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Contribution of data-driven methods to risk reduction and climate change adaptation in Hungary and beyond

Edina Birinyi[1,2,*], **Boglárka O. Lakatos**[3,4], **Márta Belényesi**[1],
Dániel Kristóf[1], **Zsolt Hetesi**[5], **László Mrekva**[5], and **Gábor Mikus**[6]

[1] *Lechner Knowledge Centre, Remote Sensing Division*
Earth Observation Department

[2] *Eötvös Loránd University, Doctoral School of Earth Sciences*

[3] *General Directorate of Water Management, International Department*

[4] *University of Public Service, Faculty of Water Sciences,*
Department of Water and Environmental Policy

[5] *University of Public Service, Faculty of Water Sciences,*
Department of Water and Environmental Security

[6] *Lechner Knowledge Center, Remote Sensing Division*
Budapest, Hungary

**Corresponding author E-mail: edina.birinyi@lechnerkozpont.hu*

Abstract— Among a series of tangible phenomena related to climate change and ecosystem degradation, the severe drought damage that occurred in 2022 urges in particular a thoughtful and long-term concept to tackle and mitigate the effects of similar events. To develop this concept, in addition to taking stock of scientific results so far, it is crucial to establish the basis for mutually supportive cooperation between the sectors concerned, including agriculture, water management, and nature conservation.

As confirmed by scientific knowledge, the continuous deterioration of the landscape's water retention and evapotranspiration capacity is associated with weakening the climate regulating function and the degradation of agricultural production conditions. Accordingly, the task is not to find new resources and interventions ensuring the continuation of current landscape use; the real goal is to find the landscape use (farming methods and water use) that will ensure sustainable human livelihoods and environmental conditions.

All the tools and knowledge are available for the first steps and subsequent ongoing monitoring and refinement of a precautionary and prevention-based approach to support all levels of ecosystem services. With continuous professional dialogue and implementation of established and new methods, several goals can be achieved simultaneously, such as the integration of economic trends into the approach, the revitalization of Hungarian landscape culture, and hence the preservation of the rural workforce.

Key-words: drought, inland excess water, water conservation/retention, prevention-based approach, data-based decision making, remote sensing, Hungary

1. Introduction

Due to the accelerated hydrological cycle and the overuse of the landscape, drought, water scarcity, flash flood, and flood events occur in the same area and more frequently than they used to ("water surplus-water scarcity paradox" – *Kozma et al.*, 2022). According to data from the Hungarian Central Statistical Office (KSH), over the past 10 years, drought has affected more than 70% of the country's territory many times; meanwhile, during wet years of the same period, up to 10–15% of regularly cultivated arable land (> 4 million hectares) was periodically flooded (*KSH*, 2022a,b). The areas affected by both phenomena overlap to a significant extent.

According to the latest data registered in the Agricultural Risk Management System (MKR), extreme water scarcity and heat wave events in the summer of 2022 are among the largest ever observed, and had a very significant impact on agricultural production and natural ecosystems, with more than 1.4 million hectares of arable land affected by drought damage (*MKR*, 2022).

Meanwhile, climate models also show a significant increase in the frequency and probability of extreme events in the Carpathian Basin (*Kis et al.*, 2017; *Torma et al.*, 2020). This situation calls for a well-founded long-term concept, in which it is crucial to establish and strengthen the mutually supportive functioning of sectors concerned, including agriculture, water management, and nature conservation. Further prerequisites are that the concept should build on (i) existing scientific results of climate change and drought research, (ii) data and indicators (statistics) for monitoring drought impacts, and (iii) modern technologies, in particular remote sensing, which can be applied not only for monitoring drought impacts but also for their prediction to some extent. However, the practical implementation of this long-term concept will only be successful if the specific characteristics of areas in question, i.e., local conditions and their effects (landscape history, soil conditions, agrotechnology, etc.) are all considered. In a number of areas, the consequences of land use unsuitable for local landscape conditions cause problems, such as the frequent recurrence of flooding in former flood plains after the regulation of rivers.

Development of monitoring networks in combination with mindful landscape management could contribute to mitigating impacts of extreme events in several ways. Reducing both risks and effects of those implies changes in land use practice to retain water mostly in its original functioning area. Water should be considered the most significant part of the land. The current practice of draining out water during spring floods in the basin is only viable in years of steady water supply, whereas in years with extremely dry spring and summer, the aim should be to maintain high spring yields. Water-focused land use system could provide the "buffer zone":

- for water retention to reduce the upcoming drought effect, or
- to stock water for supporting evapotranspiration, irrigation, and local reduction of temperature, and
- to provide habitat and support at all levels in ecosystem cascades.

