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Climate Change as an Environmental Threat on the Central Plains of the Carpathian Basin Based on Regional Water Balances

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Abstract

Climate change is an essential environmental challenge nowadays. Its effects are already being felt in multiple ways. In the future, we will also have to adapt to its effects because of our farming and our daily lives. In our research, we assessed the climate sensitivity of the lowland areas of Hungary through the changes in landscapes and the changes in groundwater resources that have the greatest impact on agriculture, using data from more than half of a century. We have quantified that at the mid-territory level (5-10 thousand km^2) the groundwater resources show up to 3-5 km^3/year changes in both positive and negative directions due to climatic effects. This significantly exceeds the anthropogenic water uses (the total water use of Hungary is about 5 km^3 per year), so the effect of climate is the determining factor in the changes of regional water resources. Future changes in water circulation were modelled using the MIKE-SHE model in two micro-regions in Hungary. We have found that already at the level of the small catchments presented in our study, the water shortage increases by hundreds of millions of m^3 per year due to the expected increase in temperature (mainly due to the increase in evapotranspiration), which cannot be compensated by current water supply solutions. Model simulations have confirmed previous results showing that groundwater movements play a very important role even in lowland landscapes. Based on our research, we would like to draw the attention of decision-makers and agricultural experts to the fact that current methods (irrigation, regional water transfers) are not sufficient for successful adaptation to climate change. So, it is not the limited precipitation but the inappropriate agricultural practices that cause a real threat in a changing climate. Based on our research, we have made a proposal for the adaptation of agriculture to climate change.

Keywords: landscape sensitivity; shallow groundwater storage; GIS; modelling; MIKE-SHE

Introduction

Nowadays, we are increasingly confronted with the fact that climate change is one of the greatest challenges of our time. Scientists have been endorsing this more and more frequently and convincingly in recent decades (Intergovernmental Panel on Climate Change - IPCC, 1990-2022), and climate change is considered by renowned economists to be one of the most important threats (eg. World Economic Forum,

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2020, 2021[1]*). Global environmental policy has been in place since the 1990s (Rio Conference in 1992; Kyoto Protocol in 1997) to halt adverse change, but the reached agreements are weak and hardly implemented in practice. That is why the "Green Paper" of the European Union (EC, 2007) states that it is not enough to protect against the harmful effects of climate change (for example, by reducing greenhouse gas emissions), but that adaptation to inevitable changes is crucial.

In different parts of the world, the adverse effects of climate change can be experienced to very different degrees and at different rates. The global warming of the atmosphere and the change in precipitation patterns and annual distribution will affect the lives of most of humanity before long. The short-term effects of more extreme rainfall distribution appear more locally in nature. Furthermore, the effects of droughts tend to last longer, and could threaten the lives of hundred million (IPCC, 2021).

Climate change already has several consequences in the Carpathian Basin. The measured meteorological data (OMSZ, 2021), the evaluation of the historical data (Szalai, 2011; Sábitz et al., 2014) and the future forecasts made with different models (eg. Bartholy et al., 2008; Blanka et al., 2012; Csorvási et al., 2016; Pieczka et al., 2019) indicate increasing average temperatures, and more extreme precipitation with larger variation within a year (Bartholy & Pongrácz, 2017). Rising average temperatures are accompanied by increasing urban temperatures (eg. Unger et al., 2010; Gál et al., 2021; Fricke et al., 2022), increasing summer energy demand, spreading many invasive pests (eg. Szép, 2010; Janik et al., 2016), significant changes in forest water use (Tölgyesi et al., 2020), and increasing water demand in general. Precipitation, which is becoming more extreme, poses the greatest threat to agriculture with the formation of inland excess waters and droughts (Pálfai, 2004; Szatmári & van Leeuwen, 2013; van Leeuwen et al., 2019).

The current study attempts to present the main changes in the water circulation of the lowland areas of the Carpathian Basin in the context of climate change. Based on detailed monthly data of more than fifty years, the changes in groundwater resources were evaluated, which are of decisive importance for vegetation. Furthermore, using an integrated hydrological model (MIKE SHE), we forecast the changes in the water balance due to the expected climate change on two micro- regions on the plains. Unfortunately, farmers or decision-makers are not fully aware or underestimate of the magnitude of changes in water resources. Based on the research results, a proposal for adaptation to climate change in the context of agriculture is presented.

Data and methods

In previous studies by the contributing authors (Rakonczai, 2011; Rakonczai & Ladányi, 2012; Farkas et al., 2017), numerous comprehensive assessments of the most important consequences of climate change on the landscape of the Carpathian Basin have been already introduced. The study showed how changes in rainfall conditions affect, for example, the transformation of some soils and the complex consequences they can have for vegetation (Rakonczai & Ladányi, 2012; Ladányi et al., 2016;). Furthermore, the authors showed that the transformation of the water circulation of the landscape is the most important factor in the changes. In addition, the key role of shallow groundwater in assessing changes in water circulation has also been presented before (Fehér & Rakonczai, 2019). Shallow groundwater resources, for example, reflect the spatial and temporal variability of the precipitation (Garamhegyi et al., 2018) and reduce the impact of extremes.

Official temperature and precipitation series for more than a century are available nationwide for nearly eighty gauges in Hungary. In the current research, the monthly and annual precipitation data of the National Meteorological Service has been considered. The regional-scale systematic and scientific observation of shallow groundwater depth began in the early 1930s. After the Second World War, the number of measuring wells increased significantly. Nowadays, the data are collected and organised by the 12 regional water directorates and compiled by the National Water Administration. Based on more than 2 000 available data series, approximately 1 300 wells were considered reliable for our research in monthly detail.

Determination of the causes of groundwater changes is complicated because in addition to dynamic natural effects, they are also affected by several human activities. Assessment of the extent of environmental and anthropogenic impacts has long been the subject of professional debate. For example, when a significant decrease in the groundwater level on the sand ridge of the Danube–Tisza Interfluve was observed from the 1980s onwards, attempts were made through a multidisciplinary approach by several sciences to find an explanation for the process (Pálfai,

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[1] Although the Covid and the war between Russia and Ukraine has changed the order of the threat to humanity in recent years.

1994). At the time, 50% of the reasons for groundwater discharge were attributed to the weather (scientists did not yet talk about climate change but rather about some unidentified shorter-term phenomena). Among the anthropogenic effects, the role of water extraction was estimated at 31% (25% for confined water, 6% for shallow groundwater). The role of land-use change (e.g. afforestation) has been estimated at 10%, and the effects of water management (sewerage, drainage) have been estimated at 7%. Another study by Szilágyi & Vörösmarty (1993) suggested that the extraction of confined groundwater might be the cause of the decline in water resources. The current research's first, most important goal was to find a measurable indicator that makes the different effects comparable.

From the beginning of the 2000s, the development of computers and GIS provided an opportunity for a new research direction (Geiger & Mucsi, 2005). Laborczi et al. (2020) found that the movement of groundwater cannot be studied itself, thus, the distinction between charge and discharge zones is proposed. We realised that instead of the traditional map-based assessment of groundwater changes (which did not allow for the examination of many essential elements of the changes), it is practical to examine the volumetric and spatial behaviour of water resources. To achieve this, the digital elevation model of the monthly groundwater level has shown the evolution of the water supply over time and was calculated based on the spatial differences of the successive periods. Monthly volumetric changes were corrected for an estimated average effective porosity of 30% in the sediments. Based on the analysis in the study areas, we found that traditional interpolation methods result in significant errors due to the greater distance between the wells measuring groundwater changes and the variability of the surface topography. Therefore, after comparing various geostatistical methods, we developed several advanced approaches (sequential Gaussian simulations in a space-time domain) (Fehér, 2015, 2019; Fehér & Rakonczai, 2019). In the first phase of these studies, to assess the effects of climate change more accurately, the boundaries of the sample areas were designed, taking into account the typical high-water levels of the larger rivers. These investigations were first carried out in the sub-areas of the Great Hungarian Plain, but in recent years the analysis was extended to the entire territory of Hungary, where the significant spatial extent of shallow groundwater can be found (Figure 1).

