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Analysing the sensitivity of Hungarian landscapes based on climate change induced shallow groundwater fluctuation

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Abstract

One of the undoubtedly recognizable consequences of the ongoing climate change in Hungary is the permanent change of groundwater depth, and consequently the sustainably reachable local water resources. These processes trigger remarkable changes in soil and vegetation. Thus, in research of sensitivity of any specific landscape to the varying climatic factors, monitoring and continuous evaluation of the water resources is inevitable. The presented spatiotemporal geostatistical cosimulation framework is capable to identify rearrangements of the subsurface water resources through water resource observations. Application of the Markov 2-type coregionalization model is based on the assumption, that presumably only slight changes have to be handled between two consecutive time instants, hence current parameter set can be estimated based on the spatial structures of prior and current dataset and previously identified parameters. Moreover, the algorithm is capable to take into consideration the significance of the geomorphologic settings on the subsurface water flow. Trends in water resource changes are appropriate indicators of certain areas climate sensitivity. The method is also suitable in determination of the main cause of the extraordinary groundwater discharges, like the one, observed from the beginning of the 1980's in the Danube–Tisza Interfluve in Hungary.

Keywords: climate change, shallow groundwater, spatiotemporal sequential Gaussian cosimulation, Markov 2-type coregionalization

Introduction

Last century environmental researches revealed, that the alterations of various landscape factors (e.g., hydrologic conditions, soil, vegetation) are closely related to the changing climate (Ladányi, Z. *et al.* 2009; IPCC 2014; NORDEN 2015; EEA 2017; Rakonczai, J. 2018). Thus, to clarify how severely our landscapes with different environmental settings are affected to the climatic changes is crucial (Faragó, T. *et al.* 2010; USAID 2017; Patron, C. 2018).

Spatial, temporal, thereby joint spatiotemporal scale-related problems in geology as well as *"dynamic up- and downscaling"* in GIS are widely distinguished problems (Wilbanks, T.J. 2002). In contrast to the well interpretable environmental dynamics at the scale of geological history, where temporary outlying inferences are averaged over time, the explanation of tendencies of the significantly noisier observations of the near past is tricky. The questioning of the existence of global warming is actually rooted to the interpretation of trends of these noisy datasets (Sterl, A. *et al.* 2009). From practical aspect, the separation of the noise from the trend is a regularly returning question, which is ultimately based on the decision of the individual modeller (Thiébaux, H.J. 1997).

Hungarian hydrological science pays special attention to the shallow groundwater, thus, provide more sophisticated analyses, than it can be found in common practice (Kovács, J. *et al.* 2010; Kohán, B. and Szalai, J. 2014). Although flow and transport modelling ori-

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ented papers mostly use the "unconfined groundwater" expression for the top subsurface water layer, these articles usually written by researchers who are more focusing on realistic simulations of underground processes. While for studies, whose perspective from above, the "shallow groundwater" expression sounds much more expressive (Dillon, P. and Simmers, I. 1998; Alkhaier, F. *et al.* 2012; Wang, X. *et al.* 2015; Gowing, J. *et al.* 2016). In addition, unlike the international literature, the historical Hungarian research distinguish different definitions to the confined and unconfined groundwater (Marton, L. 2009).

The past two decades of the Hungarian climate research inferred that alteration of the shallow groundwater can be a substantial indicator of climate change (Rakonczai, J. 2011). The temporal pattern of the groundwater smoothly follows the changes of cumulated precipitation (Rétháti, L. 1977). Furthermore, the significant alterations of the groundwater depth at certain areas has triggered further transformation in the vegetation (Ladányi, Z. *et al.* 2009; Mezősi, G. *et al.* 2013; Gulácsi, A. and Kovács, F. 2018).

Based on interactions between different environmental factors (*Figure 1*), presumably changes of climatic conditions (particularly alteration of amount and temporal distribution of precipitation) triggers the changes and fluctuations of groundwater level. While less precipitation results less amount of infiltration, during heavy rainfalls large amount of water runs off on the surface, instead of infiltrating into the soil (Margóczi, K. *et al.* 2007; Pongrácz, R. *et al.* 2016; Gulácsi, A. and Kovács, F. 2018). Climate forecasts show that in the Carpathian Basin, the global warming leads to less precipitation averages in the warm half of the year, triggering more extreme rainfalls, along with decreased precipitation volume in the cold season (Van der Linden, P. and Mitchell, J.F.B. 2009; Stábitz, J. *et al.* 2014). The generally less

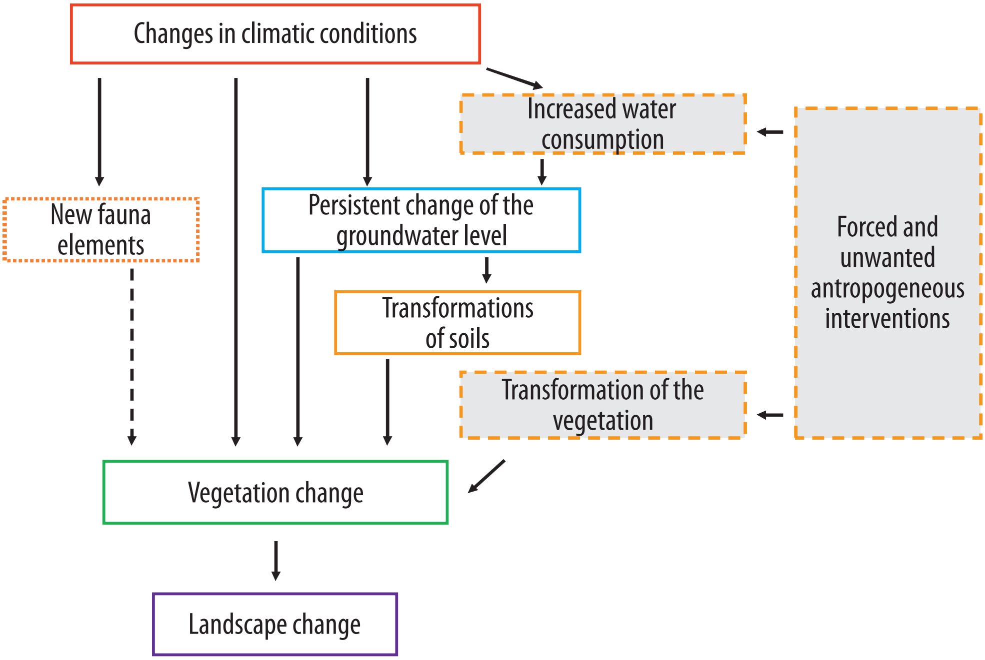

Fig. 1. Schematic relationship between climate change and landscape alterations in Hungary. Based on Farkas, J.Zs. *et al.* 2017.

precipitation would most likely reach the shallow groundwater reservoirs, too.