Adaptation to extreme weather events in the Carpathian Basin ultimately requires the implementation of circularity among a number of factors such as precipitation, soil conditions, vegetation, new types of crop production, water, nutrients, and (evapo-)transpiration. With the support and extended use of remote sensing data, we are, for instance, able to assess topsoil conditions and infer the available, cost-effective methods to improve soil conditions and health. The purpose of the article is to raise attention to data-driven methods that could take into account certain aspects listed above and contribute to drought-risk reduction and climate change adaptation.

2. Important historical background

2.1. Water management interventions in the Carpathian Basin

In the Carpathian Basin, the Sarmatians already carried out large-scale interventions that had an impact on the hydrographic conditions (e.g., Csörsz ditch), and the Romans also invested in, among other things, ensuring the navigability of rivers. Later, the water management system of the Árpád age, the spread of water mills, crop farming, deforestation under Turkish rule, flooding for military defense purposes, etc., all contributed to the continuous transformation of the hydrographic conditions and the expansion of the bog and marsh world (*Horváth*, 2018).

However, the development of agriculture, the spread of large-scale farming, and the rapidly increasing demand for agricultural crops (mainly grain) have led to more and more water management initiatives in order to increase production areas. In the meantime, commercial shipping also gained more and more space with the appearance of steamships, as well as the reduction of damage caused by floods and the rise of riverbeds caused by sediment deposition. In addition to preventing ice jams, the effective removal of ice dams became an important goal - the latter primarily on the Danube.

In the 19th century, the basic purpose of the regulatory works that began with great force was to help excess waters drain faster, to make water-logged and water-covered areas suitable for arable cultivation by draining them, and to ensure the navigability of our large rivers.

According to *Babinszki* (2017): "Before the river regulations, 13.7 percent (38,771 square kilometers) of historical Hungary was a floodplain, of which 36,700 square kilometers were exempted from flooding. The original floodplain of our country was 22,000 square kilometers, of which the tidal area under the control of our rivers is only 1,500 square kilometers. By the beginning of the 20th century, bends were cut in 18 places on the river Danube, shortening the river by 123 kilometers. The enormous change in natural geography is even more evident in the data of the Tisza watershed: the 112 crossings of the river Tisza reduced the length of the river by 453 kilometers, and the 248 bends of the rivers Körösök caused a shortening of 546 kilometers".

Thanks to the dam system, which was built as part of the river regulation and got later expanded and gradually heightened, the proportion of areas that could be brought under agricultural production increased, and the settlements in the exempted areas also expanded intensively.

Agricultural production in the landscape, transformed to a great extent due to changed conditions, has thus become more and more intensive, but at the same time has been struggling to this day with numerous negative phenomena partly caused by intensification and land use incompatible with the original landscape conditions. This also includes inland wetlands, whose potential territorial extent shows the pattern of hydrographic conditions before the regulations (*Babinszki*, 2017) (*Fig. 1*).