To investigate future impacts of climate change on water resources, two small catchments were modelled

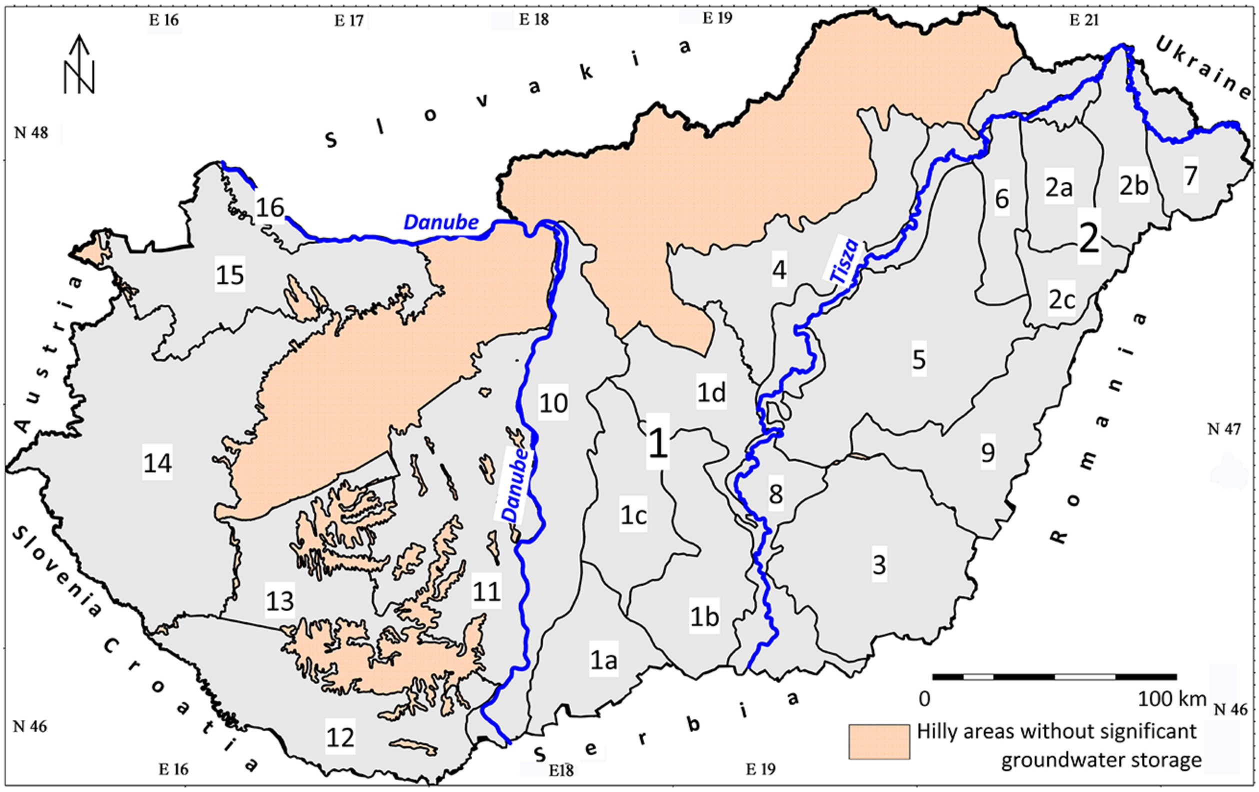

Figure 1. Areas included in the shallow groundwater resource assessment in Hungary

Regions and micro-regions: 1: Danube–Tisza Interfluve; 2: Nyírség; 3: Maros–Körös Interfluve; 4: North Periphery of Great Hungarian Plain; 5: Central Tisza Plain; 6: Hajdúság; 7: Upper Tisza Plain; 8: Tisza Valley; 9: Berettyó–Körös Plain; 10: Danubian Plain; 11: Mezőföld; 12: Dráva Plain; 13: Somogy Hills, 14: West Hungary; 15: Little Hungarian Plain; 16: Szigetköz. (For practical reasons, the boundaries of the assessed regions do not exactly match the natural geographical boundaries) using the MIKE-SHE hydrological framework. This model includes a comprehensive, integrated water balance tool capable of completing local and entire catchment water balance calculations at any time interval, thus enabling the integration, mapping, and visualisation of water flow processes of the catchment components over the entire watershed (DHI Group, 2017; Graham & Butts, 2005). Two catchments were chosen for the current study, where sufficient spatial data was available to enable the calibration of a proper model (Nagy et al., 2019). The calibration was performed by the sensitivity analysis of the changing input parameters of the model (Tran, 2021). By considering the future climatic scenarios and past extreme precipitation conditions, future trends of water balances were simulated. Since such detailed spatial studies are very data-intensive (which can hardly be provided in sufficient detail in practice), methodologically significant analyses of the sensitivity of both spatial data requirements and some landscape features were also performed. The simplest methodology of sensitivity analysis (Hamby, 1994), the one-at-time method was used for the studies. This essentially means that the degree of sensitivity is determined by changing each parameter independently, while not changing any of the other parameters. The one-at-time methodology was applied with a comprehensive, spatially, and temporally integrated hydrological model, MIKE SHE, which can calculate each hydrological parameter and the water balance of the local or the entire catchment, and for any time interval.

Results

Groundwater resources as an indicator of climate change

A significant change can be observed when assessing climate change through the national rainfall conditions of the last 120 years. Based on the whole period, a decreasing trend can be observed; however, if we look only at the past 50 years, the trend is exactly the opposite. In addition, increasing precipitation extremes have developed over the last two decades (Figure 2). The changes are even more significant when looking at different parts of the country. A decreasing precipitation trend can be observed in the more humid Transdanubia while slightly increasing precipitation occurs in the eastern part of Hungary. The fact that annual rainfall is not the best climate indicator is reflected by the seemingly uncertain connection with the drought occurrence (Figure 3). It is not surprising that there is no significant drought in rainy years is. However, it is already more difficult to understand that in years of equal annual precipitation sum, some-