In areas where surface water is not available for agricultural usage, and during drought periods, farmers are forced to irrigate from subsurface reservoirs, thereby water extraction further amplifies groundwater discharge. As a consequence of steady groundwater decrease it might happen to reach a critical depth when certain plants cannot obtain sufficient moisture. Decade-long alteration of the groundwater table might even trigger the change of soils and ultimately vegetation changes can be observed (Rakonczai, J. *et al.* 2012; Ladányi, Z. *et al.* 2016). The alteration of the vegetation as a response to the climatic effects can be often experienced even without the change of the groundwater level or the soil settings (Gulácsi, A. and Kovács, F. 2018). Climate change might have further impact as well as on fauna. As a consequence of the milder climate, appearance of new pests in Central Europe is a typical example of that (Laštůvka, Z. 2009; Farkas, J.Zs. *et al*. 2017). These briefly described processes may jointly trigger significant landscape changes, in which the depth of water table is a key factor.

Objectives in the light of unanswered questions

From the 1980s a regional scale groundwater discharge has been experienced in Hungary. Due to its severity, the majority of domestic research focused on the Danube–Tisza Interfluve. The region itself provides an interesting framework for various disciplines due to its topographical and geological settings, hydrological characteristics (lack of major rivers) and the complex human interventions supplemented by the consequences of changing climate. The area itself is formed by sedimentary deposits from river Danube, which is later covered by windblown sand. The elevation of the area is between 83–172 metres a.s.l.

First and foremost, experts of the Kiskunság National Park had challenged with the adverse effects of shallow groundwater discharge, when drastic transformations of the wetlands were perceived (Pálfai, I. 1992, 1994). Nearly 1,000 mm lack of precipitation piled up between 1971 and 1985 (Major, P. 1994), which would infer almost 8.3 km^3 water shortage on the surface (Rakonczai, J. and Fehér, Z. 2015). The rate of mean areal decrease of shallow groundwater exceeded two meters (it would equal to 2 km^3 water deficit), while much higher rates occurred at the most elevated regions. Since then, drier conditions of the highest areas have not been able to recover even after longer wet periods (Margóczi, K. *et al.* 2007; Ladányi, Z. *et al.* 2009; Faragó, T. *et al.* 2010; Rakonczai, J. *et al.* 2012; Rakonczai, J. and Fehér, Z. 2015).

Various opinions on the background of groundwater depletion

After recognition of the problem by the early 1990s, scientists of various disciplines prepared their analyses of the possible reasons (Pálfai, I. 1994; Szilágyi, J. and Vörösmarty, C.J. 1993, 1997; Völgyesi, I. 2006). These studies clearly pointed out that their authors built in their arguments logically on their own specialized, thus, restricted professional fundaments. However, the final conclusions are diverse, sometimes even contradictory in several aspects.

It is agreed that one of the main reasons is the decade-long arid period, although afforestation, extraction of underground water, regulation of surface water bodies, (mainly the drainage of periodically occurring excess water) are also enlisted among the attributed reasons. Changes in land use and consequences of hydrocarbon production may also act as additional factors (Rakonczai, J. and Fehér, Z. 2015).

Surprisingly, even the role of rainfall shortage is very differently judged by certain researchers. The model study of Szilágyi, J. and Vörösmarty, C.J. (1993, 1997) recognized only 15 per cent of importance, another researcher team led by Pálfai, I. (1994) attached an importance of 50 per cent to shortage of precipitation, while the analysis of

Völgyesi, I. (2006) considers 80 per cent for the role of weather as a determinate factor for the higher parts of the sand ridge.

We experience nearly similar differences in reference to the assessment of underground water extraction. It is considered to be the main cause (70%) of groundwater discharge according to Szilágyi, J. and Vörösmarty, C.J. (1993, 1997). In the meantime, Pálfai, I. (1994) calculated a 25 per cent role of that, to which the extraction of groundwater contributes a further 6 per cent. However, Völgyesi, I. (2006) considered an almost insignificant 2 per cent for the role of underground water extraction for the analysed 10 years.

The arid period coincided with new constructions of water supply (thus with increased extraction of underground waters), and the intensified hydrocarbon exploration in the area. On most part of the Danube–Tisza Interfluve, positive hydrodynamic gradient can be experienced, therefore the infiltration from above prevails on the landscape even until 300–400 m depth (Erdélyi, M. 1978). Hydrological research considers annually 20–40 mm infiltration, thus on 6,000 km^2 area. This means that from the shallow groundwater to the confined water zones approximately 440–660 thousand m^3/day infiltration can be estimated. However, the amount of confined water extraction in the 1970s–1980s was only a third of this volume (Liebe, P. 1994). Thereby the full amount of extracted confined water would trigger maximum 40–50 cm groundwater discharge (Rakonczai, J. and Fehér, Z. 2015).

The role of confined water extraction on the landscape between 1960 and 2000, at most 2 km^3 in total (*0.20–0.45–0.70 and ~0.60 km*^{3} by decades correspondingly) (Rakonczai, J. and Fehér, Z. 2015). However, as it is going to be presented in current paper, the climatic effects are able to cause such volume of change even within a year (in a positive and a negative way alike).

One of the priority objectives of the current paper was to find some "truth" among the very different opinions above. After the quantitative analysis of changes in groundwater resources, we aimed to evaluate the role of climate change on selected areas with various natural conditions of the Great Hungarian Plain.

Study areas and datasets in the light of the natural background and processing issues

Current research was carried out for the area of the Great Hungarian Plain, whereto an adequate number of shallow groundwater time series is available. The area consists of several mesoregions with significantly different geographic conditions. Some significant details related to the groundwater dynamics are collected into *Table 1.*

Previous research has revealed that the official shallow groundwater database of the National Water Directorate of Hungary struggled with numerous errors (Mezősi, G. *et al.* 2017; Fehér, Z. 2019). The missing, mistyped or incorrect geographic elevation and reference zero points of observation gauges, as well as data conversion, database integrity and query errors resulted sudden jumps on the hydrographs. Sometimes these sections cannot be corrected, causing ignorance of decade-long valuable observations.

Sufficient length of the hydrographs (in this case 10 years was chosen as a criteria) is important to discover the temporal pattern and relation to nearby gauges. The research attempted to minimize effects of obvious, short range anthropogenic and environmental inferences, like irrigations or floods.