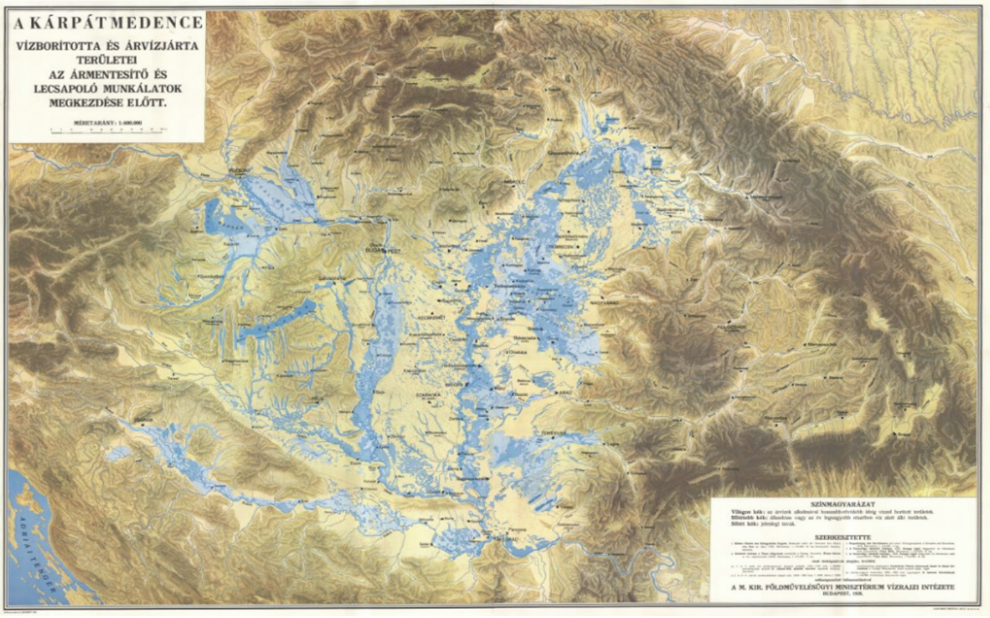
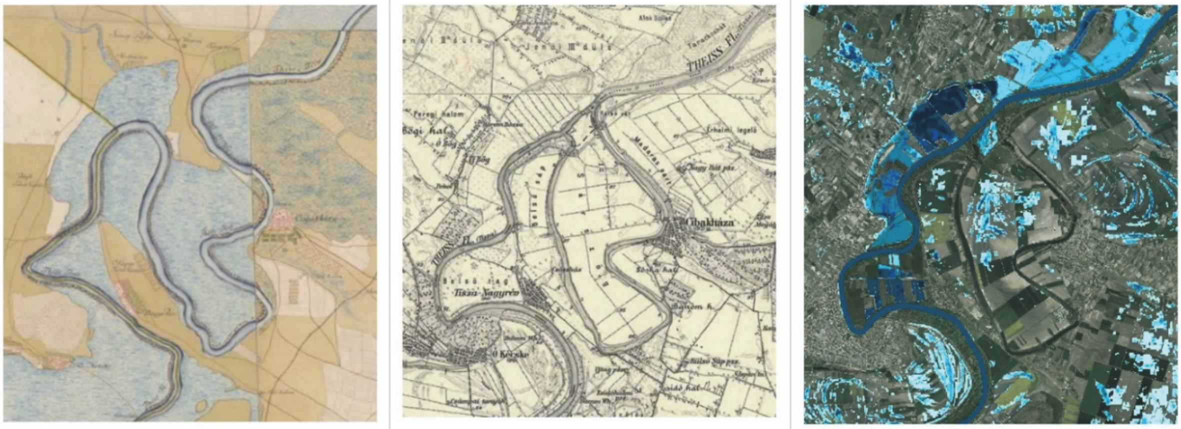


Fig. 1. Water-covered and flood-prone areas of the Carpathian Basin before the start of the relief and drainage works. *Source:* MBFSZ, 2023.

By comparing the maps of the first (1763–1787) and the third (1869–1887) military surveys *(Fig. 2*), some waves of regulatory work can be easily traced. The map sections below show the effects of cutting through the river bend on the example of Tisza River.



First Military Survey
(1763-1787)

Third Military Survey
(1869-1887)

Cutout of relative inland water frequency map (1998-2021) fitted to orthophoto (Cibakháza)

First Military Survey
(1763-1787)

Third Military Survey
(1869-1887)

Cutout of relative inland excess water frequency map (1998-2021) fitted to orthophoto (Tiszakeszi)

Fig. 2. Comparison of the first and third military surveys, and the relative inland water frequency map sections on examples along the river Tisza. Darker shades of blue represent more frequent inundation. *Source:* Arcanum Adatbázis Kiadó, 2023; LTK, 2023.

2.2. The original landscape-friendly water management

Flood is a natural phenomenon (*Kiedrzyńska et al.,* 2015), it is necessary both for nature as a whole and for farming as well. Groundwater resources along the river can be recharged during floods, which is also necessary for the climate-regulating activities of the forests and groves near the water (*Makarieva et al*., 2005). The floodplains and endemic forests along watercourses are important elements of the natural water system. Their role is essential in balancing the flow of water, preventing flood and drought disasters, and preserving and utilizing incoming water (*Pálfai et al.,* 2000; *Balogh*, 2001;). Under the influence of the geological structure, the morphological pattern and the natural vegetation cover, the surface and subsurface water cycle sections, the natural systems of the flat and mountainous areas of the Carpathian Basin are connected in a unique way into a cooperative water balance system. Therefore, it can be stated that mountain and lowland forests are the most important governors and preservers of waters of the basin.