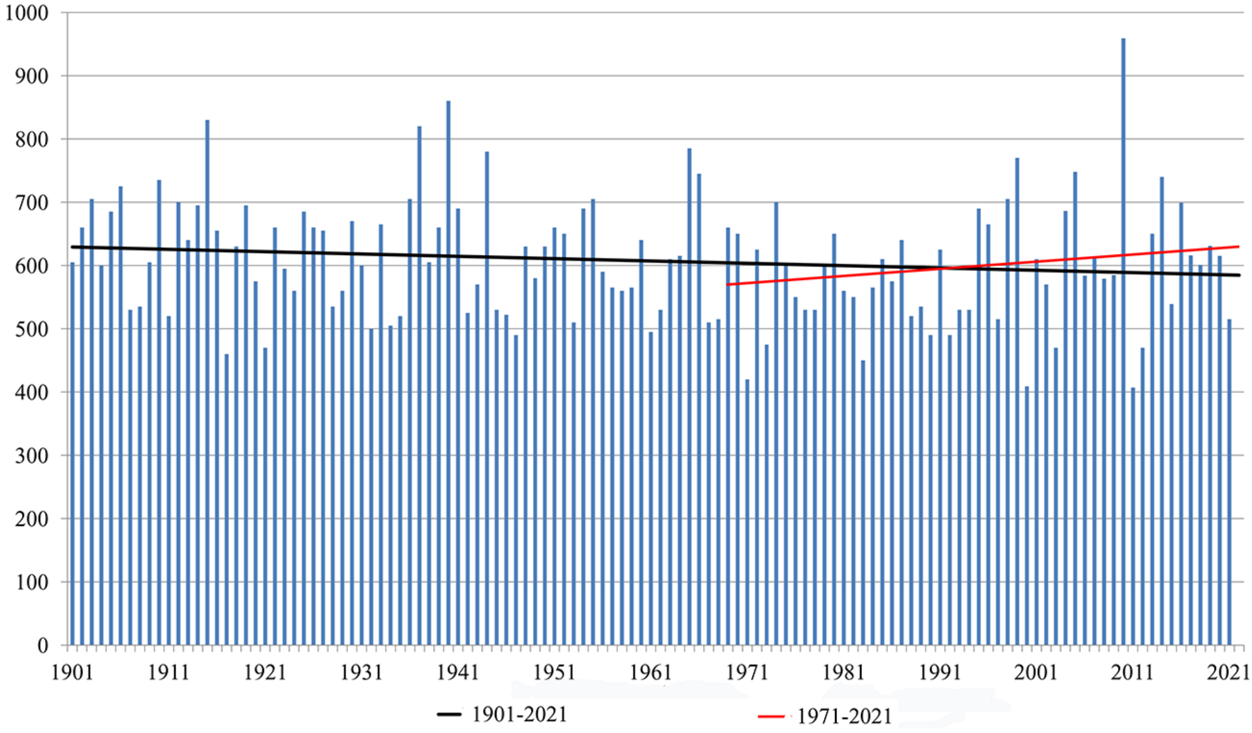

Figure 2. Annual rainfall (mm) in Hungary in 1901-2021 and its 120-year and 50-year trends (based on data of the Hungarian Meteorological Service)

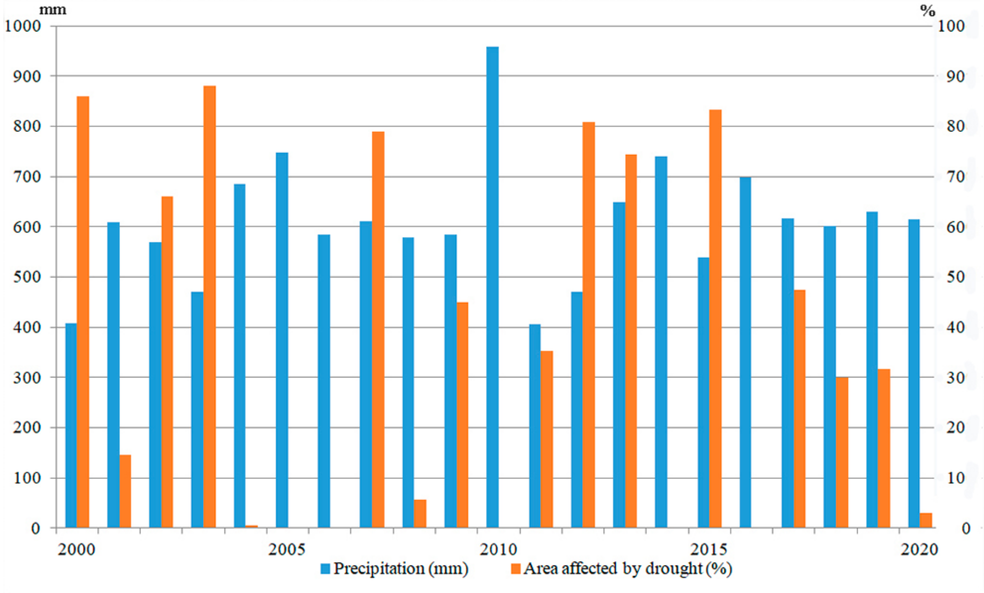

Figure 3. The relationship between the amount of annual precipitation and drought-affected areas in Hungary in the period 2000-2020 (based on the Hungarian Central Statistical Office)

times the area affected by drought is large, while other times it is much smaller. Examining the background of the phenomena, we can suppose that the water supply of the preceding period largely determines the intensity of drought of the given year. The best example of this is the rainy year of 2010, followed by one of the driest years of the century, yet only 1/3 of the country was under drought conditions in 2011. The next year was wetter than average, but at least 4/5 of the country was affected by drought in 2012. This can be explained by the decreased amount of water stored in the soils and the shallow groundwater in the previous year. Based on the above-observed processes, it was necessary to assess changes of a natural factor (shallow groundwater), which can express the environmental changes more accurately in a trend-like manner.

In the first stage of the research, taking advantage of the potential of geoinformatics, the quantitative changes in the groundwater supply as an environmental process were assessed on four regions on the Great Hungarian Plain (Figure 4) (Fehér & Rakonczai, 2019; Rakonczai & Fehér, 2015). These studies have clarified several essential questions. We have demonstrated that, at the landscape level, climatic effects are the decisive factors in the quantitative change of groundwater resources. For example, on the sand ridge of the Danube – Tisza Interfluve, the groundwater supply can change by as much as 3-4 km^3 in both positive and negative directions in just 1-2 years, depending on the amount of precipitation. Furthermore, during a 40-year period (between 1960 and 2000) only 2 km^3 of confined water was extracted. Consequently, the change in water resources is undoubtedly closely related to the amount of precipitation. Thus, the main reason for the decline in groundwater levels was not drinking water extraction.

We also succeeded to show that in Nyírség (the NE of the Great Hungarian Plain), which has similar geomorphological and hydrogeological characteristics to the ridge between the Danube and the Tisza (higher than its surroundings, and groundwater can only be replaced by precipitation), a similar decrease in groundwater resources has developed. The only difference in the water resources change in the two landscapes is that a lack of rainfall developed later in Nyírség and its volume was also slightly less. In these two landscapes, it was well demonstrated that due to the longer period of rainfall shortage, there is a significant runoff of the groundwater resources from the higher altitude areas to the lower ones. Thus, the decrease in groundwater levels is greater in higher altitudes, and even in very rainy years, the water shortage cannot be fully compensated.

The changes in the water resources of two additional landscapes (Maros-Körös Interfluve, and the North Periphery of the Great Hungarian Plain) were examined. Due to hydrogeological conditions, subsurface recharge from other (higher) landscapes is possible in these areas. During drier years, a slow decline in water supplies has been observed. Water scarcity could be quickly replaced during periods of high rainfall, so even in case of more extreme rainfall distribution, there is no permanent shortage of groundwater, if there are periods of high precipitation.