Reliably accurate results could be inferred on four regions of the Great Plain (areas of 4,700–8,300 km^2), on nearly 25,000 km^2 *(Figure 2).* Only the areas above the maximum measured flood levels of the major rivers (Danube, Tisza and Körös) were considered in the analysis, thereby their interference could be filtered out.

Since water table trends slowly follow the cumulated precipitation, consideration of the monthly aggregated groundwater level is sufficient, and spares significant computation capacity. For current research monthly median was considered, which is capable

Table 1. Environmental characteristics of the study sites

Study area	Typical rocks and soils	Geomorphological characteristics	Watercourses, the water resources and their anthropogenic influences
Danube–Tisza Interfluve	– Blown sand – Sandy soils with low fertility – Soils with low water retention capacity	– Aeolian sand forms, which are stabilized by forests (mainly pines with small water demand) – North–South oriented ridge area, steeper western slopes	– Lack of permanent watercourses – Canals with temporal water flow – Unconfined aquifers – Local water withdrawal from aquifers for irrigation
Nyírség	– Blown sand – Sandy soils with low fertility, soils with low water retention capacity	– Stabilized aeolian sand forms	– Lack of permanent watercourses – Unconfined aquifers
Southern Tiszántúl	– Occurrence of versatile fluvial sediments	– Alluvial plain with abandoned river-beds	– Lack of permanent watercourses – Alternated appearance of confined and unconfined aquifers
Foothills of the North Hungarian Mountains	– Deluvium, blown sand – Loessy sediments	– Increasingly sloping plain to the South direction, with some small alluvial plains	– Several small watercourses with insignificant runoff – Large amount of subsurface water extraction in order to support open-cast mining in two areas
Central Tisza Region	– Poorly permeable clayey surface – Frequent occurrence of saline soils	– Plain with low relief, whose significant part was regularly flooded before the river regulations in the 19th century	– Occurrence of rare natural water courses – Separated by irrigation channels – Groundwater-table under strong anthropogenic impacts

to filter outliers and insensitive to the number of observations in any given month. Thereafter the temporal outliers were filtered out using a 2-year moving box-plot. Finally, 848 of the 1,131 available time series were considered in the current study.

Weaknesses of conventional groundwater change maps

For a long time, changes in groundwater resources were presented on such maps where the depths of groundwater were related to the average of a particular reference period. While in the late 1960s anthropogenic interventions strived to mitigate with significant water surplus (like inland excess water), the precipitation increasingly reduced from the mid-1970s. These changed circumstances caused significant question of the proper designation of the widely used *"30-year reference-period"* in the discipline.

Figure 3. displays the water level changes after three consecutive, extreme dry years in 2003 compared to the mean water depth between 1956–1960. Three regions with different characteristics can be designated: A significant reduction in water level can be seen in the sand ridge area of the Danube–Tisza Interfluve (*Figure 3*, site A). This is an area with higher altitude than its surroundings, thus other surface water recharge cannot be gained, except from precipitation.

Contrarily to this, an increase of water level can be discernible on the Central Tisza Region, which is one of the most arid areas of Hungary (*Figure 3*, site E). After the reference period, a considerable number of irrigation canal structures has been established on this site. Besides conventional irrigation, the flooded rice production means further influence on ground-

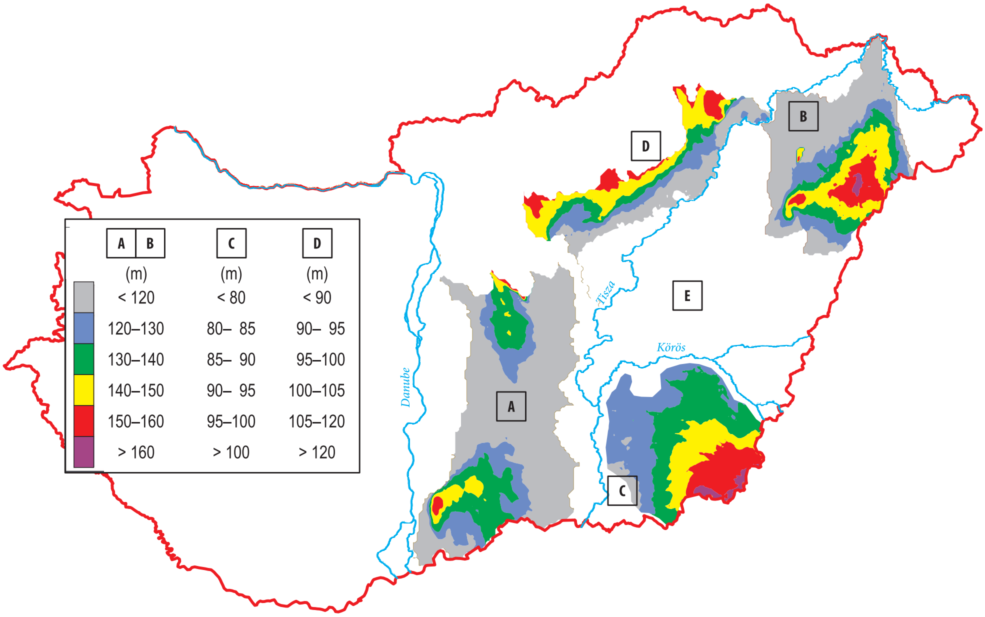

Fig. 2. Elevation map of areas involved in evaluation of fluctuation of groundwater table. Study areas: A = Danube–Tisza Interfluve; B = Nyírség; C = Southern Tiszántúl; D = Foothills of the North Hungarian Mountains; E = Central Tisza Region

