-sectional line is presented on the interpolated maps (Figures 6, 8, and 9). The data shown in the cross-sectional figure are also confirmed by the description of hydrogeological wells (Figure 8, yellow values).

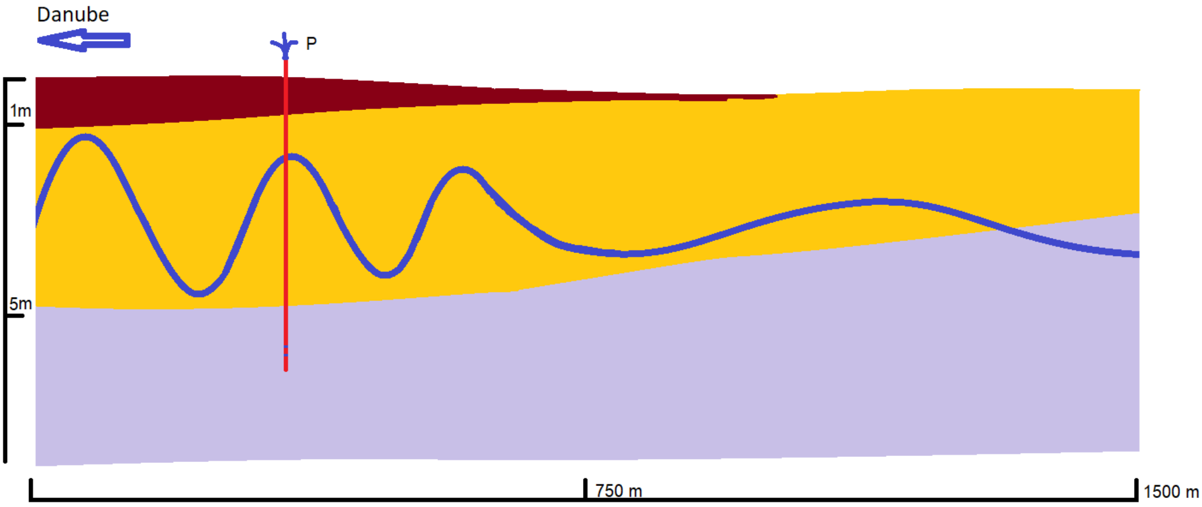


10. Figure – Cross-sectional layer sequence and alluvium thickness map in the vicinity of middle production wells. 1 - coarse sand, sandy gravel; 2 - fine-grained sand; 3 - fine sand; 4 - muddy fine sand; 5 - muddy rock flour; 6 - swamp formations (HERVAI A. et al. 2020a)

If we observe more precisely the geological map of the monitoring wells near the middle production wells (Fig. 10) and the strength of the monitoring well connections with the Danube (Figures 6, 8, and 9), we can see that at a distance of 500 m from the bank the clayey confining layer becomes thinner. Exactly where the relationship is drastically reduced.

Beyond the distance of 500 m from the bank, there is only sporadic stratigraphic data on the area. However, these two drilling log data (Fig. 8, yellow 0 values along the cross-sectional line) and the geological cross-sectional chart together prove that the area becomes uncovered moving towards the interior of the island. The value of the average coefficient of determination decreased suddenly here (first from 0.9 to 0.6 at 700, then from 0.2 to 0.3 at 1500 meters). Moreover, the delay time suddenly increases from one week to one month, while the distance only doubles.

In summary, as I illustrated in a schematic diagram (Figure 11), the groundwater wave traveled at a constant speed under high pressure in the not completely impervious siltstone sand, which was still covered with a layer of clay about 1 m thick near the bank. The waves then reached an increasingly uncovered, thinner layer of sandy mud 500 m from the shore and became elongated (HERVAI A. et al. 2020a). Looking at the chart of delay times (Fig. 7), it can be calculated that the average velocity of the pressure heads generated from the floods, under confined conditions was 80 m / day (F-2, F-3,400 at 400 m). This rate is later reduced to 16 m per day in uncovered conditions (F-31, VF-1 at 800 m).



11. Figure – Schematic diagram of the elongation of groundwater waves in the area of middle production wells during the 2013 flood, away from the shore (HERVAI A. et al. 2020a)

Possibilities of utilizing the results

My research supports future research about the natural and social processes of Mohács Island. My study helps to interpret landscape change at the local level and to evaluate GIS data from the past. Problems evolving from climate change and the extreme water levels of the Danube are causing the groundwater level to fall. My results can also help to present the regional differences of this decrease. Based on my results, we can also answer the question of in which areas inundations can be expected due to a major flood or precipitation event. The research is directly related to the most important local tasks of nature conservation, especially the maintenance of wetlands. My maps show in which areas and for how long the different types of habitats have been found. Since thousands of years have not passed since the landscape was transformed, the soil as a gene bank still contains the plant seeds of the original habitats. The maps generated from the Danube, groundwater, and meteorological data show which areas are still affected by the Danube flooding at medium or low water levels. My research can help to provide a theoretical basis for the review and transformation of agricultural activities on Mohács Island (development of fruit production, tourism, and fish farming). The National Park has several piezometers on the left bank of the Danube at Béda and Gemenc. I also plan to process their data to obtain a more accurate picture of the groundwater operation of the entire floodplain. Margitta 92 'Ltd., formerly Margitta TSZ, which has been farming on thousands of hectares on the island for a very long time, agricultural data and genetic soil maps. I plan to assess which soils have altered as a result of landscape change and how agriculture can integrate into the floodplain system. Finally, the GIS application of the historical and archeological research of the island may also be one of the possible practical utilization goals.

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