In the second phase of the research, the investigations have been extended to most of Hungary. The assessment of the landscapes mostly affected by groundwater depletion (Danube-Tisza Interfluve, Nyírség)

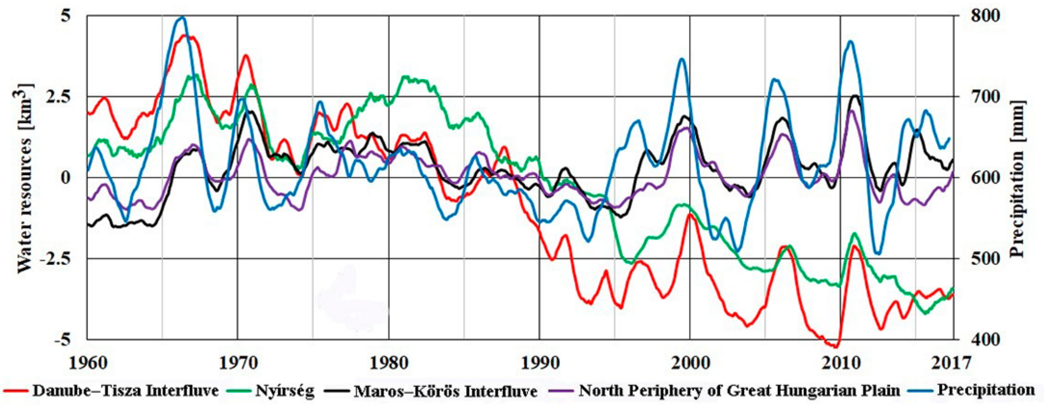

Figure 4. Precipitation and groundwater resources in four regions of the Great Plain 1960-2017*
** The volume of precipitation was displayed as the 24 months moving average of the annual precipitation. The reference „0" value of the shallow groundwater resources was determined as the mean of the estimated values for the period of 1950-2010*

has been further separated into sub-regions. The results highlight well that the landscape's geomorphological features and hydrogeological situation fundamentally determine the relationship between climate change and groundwater resources. In the Danube-Tisza Interfluve, shown as an example, the higher altitude landscapes reflect changes in precipitation well. Meanwhile, water level changes can hardly be observed on the Danubian Plain (Figure 5).

The analysis of the central, lower areas of the Great Hungarian Plain (Central Tisza Plain and Berettyó–Körös Plain) revealed a significant relationship between the change in water resources and the precipitation conditions. The magnitude of the changes is similar to that of the higher areas; meanwhile, no long-term trends could be identified. There might be several reasons for this. The eastern part of the area is hydrogeologically connected to the higher part of the basins through the river network. Thus, the region receives water replenishment by surface runoff and subsurface flow. There are remnants of the former riverbeds (paleo riverbeds) and many artificial canals in the landscape, allowing for more permanent surface infiltration. Agricultural production is assisted by irrigation with water supplies from nearby areas (mainly from the Tisza River). In addition, underground inflow is also coming from the direction of Nyírség.

The analysis of the areas west of the Danube (Figure 6) revealed several important findings. Similarly, to the Great Hungarian Plain, a close relationship between precipitation and groundwater resources can be observed. Still, the volume of the changes is smaller and regionally heterogeneous. The changes in the Mezőföld and Somogy hills show many similarities to those in the Danube–Tisza Interfluve and Nyírség, but they react to the extreme meteorological conditions abruptly. In some periods, groundwater resources of the western part of the country show striking changes that differ from the typical national trends and other Transdanubian areas. Examined in more detail, this may also be due to differences in precipitation distribution. For example, in 2010, when precipitation was 1.5 times higher than the long-term average in Hungary, only slightly above the long-term average precipitation was measured in the western part of the country. Still, the effects of the drought period in the early 2000s were also more pronounced.

In addition to the climatic effects, the dams of the Dráva River cause persistent low water levels in the Dráva Plain. Supposedly this may play a role in reducing water resources. Due to the closeness of the Dan-

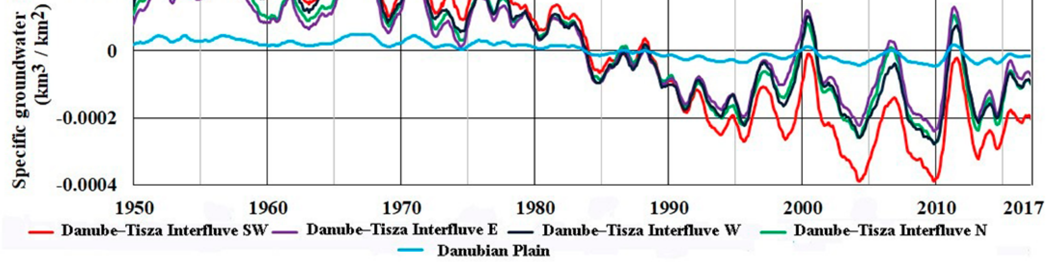

Figure 5. Changes in specific water resources in five sub-regions of the Danube-Tisza Interfluve 1950-2017

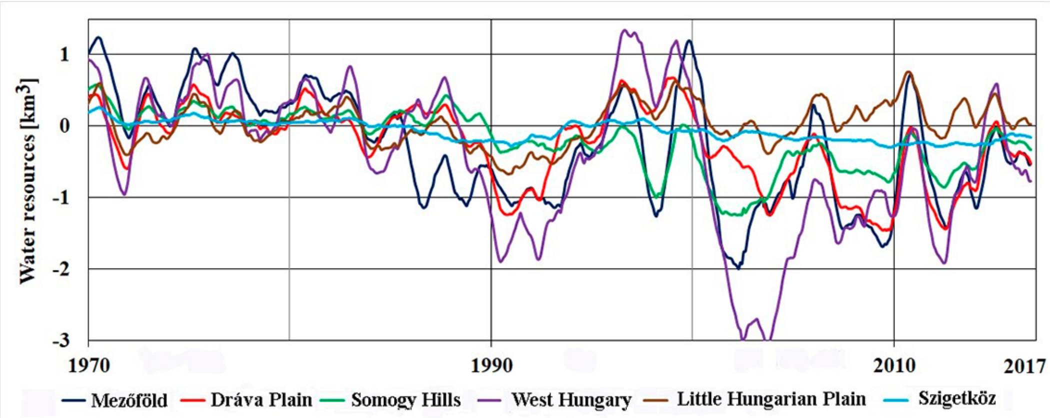

Figure 6. Changes in water resources in the areas west of the Danube 1970-2017

ube River in Szigetköz, the climatic effects can hardly be detected. However, the diversion of the Danube (due to the Gabčíkovo hydroelectric power plant) caused a 0.3-0.4 km^3 discharge in the water resources.

Solutions to extreme climate events after World War II

The river regulations and water management interventions carried out in the second half of the 19th century fundamentally changed the hydrological conditions of the Carpathian Basin. After the drainage of the excess waters from the former floodplain areas, agricultural cultivation of more than ten thousand square kilometres of arable land began. Groundwater levels decreased in a large area over the summer season compared to the previous period. As a result, agriculture was more dependent on weather variability. To compensate for the water shortage in agriculture, several large-scale irrigation development programs were launched after World War II based on the water resources of the Tisza River. In contrast, inland excess water generated during hydrologically wet periods was discharged by surface or subsurface water management methods. Following the establishment of the large-scale agricultural farming structure of the socialist period, subsurface drainage programs came to the forefront in the early 1970s.

Subsurface drainage interventions were implemented as part of financial support by the State for agriculture and consisted mainly of field-level water management. By using tile drains, the goal was to achieve a balance in terms of water management in the areas to be treated. As a connecting link, the subsurface drains simultaneously serve the accelerated discharge of excess water from the soil into the recipient channel. Furthermore, it also regulated the groundwater level locally. In case of proper operation, the groundwater level could not rise above the installation depth of the drains within the treated agricultural plot. The implementation of the subsurface water management works already raised several problems during the construction. Due to the change of land ownership after the change of regime in the late 1980s, the subsurface drain networks were almost forgotten.

As one of our research objectives, we also surveyed the condition of the subsurface drained areas in the SE part of the Great Hungarian Plain and we also developed a complex methodology to analyse the detailed field-level studies along the River Hármas-Körös (Túri et al., 2021). Basically, our research results are quite unfavourable. The existence of subsurface drainage networks, once implemented with significant financial resources, has been almost forgotten over the decades. Often the networks are not properly maintained by the owner or operator. In many cases, they do not even know about their existence below the surface (Túri, 2021). Our detailed soil investigations have also revealed that the utilisation of tile drains on heavy texture soils is very limited. The main limiting factors for the operation of the tile drains are the lack of proper agrotechnics applied, the loss of the connection between the tile drains and the open recipient channel, and the insufficient water carrying capacity of the receiving channel system. The limited operation of tile drains installed decades ago has been found by researchers in other European countries as well (Tlapáková, 2017; Matcic & Steinman, 2007). Based on their experience Djurović & Stričević (2004), also pointed out that the functionality of an improperly maintained subsurface drain system deteriorated significantly in just over a decade.