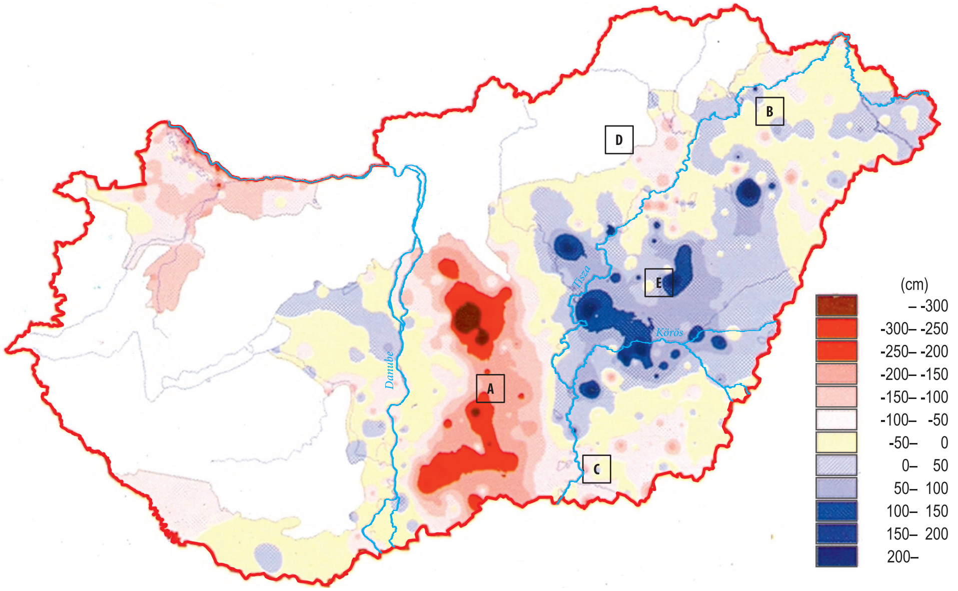

Fig. 3. Deviations of the annual average in the extreme dry year 2003 from the average shallow groundwater level 1956–1960. For study areas A–E: see *Fig. 2. Sources*: KSH=VÁTI 2005; original source: VITUKI.

water. Thus, supposedly the increase of the groundwater is a consequence of some specific purposive anthropogenic interventions.

Although, the national construction of drinking water networks had been carried out during this period too, which accompanied with intensive extraction of the confined water. In addition, due to the absence of wastewater network, the amount of wastewater leakage increased the groundwater table as well. After all, the Central Tisza Region was excluded from the current study, due to the spatially and temporally irregular intensity of significant anthropogenic impacts on the groundwater table. The presented methodology is not capable to handle such a complex problem.

The biggest issue is to decipher possible reasons for significant differences between Nyírség (*Figure 3*, site B) and Danube–Tisza Interfluve, in spite of the fact that Nyírség bears similar natural characteristics. Despite the less amount of precipitation in Nyírség, the question is, that whether Nyírség does not face any shortage in groundwater or the discharge is barely not seen for some reason.

Such maps were created by some traditional, isotropic spatial interpolations, whereas the gravitational flow mechanisms and geological settings were entirely ignored. The unsystematic river floods in some areas may interfere the assessment of the groundwater resources. Moreover, maps which has traditionally been prepared to indicate fluctuation of groundwater, are often not proven to be suitable to detect the most important changes. However, the most important factor was the lack of such an index that allows the comparison of various effects. Yet another problem is that these kind of maps do not allow the realignments of subsurface water resources. However, they are capable to highlight the areas face with long-term water shortage.

Methodology

Since correlations between the groundwater table and terrain is significant, a Digital Elevation Model (DEM) can improve the water resource estimations (Fehér, Z. and Rakonczai, J. 2012). However, estimation by means of simple linear regression equation will not give proper results, since the higher (more affected) altitudes significantly diverges from the regression line. Only single and bivariate kriging techniques (Goovaerts, P. 2000; Fehér, Z. 2007), capable to handle the geographical anisotropy properly. In most cases the spatial anisotropy is modelled by the so called variogramm models (Pannatier, Y. 1996).

Our experiences confirm that the order of magnitude of groundwater volume changes are fairly similar, if the estimations are performed based on similar spatial data structures (with the same spatial structure of the conditional dataset, identical interpolator and slightly different spatial parameterization) (Fehér, Z. and Rakonczai, J. 2012; Fehér, Z. 2015a). In case of same estimation method, however, the comparison of estimates between two time instants results miscalculations close to the gauges of non-complete series (Fehér, Z. 2015a). The different conditioning datasets constitutes differently structured equation systems of the spatial estimation functions. Since more or less missing sections can be observed on every single hydrograph, thus these missing values have to be handled. Ultimately, the comparison of point- and volumetric estimations become questionable in the presence of missing data (Fehér, Z. 2015b). Straightforward solutions to minimize the effect of the non-complete dataset can be either to ignore them (Kohán, B. 2014), or to apply mathematical estimation of the missing data based on some time series characteristics (Réth※áti, L. 1977). While the former solution results lower level of information content, application of the latter way becomes problematic if unmeasured periods exceed the temporal autocorrelation.

The benchmarks of bivariate kriging interpolators revealed the efficiency and flexibility in parameterization of the versatile cokriging solutions (Fehér, Z. and Rakonczai, J. 2012; Kohán, B. 2014; Rakonczai, J. and Fehér, Z. 2015). Geiger, J. (2015) published that the Markov 1 type (De Almeida, A. and Journel, A.G. 1994) variogram construction is mostly effective in the case of groundwater depth estimation in temporal sequence, since the variogram estimation is based on the distance of the groundwater from the surface. These variogram parameters are very variable, and related to the hydrometeorological conditions, thus need to be modelled for each instant separately. While Fehér, Z. and Rakonczai, J. (2012) revealed that variogram construction in case of water table elevation is more effective by exploiting the spatial continuity function of the DEM. Since observed geographical superposition of the groundwater table has a high impact on the subsurface water flow, and the temporal variability of each time series is lesser scale, thus the spatial structure in two extreme states is fairly identical (Fehér, Z. 2015a, 2019). This revealing led to the application of the Markov 2-type variogram construction. This approach minimizes the manual parameterization demand and calculates the necessary spatial continuity parameters automatically for each time instant (Shmaryan, L.E. and Journel, A.G. 1999).

In the past 15 years, two complex, GIS-based approaches have been developed for the evaluation of the shallow groundwater, as a spatiotemporal phenomenon. The approach of spatially correlated time series undermines the detailed temporal characteristics of the hydrographs, thus capable to estimate groundwater depth changes of any hydrographs over the temporal range and capable to simulate artificial time series at any locations inside spatial range very accurately (Kyriakidis, P.C. and Journel, A.G. 1999). However, this approach is less sensitive to the geographic elevation of the area (Fehér, Z. 2015a). In contrast, the currently applied recursive stochastic method is a straightforward process, which is very robust in the presence of a non-complete dataset for the concerning time instant, while honours the geographic elevation in the same time. The latter process performs well in processing near real time estimations for the groundwater level, undermining the short-memory dependencies with the previously estimated state of groundwater level (Kyriakidis, P.C. and Journel, A.G. 1999; Fehér, Z. 2011, 2019).