Drought periods, which are becoming more frequent, regularly demonstrate the need to improve irrigation. Currently, irrigation is mostly possible from water resources taken from the Danube and the Tisza rivers. The extent of irrigated areas was the largest in the period of large-scale farming under the socialist era in the early 1970s (exceeding 300,000 hectares in some years) but barely exceeded 100,000 hectares in recent decades (Figure 7).

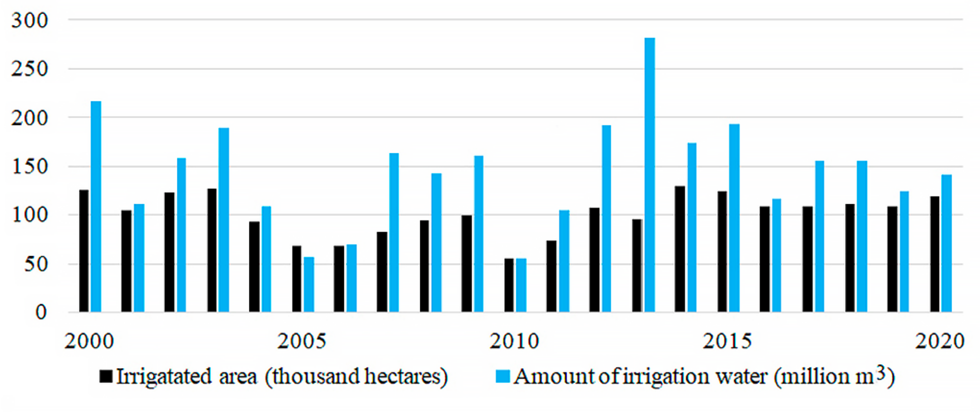

Figure 7. The extent of irrigated areas and the volume of irrigated water in Hungary between 2000 and 2020 (based on the Hungarian Central Statistical Office)

Assessment of impacts of future climate change on the water balance of micro-regions using the MIKE-SHE hydrological modelling framework

As previously introduced, diverse climatic effects may cause different effects on various landscapes due to their geographical location, and geomorphological and hydrogeological differences. The water balances of two micro-regions in one dry and one rainier year were selected to assess the future effects of climate change. Subsequently, the impact of the expected future temperature rise was also modelled. The spatial extensibility of our studies was also examined based on the extent to which reducing the data density of data-intensive models affects the accuracy of the water balance estimations.

Dong-ér catchment

The inland excess water protection management system of the Dong-ér main brook is located in the central-eastern part of the sand ridge of the Danube–Tisza Interfluve, about 50 km from the southern border of Hungary (Figure 8). The total area of the catchment is

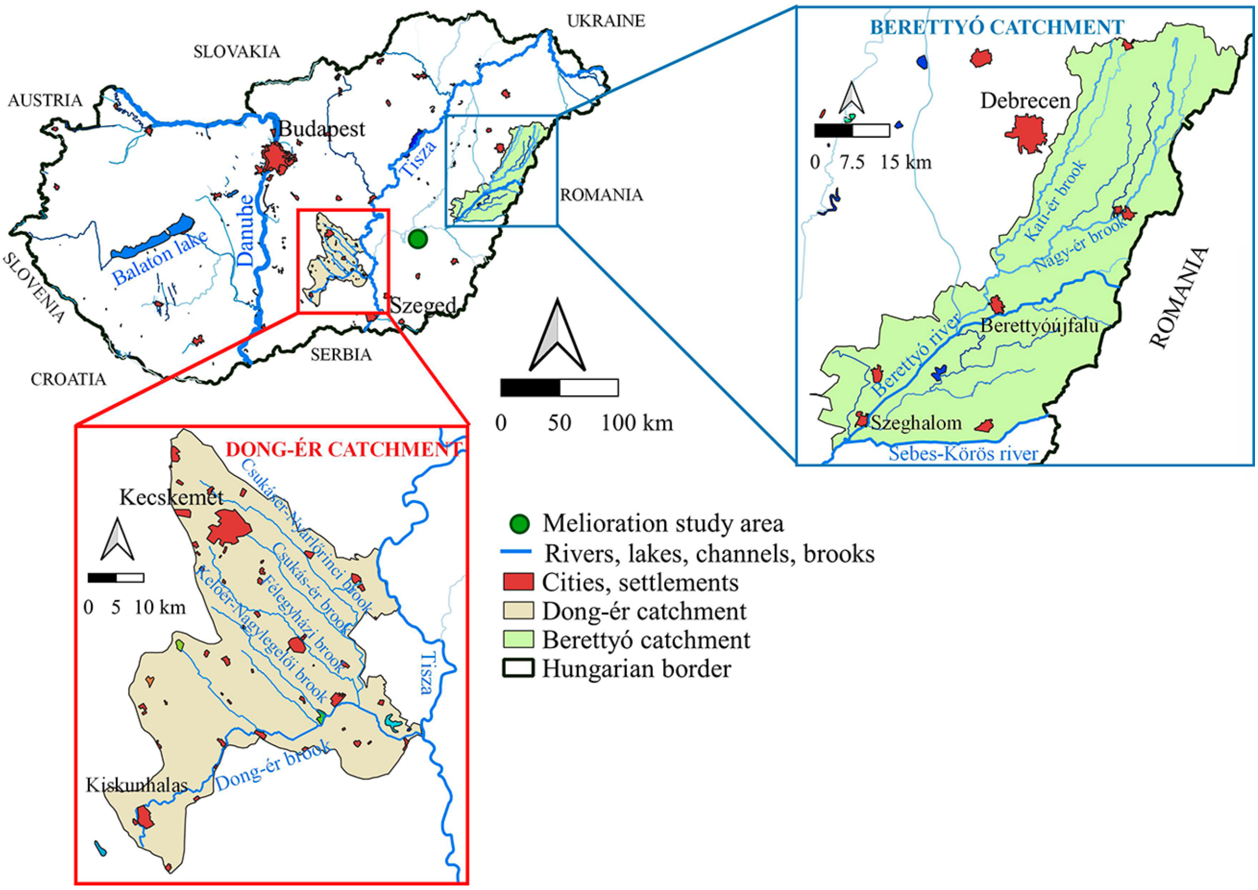

Figure 8. Location of the study areas

2 127 km², and it is characterised by a small relative relief (<2 m/km²) - the area slopes from west to east. The western, higher altitude area consists mainly of highly permeable sandy sediments. The eastern part is mainly covered by river sediments with minimal slope and lower hydraulic conductivity.

The effects of climate change on the water balance of the Dong-ér watershed were investigated by the following simulations:

- The simulations of the hydrological processes and water balance for 2018. The results of these simulations are considered a reference value for the comparison with further scenarios of extremely dry and extreme wet hydroclimatic conditions.
- Simulations of the unusually rainy year of 2014.
- Simulations of the effects of +1.5°C temperature rise, according to the forecasted IPCC scenarios (IPCC, 2018).

The comparison of simulation results performed for the years 2000 and 2014 with the results of the reference model of 2018, enabled us to examine the changes in hydrological parameters and water balance components in the context of the main characteristics of climate change. The results show that the deficit values of the unsaturated zone are much higher than the values of the other parameters (Figure 9). This means that the area is suffering from severe drought. A direct correlation can be found between the precipitation events and infiltration; nevertheless, the amount of water in the root zone and the unsaturated zone is negligible.