In contrast to the widely known kriging interpolators, modern geostatistical approaches, like stochastic simulations, account with small-scale spatial variability (Deutsch, C.V. and Journel, A.G. 1998; Szatmári, G. *et al.* 2015). The currently applied sequential Gaussian simulation (sGs) enables to mimic the process of the information gathering, by making large number of assumptions to the groundwater level at non-gauged spatial coordinates (Mucsi, L. *et al.* 2013). The algorithm designates the order of estimation nodes randomly, and considers the already estimated values as observations (in contrast to any kind of interpolations), until the last unknown spatial coordinate is estimated. Repeating this random path estimation multiple times, a large number of estimated groundwater grids (realizations, ensembles or stochastic images) are created. However, none of these images can be considered as the "*best one*", but in contrast to the single optimal estimate of any interpolations, it results multiple, *equally probable* spatial patterns of the groundwater state (Fehér, Z. 2008). In case of proper parameterization, each of these stochastic images entirely reproduce the statistical distribution of the input dataset, as well as fully honour the variogram model applied (Mucsi, L. *et al.* 2013). The sequential Gaussian simulation (sGs) enables to use any kind of kriging interpolator, including the currently applied cokriging with Markov-type variogram constructors (Fehér, Z. 2015a). By aggregating the estimated grids, different consequences, like the most probable level of groundwater table, can be expressed at each coordinate (Fehér, Z. 2008; Mucsi, L. *et al.* 2013).

The main goal of the recursive scheme was that the statistical distribution of differences between simulated grids reproduce the statistical distribution of the calculated water change per gauge for any two chosen time instants properly. This comparison was elaborated by visual cross-validation of percentiles. This is a straightforward process, if the parameters and the spatial structure doesn't differ significantly (*Figure 4*, left col).

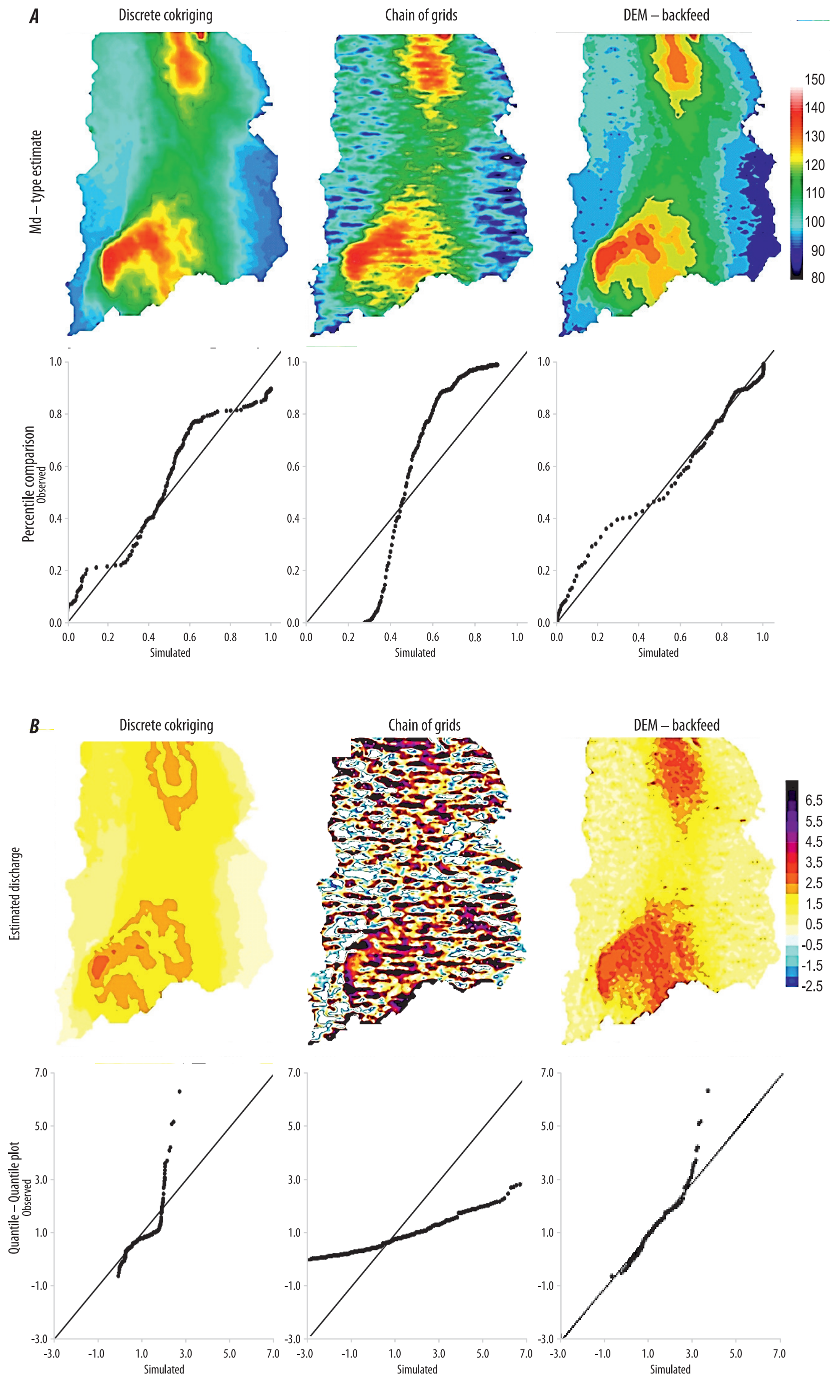

Fig. 4. Estimation and cross-validation of the groundwater table (A) and change of groundwater level (B) applying three different spatiotemporal schemes.

In spatiotemporal case however, the previous state is undermined to estimate both the actual spatial pattern and its parameters, while it has to consider the missing data and the DEM as auxiliary data too. The previously available recursive algorithms for this task (Kyriakidis, P.C. and Journel, A.G. 1999; Geiger, J. 2015) are not adaptable properly, since the relation between groundwater and DEM is significantly distorted, as well as the cross validation shows weak results as it is well noticeable already after the 28th consecutive recursive step in our benchmark example (*Figure 4*, middle col).

However, the disturbance mentioned above can be eliminated by the following steps:

1. estimation of the past spatial pattern of groundwater level, based on a complete dataset, by performing sGs and considering DEM as an auxiliary data;
2. estimation of the current spatial pattern of groundwater level, based on a non-complete dataset, using sGs and considering previous groundwater estimate as auxiliary data;
3. filling out the missing observations of the current dataset with the estimations from step 2;
4. estimation of the current spatial pattern, based on the already completed dataset, using sGs and the DEM as auxiliary data.

The algorithm keeps the spatiotemporal integrity of both the groundwater levels *(Fig. 4,* A, right col*)* and correctly reproduces the statistical distribution of the groundwater resource changes expected by mathematical calculations from gauge measurements *(Fig 4,* B, right col).

Results

The groundwater table estimation

The quantitative analysis of the temporally varying water resources has been carried out for each month between 1950 and 2017 applying the above introduced recursive sGs, with the Markov 2 type coregionalization model. A 1,000 m resolution auxiliary dataset has been generated from a 5 m resolution DEM. The resolution switch was carried out by the means of median-based downscaling, which enables to consider the most typical elevation value from the measured 200 × 200 values over every 1 km^2. In addition, this calculation enables the robustness against outlier values in the elevation database.

For each month, 125 alternative, equiprobable realization of groundwater table elevations were generated, and the most probable (median type estimation) simulated value were chosen for each spatial location and each time instant (median of simulated values, Md-type estimation). The difference of the Md-type values between two time instants resulted the relative volumetric change. Since no proper geological map is available, which would honour spatial heterogeneity from geostatistical aspect, the effective porosity was considered as an aggregated 30 per cent, according to Marton, L. (2009). The results allow the quantitative comparison of the water resources as a *"common denominator"*.

Analysis of quantitative changes in groundwater resources for natural regions

Based on the monthly water table estimations for each of the four designated sites between 1960 and 2017 *(Figure 5)*, the average of the estimations of the whole examined period was chosen as a reference *"0 value"*.

Generally, the estimated water resources for the four regions closely follow the precipitation patterns (the depicted precipitation is estimated by the following steps: ordinary kriging of monthly precipitation sums for each time instant is divided by the area under study, then half of the sum of the estimated precipitation volumes of the previous 24 months formulates the considered precipitation volume.). However, it can be seen, that on two of the sites, where the groundwater can be recharged from nearby external (higher areas), only some minor anomalies can be sensed on the estimated resources. The volume of these irregularities does not exceed 1.5 km^3, and reflects the precipitation well.

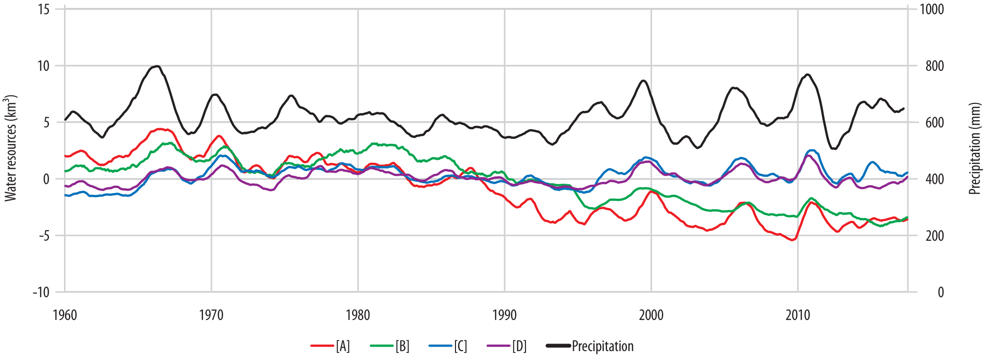

Fig. 5. Deviation of the estimated shallow groundwater compared to the long-term average, on the four study areas (1960–2017). Study areas: A = Danube–Tisza Interfluve; B = Nyírség; C = Southern Tiszántúl; D = Foothills of the North Hungarian Mountains. In addition, the annual sum of biannual moving average of the precipitation.

In contrast the two sandy areas (Danube–Tisza Interfluve and Nyírség), where the recharge of the groundwater is restricted to the local precipitation, a significant groundwater discharge can be observed over nearly 60 years. The estimated volume of this discharge is 6–8 km^3, compared to the second half of the 1960's.

However, the impact of rainy and dry periods is pronounced much faster on the Danube–Tisza Interfluve, because even a single dry or wet year can trigger 2–3 km^3 alteration in the groundwater resources. In contrast, the water resources of the Nyírség are rather characterized by slow, trend-like changes. The different dynamics of the two landscapes will be interpreted later in this study.

Thereby significant resource discharge can be measured on the Nyírség region definitely. However, it needs to be explained, why this discharge is hidden on the maps above analysed. It can be detected by detailed areal analyses, that during the 1970–2000 period, which in recent years was considered as reference data, there is a short period (between 1979–1983), when significant rainfall difference was evolved between the Nyírség and the Danube–Tisza Interfluve.

During this 5 years, 400–600 mm more rain fell on the Nyírség. Because of the significant precipitation surplus, until the middle of the 1980s, the groundwater level raised slightly higher than average, thus the dry period began later and lasted shorter. In addition, the recharge of the groundwater can be faster, since the water table is closer to the surface.

Connection between relief and changes in groundwater resources

The next step was the calculation of specific groundwater resource, namely the groundwater changes by unit area (km^2). These calculations were performed for each study site and evaluated according to the relief *(Figures 6–9).* The analysis allows to find relationships between certain reliefs and volume of changes. In addition, we can compare fluctuations for the different areas mentioned above. Besides, it allows to infer variations of groundwater resources within certain regions.

Changes have been well identified from the mid-1970s (started from a position well above the average), fully playing its role by the mid-1990s, in accordance with the shifting in precipitation patterns. Indeed, stagnation has been observed until the early 1980s: groundwater tables were practically unchanged–except for the moderate effects of the years 1966, 1967 and 1970, hit by inland excess waters.

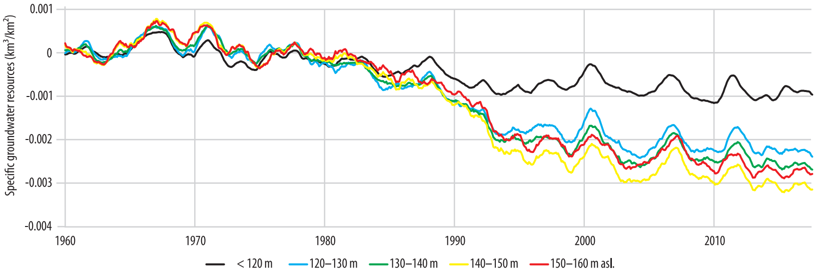

Fig. 6. Estimated specific groundwater resources according to relief, referred to Danube–Tisza Interfluve (reference period: 1961–1965).