In addition, the actual evapotranspiration is higher than the amount of precipitation. The high sand content of the soil makes it highly permeable; meanwhile, the leakage coefficient of the sand is minimal, about 10-5 m/s. Consequently, during long periods of drought, most characteristically very intense, but short-term rain showers can hardly reach the deeper unsaturated zone. The results show that, besides evapotranspiration and precipitation, the subsurface inflows and surface runoff also have a high impact on the water balance of the entire catchment (Figure 10). This confirms our results obtained in the study of groundwater resources.

Based on the results, precipitation and infiltration are directly proportional (from 32 mm in 2000 to 138 mm in 2014). The water lost through evapotranspiration was more than precipitation in the studied years. It can be stated that the source of surface runoff in the Dong-ér catchment is primarily not precipitation or surface inflows. The question is, from where does the surface runoff get its water? The surface runoff is minimal due to the sandy surface, thus, infiltration of settlement's treated wastewater and groundwater resources into canals can be a source.

According to the results, it can be confirmed that there is a close relationship between the subsurface inflows and surface runoff components for the entire water balance of the catchment. Subsurface water flowing from the outside into the Dong-ér catchment provides ~90% of the water for the brooks, and this relationship mostly determines the water balance of the Dong-ér catchment. This is consistent with the results of a study by Kozák (2020). A comparison of the water balance results of extreme hydroclimatic conditions in 2000 and 2014 shows that the sensitivity in descending order to the following components is: infiltration (331%), overland flow to brooks (100%), subsurface water storage (-95%), evapotranspiration (75%) and overland water storage (58%) (Figure 10).

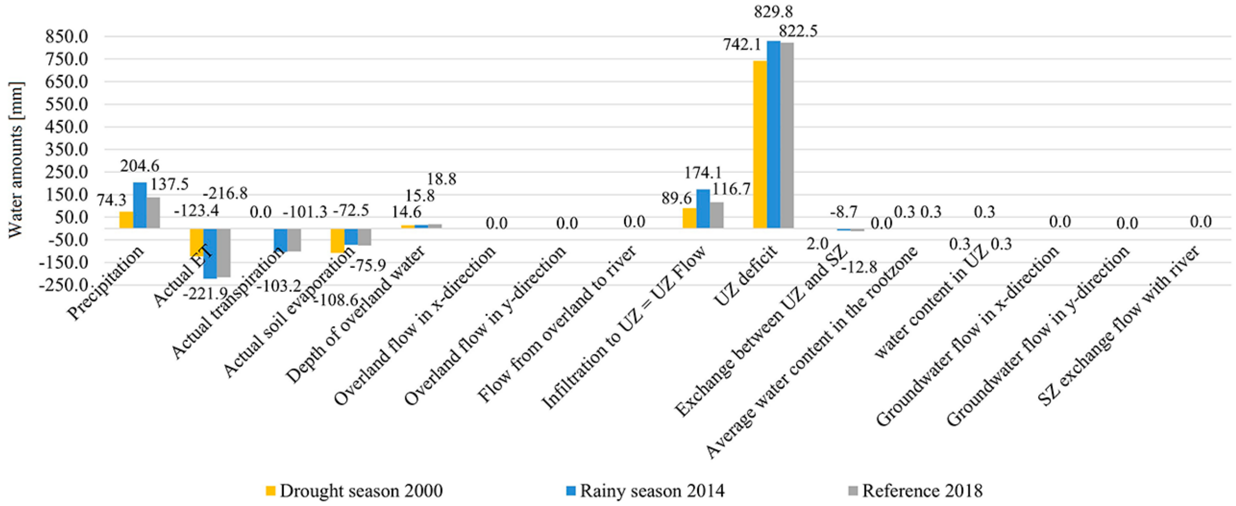

Figure 9. Average of simulated hydrological parameters from 1 March to 31 May in the drought year 2000, the rainy year 2014 and the reference year 2018
(ET: Evapotranspiration, UZ: Unsaturated zone, SZ: Saturated zone)

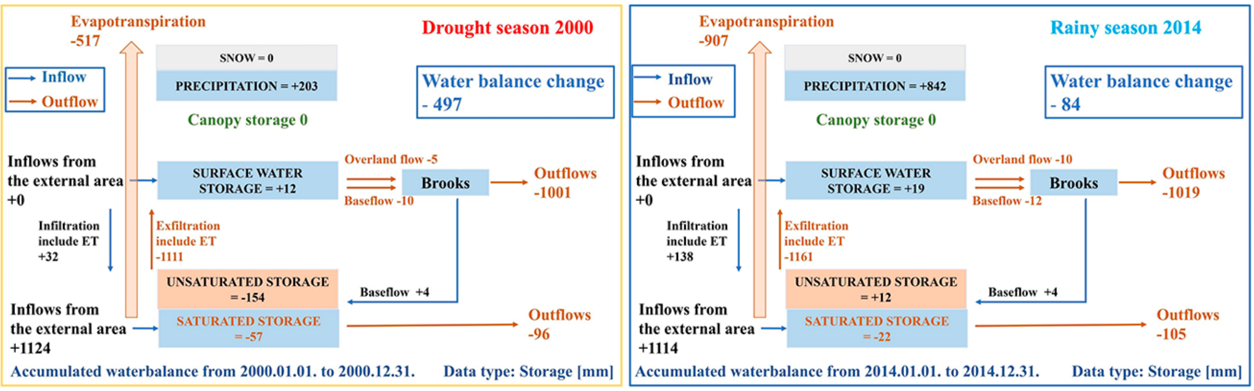

Figure 10. Water balance of the Dong-ér catchment in the drought year 2000 and rainy year 2014

Berettyó catchment

The Berettyó river originates from Romania. The current study was carried out for the 2 748.4 km² Hungarian part of the river basin area (Figure 8). Based on the topographical features, the catchment can be divided into two main parts. One-third of the basin in the NE is a sandy cone plain covered with wind-blown sand, where the surface is covered with sand and sandy loam soils. The altitude varies between 104 m and 159 m above sea level. The rest of the catchment has small relief intensity (approx. 2 m/km²) and is located at an altitude between 86 m and 101 m above sea level, sloping towards the SW. The surface features are predominantly of fluvial origin. Most of the surface contains clayey loam, clay, and loamy texture soils with low and extremely low hydraulic conductivity; thus, the infiltration properties of the surface are less favourable than in the Dong-ér catchment.

The simulated water balance of the catchment for 2018 has been presented in comparison with the Dong-ér catchment (Figure 11). In addition, a simulation was performed for a +1.5°C increase in mean temperature based on the IPCC climate scenario, and the model's sensitivity to the spatial density of cross-sections along the watercourses was investigated.

The analysis of the model outcomes highlights significant differences in the estimated water balance components, depending on the river cross-sections at every 0.5 km or 5 km. With a density of cross sections 5 km apart, the overland flow to brooks component is less than 98 mm, equivalent to nearly 270 million m³ of water. Besides, in the 5 km cross section data density model, the surface runoff exceeds 71 mm, and the water balance component shows a 27 mm surplus (80 million m³ water equivalent). Consequently, the selection of proper sampling density of river cross-sections plays a key role in the reliability of the hydrological model and thus indirectly on the water management strategies for the long-term adaptation to climate change.

The simulation results of the Berettyó river basin well reflect the low and extremely low hydraulic conductivity conditions of the soil. The surface water storage, surface runoff, and the water storage of the unsaturated zone exceed the values estimated for the Dong-ér catchment, made up of predominantly sandy sediments. The water balance of the Berettyó catchment – like the Dong-ér catchment – is highly dependent on the influence of subsurface boundary inflows from the neighbouring areas. Similar to the Dong-ér, the Berettyó river basin was also under water stress in 2018, but to a lesser extent.

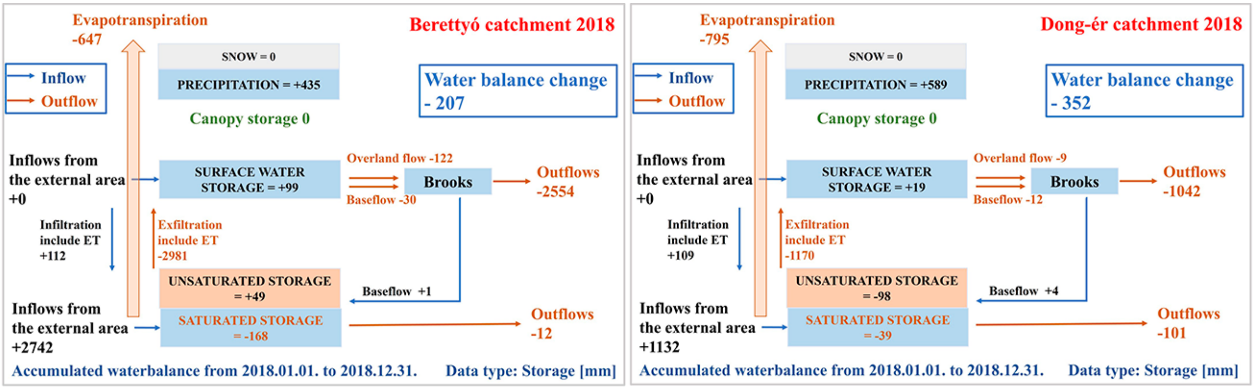

Figure 11. The water balance of the Berettyó and Dong-ér catchments in 2018

Discussion

As we have seen, the process of climate change over the last few decades has resulted in significantly different changes in water resources important to vegetation (and to agriculture in particular) across various landscapes. In smaller areas, adverse effects can be mitigated (irrigation, drainage), but long-term changes are determined by natural processes. Our study allowed us to assess the sensitivity of landscapes to climate change. Our assessment covered approximately 64 000 km^2 (68% of the territory of Hungary), and we separated six sensitivity groups (Figure 12).

a) *Landscapes at high risk to climate change.* These include the four sub-areas of the Danube-Tisza ridge and the three sub-areas of the Nyírség as well as the Hajdúság. Of the two contiguous areas, the longitudinal sand ridge of the Danube–Tisza Interfluve is more sensitive to drought periods because of its shape since the subsurface outflow is much more intense. The main reason for the significant water shortage in the area is the almost constant below-average rainfall from the late 1970s to the mid-1990s, when the volume of the accumulated rainfall deficit exceeded 1100 mm, and the intense rainy years were absent. The resulting water shortage of at least 5-6 km3 in the higher parts could not be compensated during the extremely rainy periods. This should be considered a long-term environmental condition. Water scarcity has been associated with significant landscape changes. The "restoration" of previous conditions is hardly conceivable and would result in substantial social conflicts since, although the majority is adversely affected by the landscape transformation, there are also beneficiaries. The development of irrigation in the region can only be economically profitable in small areas. On average, the landscape receives sufficient rainfall over many years that conscious conservation (especially in the soil, by increasing infiltration and reducing evaporation losses) can enable effective management. The area of Nyírség isdue to its shape better protected from the subsurface outflow. It is also slightly wetter, and sometimes it is even possible to regenerate the water resources in several heavily rainy years. However, a moderate depletion is more likely to persist.

b) *Regions threatened by climate change.* Mezőföld and Somogy hills were included in this category. Mezőföld has shown many similarities with the changes in the sand ridge of the Danube–Tisza interfluve since the 1970s. However, after a significant decline in resources, water resources appear to be normalising during the years with high precipitation of the 2000s.

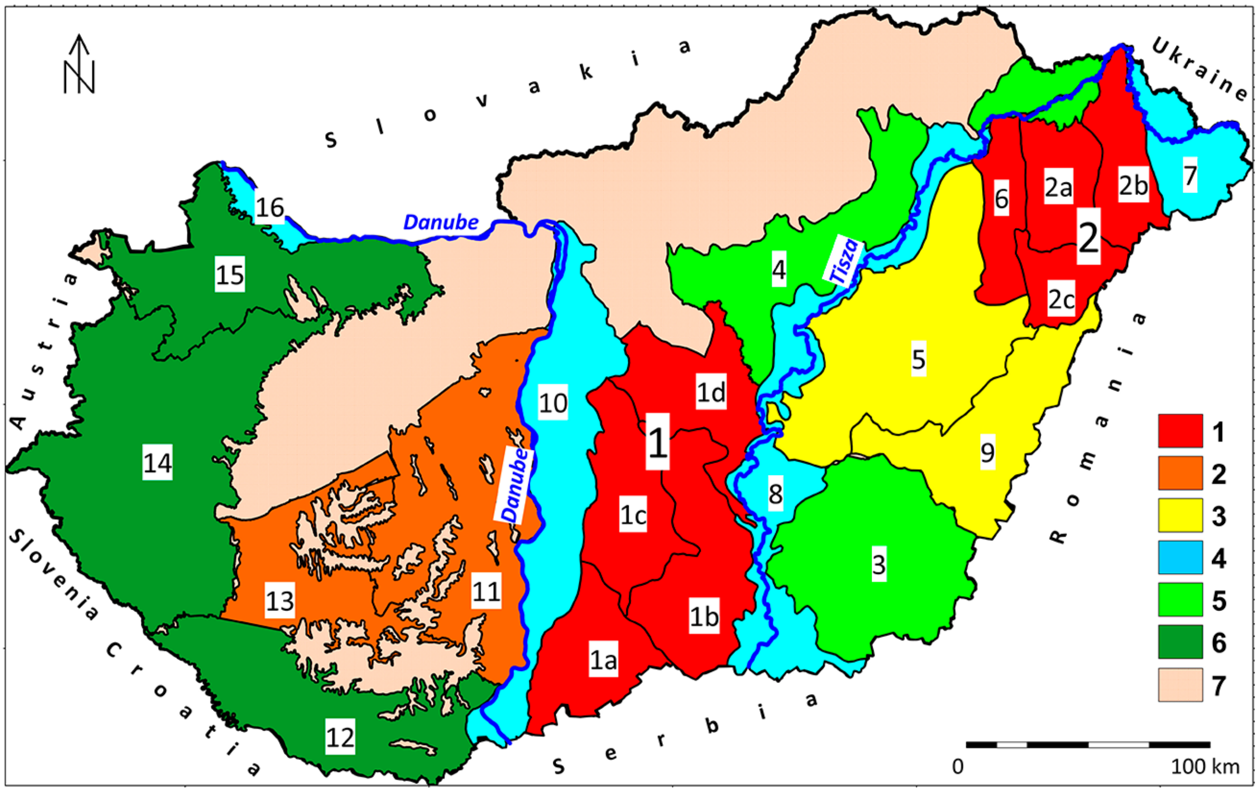

Figure 12. Climate sensitivity of Hungarian landscapes based on their water balance characteristics
a: Particularly vulnerable, b: vulnerable, c: moderately vulnerable, d: partially influenced by large rivers,
e: less vulnerable, f: hardly vulnerable, g: not assessed

However, a considerable decrease that appears relatively quickly can be observed during dry periods. Several consecutive wet years would only provide an opportunity for water supplies to rise to a multi-year average. In the Somogy hills, the network of measuring wells is incomplete, and its topography is heterogeneous. Therefore, the classification of this area is somewhat uncertain. However, faster changes in water resources suggest significant climate sensitivity.