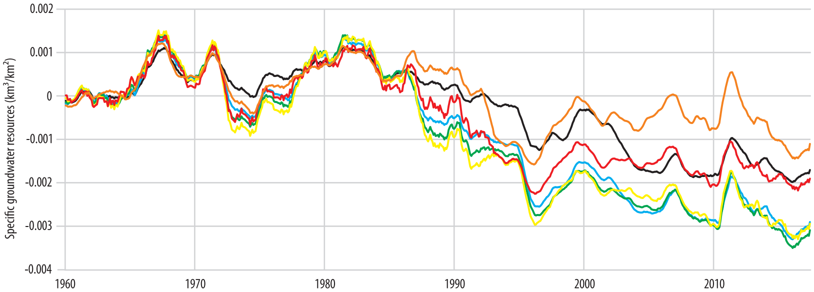

Fig. 7. Estimated specific groundwater resources according to relief, referred to Nyírség (reference period: 1961–1965).

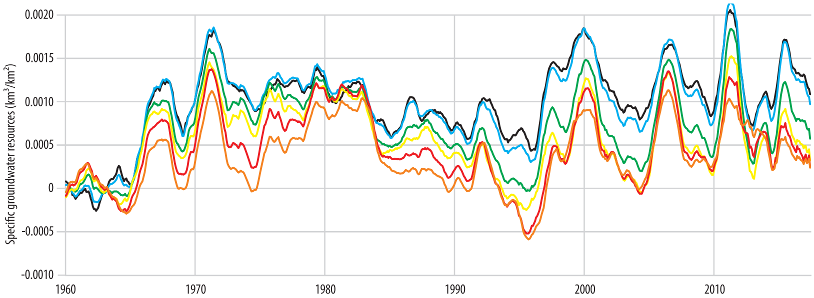

Fig. 8. Estimated specific groundwater resources according to relief, referred to Southern Tiszántúl (reference period: 1961–1965).

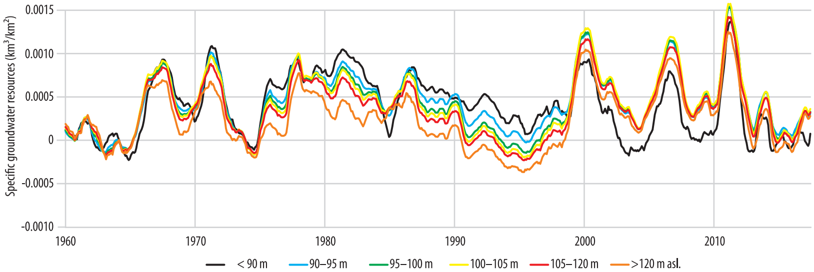

Fig. 9. Estimated specific groundwater resources according to relief, referred to the Foothills of the North Hungarian Mountains (reference period: 1961–1965).

Movements of groundwater under the surface is particularly visible in those sand-covered areas which can gain water supply solely from rainfall. Areas with low relief face less shortage of water even on the course of rather drought years, because of down streaming from higher areas. The highest decrease depends on the relief, namely the inclination of groundwater (see Darcy's law). The most moderate decrease of specific groundwater resources can be observed at the areas with the lowest reliefs; however, the steepest decline did not occur at those areas with the highest relief.

Evaluations revealed that the main reasons are either the deeper levels of groundwater (related to the surface) as deeper groundwater responds less sensitive to external influences, and that, on the other hand, limited inclination of the groundwater table. The steepest decline of specific groundwater does not occur within the two, particular sand-covered areas (as their surface inclination is not the steepest in their highest parts), but its surroundings with higher relief.

The facts depicted above are confirmed by the figures, displaying sensitivity of groundwater levels to environmental impacts (*Figures 10–12*). These maps were generated by averaging the groundwater changes occurred within 3 and 6 months respectively. Since absolute value of changes is considered, these maps are independent of whether the groundwater table increases or decreases. The results are not capable to express the expresso of the direction and proportion of the natural and anthropogenic effects):

$$\sum_{t=1}^{T-1} \frac{\left|GWL_t - GWL_{t+p}\right|}{T - 1/p},$$

where t means the beginning month of the analysis, T represents the count of monthly estimates considered, p is the selected period of the analysis (3- and 6-month periods), and GWL_t and GWL_{t+p} means the groundwater estimation for the respective time instant.

The results are the most clearly interpretable for the Southern Tiszántúl region where the decrease of elevation is coupled with decreasing sensitivity, changes are rather balanced.

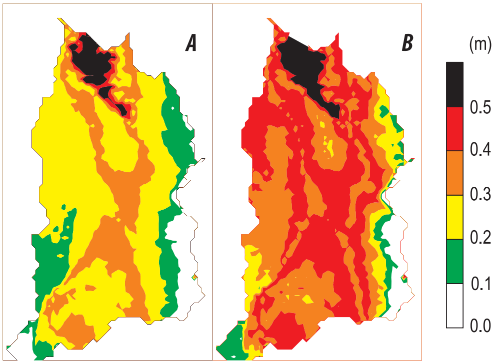

Fig. 10. Sensitivity of groundwater table for Danube–Tisza Interfluve to the environmental impacts. – A = 3-months period; B = 6-months period

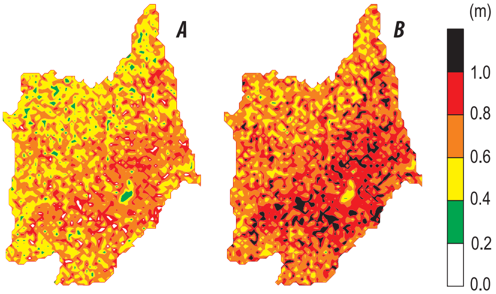

Fig. 11. Sensitivity of groundwater table for Nyírség to the environmental impacts. – A = 3-months period; B = 6-months period

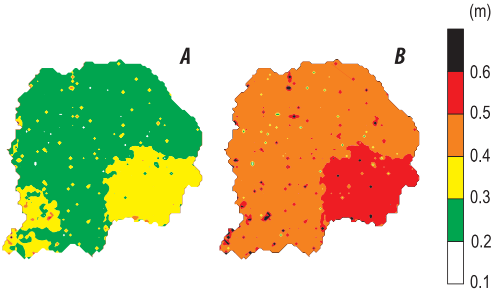

Fig. 12. Sensitivity of groundwater table for Southern Tiszántúl to the environmental impacts. – A = 3-months period; B = 6-months period

Sensitivity map for Danube–Tisza Interfluve reflects the characteristics of its relief: minor changes occur at the lowest parts; major changes take place at those parts surrounded by the higher parts of its neighbouring areas.