c) *Moderately endangered landscapes.* Although the landscapes in this group have been intensely exposed to climatic effects, water management interventions have significantly reduced this vulnerability. The Central Tisza Plain and Berettyó–Körös Plain classified here are characterized by significant water resources fluctuations. A period of depletion due to climatic reasons from the 1980s to the mid-1990s can be observed, but to a lesser extent than would be justified by climatic effects due to extensive irrigation in the area. In the wetter period that followed, there was a significant increase in the water resources, also due to substantial inland excess water inundations). Thus, we experience larger reserves at the end of the period than 30-40 years earlier. Consequently, due to water management interventions, the impact of climate change is not visible. Thereby, maintaining current water management practices can largely eliminate the effects of climate change. It should be noted, however, that in a landscape divided by canals and smaller or larger watercourses, interpolation can show significant uncertainty.

d) *Areas partially influenced by large rivers.* Four distant areas were included in this category. They are characterized by close hydrological links with the large rivers in their vicinity. The Danube Plain on the left bank of the Danube can receive significant water replenishment through the previously deposited gravel sediments and riverbed remnants of the river. The Szigetköz after the diversion of the Danube receives water through water replacement systems. In a significant part of the Tisza Valley, dams influence the minimum water level of the river. In the case of the Upper Tisza Plain, rivers and subsurface flow from higher areas can provide additional water replenishment. Although previous research has not considered the impact of rivers larger than a few km significant, this needs to be reconsidered in recent decades. The effects of persistently lower water levels and dams change these views. Except for the Tisza Valley, a slow to moderate decline in water resources can be observed in all areas. However, reserves are already declining since there has been no significant flooding of the Lower Tisza in the last 15 years.

e) *Areas less vulnerable to climate change, as long as there are regular periods of heavy rainfall.* Despite the alluvial plain of the North Periphery of Great Hungarian Plain and the flat surface of the Maros–Körös Interfluve, they are closely linked to the mountainous areas to the north and south-east of the micro-regions, from where groundwater recharge is ensured, not only for the confined groundwater but also for the shallow groundwater. Based on recent periods, it can be concluded that while extreme rainfall distribution sometimes results in significant precipitation, the amount of groundwater can be continuously replenished from neighbouring regions.

f) *Landscapes least threatened by climate change.* We classified three regions in Western Hungary into this category. These were characterized by significantly more precipitation and fewer extremes during the last half-century than the national average. In the case of Kisalföld and Western Transdanubia, the local rainfall is presumably supplemented by reserves from the subsurface flow. In the case of the Drava plain, the role of the river in increasing water resources is less pronounced due to the topography and the effect of the dams established on the river and therefore, they are not classified in category d. Since the spatial change in the distribution of precipitation due to climate change and the increasing evaporation, the classification of the vulnerability of the landscapes may even change in the long run. There are two signs of this process. Based on the observations of the last 80 years a trend in the change of the precipitation distribution of Hungary can be suspected, with increasing occurrence of extreme hydroclimatic conditions, the eastern parts are slightly increasing, the western ones are decreasing. Furthermore, 2010 was the wettest year measured so far. This year the Kisalföld and Western Transdanubia received much less rainfall.

Our hydrodynamic models for the two small catchments based on future climate change show that the 1.5 °C temperature rise in the Dong-ér catchment will probably cause more severe water shortages than what we experienced as the consequence of the drought conditions of 2000. In the case of the Berettyó catchment, a 1.5°C temperature rise may reduce the area's water resources by 13%, equivalent to almost 80 million m^3 of water. According to the results, the water leaves the hydrological system primarily through evapotranspiration. The topographical setting enables a sufficient amount of groundwater to flow into the region from higher altitudes, ensuring to largely compensate for the water deficit but is insufficient to keep the balance of the water resources permanently. The models highlighted that subsurface inflow and evapotranspiration are the two main driving forces regulating the catchments' water balance in the Carpathian Basin. Among the water balance factors of the two investigated small catchments, the sensitivity of the components to the

1.5°C temperature rise is the following (in descending order): infiltration, water balance change, subsurface water storage, overland flow to the brook, and evapotranspiration.

Conclusion

Both society and agriculture need to adapt to the changing climatic conditions. In the Carpathian Basin, the more extreme rain distribution results in less precipitation remaining in place. Some of the extremely high rainfall flows in the form of floods out of the rivers. At the same time, efforts should be made to keep as much water as possible in the landscape.

The presented results have shown that the most crucial shallow groundwater resources for vegetation and thus for crop production in the last fifty years are generally shaped by precipitation conditions instead of human activities. Using the presented method, we show that in the mid-region's with an extent of 5-10 thousand km^2, the climate can change the water resources in both positively and negatively direction by up to 2-4 km^3 in 1-2 years of extreme rainfall, while in the Danube-Tisza Interfluve region with the highest groundwater depletion, the extraction of confined water over the past 40 years has been 2 km^3.

Changes in climatic conditions significantly affect the landscapes to varying degrees due to their natural environmental conditions. Through social adaptation, we must mitigate this, for which the results of the current study can provide vital support. Recognizing this, the *presented results were also incorporated into Hungary's updated River Basin Management Plan* completed in 2021 (OVF, 2021). Furthermore, our results have been considered in drafting the Hungarian legislation on regulating water abstraction for irrigation purposes. The next important step would be to consider the results for agricultural policy. Unfortunately, the answer to the extreme weather conditions is still drainage and irrigation. Yet the comparison of the spatial extent of the irrigated areas and the trends of irrigation water consumption shows the limitations undeniably (see Figure 7). In the last twenty years, the extent of irrigated areas is typically 1 000-1 200 km^2, while the area of arable land is more than 43 000 km^2. Characteristically, the irrigation water usage does not exceed 0.2 km^3 in most years. This volume is less than a tenth of the amount that climatic effects can cause to subsurface water resources annually.

In addition to irrigation, policymakers are seriously thinking about alleviating the problem of water-scarce regions through water replenishment. The other part of our research draws attention to the fact that this cannot be a satisfactory solution either. For example, 100-200 million m3 of water per year is planned to replenish the Danube-Tisza Interfluve sand ridge's water storages, which is no more than the amount that the small regions presented in our study lose through evapotranspiration due to the increasing temperature caused by climate change.

Considering landscape conditions in water management, efforts should be made to address water-balance conditions due to climatic effects. Soil scientists have long emphasized that soil is the largest natural reservoir, and that the top one meter can conserve up to one year of rainfall volume (Várallyay, 2007; Gálya et al., 2018). Therefore, improving soil structure and soil water balance properties might be the solution to the successful adaptation to climate change. Soil regeneration farming without deep plowing has proven that this can be successfully achieved in practice. Improved soil structure can retain more water in the soil layer during prolonged rainfall events, allowing for more efficient replenishment of the shallow groundwater. During drought, vegetation can access subsurface water resources easier. Unfortunately, yet only a few farmers are taking advantage of the versatile benefits of environmentally conscious and economical soil regeneration farming nowadays (, in addition to for example better water management, less fertilizer, and fuel use, less deflation, carbon sequestration, and significantly better crop yields). This type of farming is an essential step toward sustainable agriculture. Agricultural policy-makers should admit that it is a cheaper and easier solution to deliver the knowledge to the farmers than the water. However, the various compensation programs and financial support schemes do not encourage farmers to prioritise the prevention of drought and inland excess water damages. Part of agricultural subsidies should be realigned to assist farmers in more effective adaptation to the challenges of the changing climatic conditions by teaching them more sustainable agricultural production methods.

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