Sensitivity of groundwater changes in Nyírség is less characteristic, however, it can be suspected, that sensitivity is more moderate for areas of lower elevation. Local surface relief of the area is more determining. Reasons are better understood if we are analysing the relationship between the amount of groundwater discharge and elevation of the area. As for Nyírség, for most of the periods, there is almost no connection between groundwater discharge and elevation, that is, changes of water surface occur uniformly for the whole area *(Figure 13)*. Correlation between elevation and changes in groundwater level can be observed only when the precipitation deviates significantly from the typical amount.

As for Danube–Tisza Interfluve, there is a high correlation between elevation and groundwater changes *(Figure 14)*. Calculations verified that groundwater flows towards the lower areas, as Pálfai, I. (1992) and Kuti, L. *et al.* (1998) confirmed it. The extremely humid year of 2010 stands a very spectacular example for realignment of groundwater. Heavy rainfalls on the Eastern part of Danube–Tisza Interfluve made groundwater rising above the surface at the elevation of 92–94 metres and caused extensive inland excess waters.

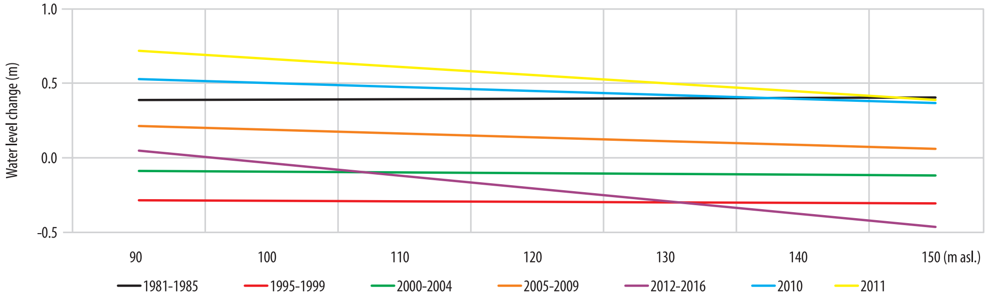

Fig. 13. Relationship between discharge of groundwater and altitude at Nyírség (reference period: 1961–1965).

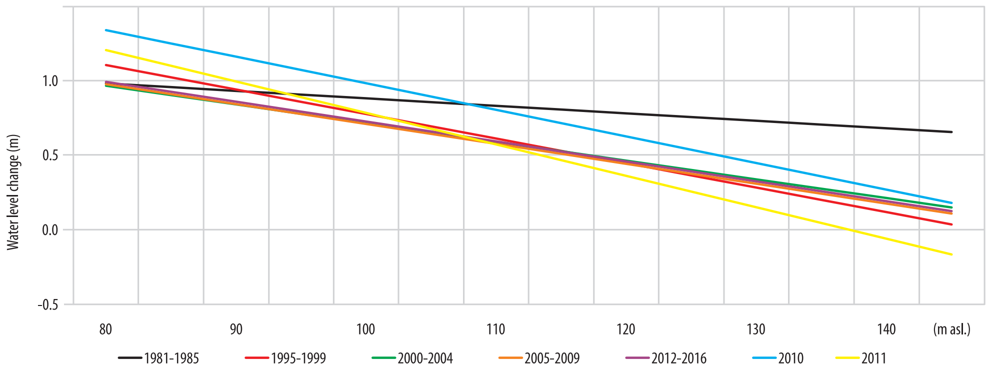

Fig. 14. Relationship between discharge of groundwater and altitude at Danube–Tisza Interfluve (reference period: 1961–1965.

Since the Southern Tiszántúl and Foothills of the North Hungarian Mountains areas show the same correlation between discharge and altitude for each analysed time periods (completely parallel correlation lines), these analyses were omitted from the current study.

Discussion

The research provided important results from several aspects. The results given by the presented GIS-based algorithm are accurate enough to allow different elements of the water-flow comparable. Thereby, real proportions have been assigned to those factors display similar behaviour in the courses of visual analyses. It substantially facilitates to define cause and effect relationships.

Our research successfully demonstrated the importance of the subsurface water flows in spatial and temporal changes of the groundwater resources. Moreover, different consequences of the distinct terrestrial and hydrological conditions have been demonstrated.

It can be said, that *areas more influenced by subsurface water inflow from neighbouring areas* (due to terrestrial and geological conditions), *are less sensitive to extreme precipitation fluctuations and consequently to climate change*. As a result of drought, slow groundwater discharge can be detected in case of these areas, contrarily, long lasting rainy periods trigger a rather fast charge of resources (see *Figures 5* and *6*). Therefore, while the consequence of the climate change in our environment is the more extreme distribution of precipitation (which can be experienced recently and forecasted by certain climate models for the future as well), effects of climate change on these landscapes cause only less prominent modifications.

Our research revealed the complex effect of terrestrial conditions on changes of water resources, too. Due to the unique geographical settings of the sand ridge region of Danube–Tisza Interfluve and Nyírség, shallow groundwater of these areas can be replenished from precipitation solely, hence during dry periods significant drop can be observed in their water resources. However, the environmental background and areal dynamics of the process is substantially differing in these two regions.

The ultimate reason for this is the diverse geometry of the two landscapes. The dominant geometric form on Danube–Tisza Interfluve is the sand ridge with a long, North–South extension and a remarkable steepness of its western slope). In contrast, Nyírség is much more proportionate, its higher regions in East–West and North–South directions are approximately similarly extended.

The different geometry triggers difference in the water resource discharge mostly during severe drought periods. Then almost the whole area of the linearly extending sand ridge of the Danube–Tisza Interfluve is unprotected against the downflow of the groundwater.

The resource change analysis based on elevation zones presents well the close relationship between altitude and groundwater dynamics (see *Figure 14*). In contrast the interior area of Nyírség, since the terrain as well as the groundwater table slope is insignificant. It provides protection against runoff. Thus, (except years of extreme precipitation), there is no significant relationship between the altitude and the groundwater dynamics. Ultimately, on the central area, which includes the utmost part of the landscape, groundwater varying almost uniformly.

On the Danube–Tisza Interfluve, besides the increasing volume of water extraction, the similar degree of decrease of the standing level of the shallow groundwater wells and the initial piezometric level of the confined water may correctly arise the casual relationship between the two water bodies. Based on the measured and calculated data, it can be stated, that the main cause of the shallow groundwater discharge comes not from *"below"* (from drinking water extraction), but from *"above"* (decrease of the precipitation infiltration).

The next stage of the research is going to focus on smaller parts of the currently presented sites. In addition, other landscapes will be involved into the analyses, thus contributing to the establishment of the long-term water management strategy.

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