The key elements of the outlined system are the floodplains of large extent and the equalizing and life-giving role of excess water management. This ensured the exceptionally good ecological features of the (inner) areas of the Carpathian Basin throughout history. Livelihood activities in floodplains were based on the active cooperation of watercourses, ecosystems, and communities. "Production" adjusted to the conditions of nature not only "withstood" the floods, but the spreading of excess water with human participation - keeping it in motion, and thereby preserving it at the landscape level, ensured the basis of livelihood, such as, for instance, traditional fishing on the Tisza, fruit growing, reed farming, livestock, and medicinal herb collection. Nowadays, the wide range of (eco)tourism opportunities can also be classified here (*Molnár*, 2005; *Kozma et al.*, 2022).

3. Connection of soil and water

3.1. Distribution and intensity of precipitation

In Hungary, increasing amounts of precipitation tend to occur outside the vegetation period; hence, to make water available for the vegetation at the right time, it has to be retained and retention capacity of the soil should be increased. Additionally, soil cannot absorb the significant amount of precipitation of increased intensity; therefore, this requires further preparation. We will examine both problems in more detail:

- Changing distribution of precipitation: Currently, a larger part of the annual precipitation in Hungary falls in the summer semester rather than in the winter one. Nevertheless, climate change models predict increasing amounts of winter precipitation (predominantly in the form of rain instead of snow), and decreasing amounts can be expected in summer. This has a negative effect on agricultural crops that still require rainfall during summer because of their longer growing period (e.g., corn, soybeans, or melons). During this period, they would need more water than the amount available from rainfall.
- Increased precipitation intensity and spatial variability: The chance of sudden rains and intense precipitation increases, i.e., the usual amount of precipitation can fall in a shorter time, and its quantity can vary to a large

extent within distances as small as a few hundred meters. The experience of the past years shows that the amount of precipitation during a specific rain event can exceed the usual amount for an entire month or even longer period, especially during thunderstorms.

3.2. Soil, fertility, tillage

During plowing, the topsoil (often containing organic material residues) and the subsoil in contact with the air change places, due to the rotating effect of the plow. However, the decomposition of organic matter is not complete. According to the latest research, the reason for this is that plowing significantly reduces the number of soil-dwelling microbes and specially fungi, while the role of these organisms is crucial in breaking down dead organic matter that forms on top of the soil, and turning it into humus (*De Vries et al.*, 2006).

All over the world, the organic matter content of soils decreases as a result of cultivation. Due to this phenomenon, estimates show that a total of 65-90 x 10^9 metric tons of organic carbon entered the Earth's atmosphere from soils. It is generally true that a 1% excess of organic matter in the soil accounts to 16 tons of organic carbon bound, and this means that an average of 45–65 tons per hectare of carbon disappeared from the Earth's soils. On 1.5 billion hectares of agricultural land, i.e., the organic matter content has decreased by 4% on average. At the end of the 1800s, organic matter content of around 10% could still be measured in the agricultural areas of Hungary; today, it is between 1 and 3% in most areas.

Furthermore, during plowing, the plow pan effect develops in the depth of the plow, i.e., the weight of the plow heads creates a hard, compacted layer during plowing, which the roots cannot break through and is highly impermeable to water. In practice, this means that the upper 25–35 cm of dusty, structureless soil layer must absorb and retain the incoming precipitation.

In addition to the formation of the plow pan layer, however, the structure-destroying effect of tillage has other consequences, as (*Dobos,* 2022a) and his colleagues draw attention to. As the crumbly structure of the soil is lost, its healthy pore system is transformed and degraded. In addition to degrading the healthy water-air ratio, the narrow pores are easily clogged, and the water absorption and retention capacity is drastically reduced. After rain, the soil becomes muddy, a significant part of the water flows on the surface instead of infiltrating, or stalling, forming inland excess water. Later on, the same surface dries out and hardens: "on a hot day, it behaves like concrete in the middle of a big city: it sheds heat from itself, drying out its surroundings, increasing the heat and drought” (*Dobos*, 2022b).

4. *State of art of water resource management, affected sectors*

4.1. Water management

In Hungary, water management is currently determined by the River Basin Management Plan (VGT) (*OVF*, 2022), which is reviewed every six years based on the Water Framework Directive 2000/60/EC 2000. The first modernized, revised version of VGT1, VGT2, and then VGT3 in 2021, summarizes the loads, condition assessment of our waters, and the progress necessary to achieve good conditions. Based on this, the environmental objectives and action programs for the period between 2021–2027 are determined. In addition, the document "Significant Water Management Issues" (*OVF*, 2019) focuses on the hydrological consequences of drought and climate change, in addition to the quantitative and qualitative issues of surface water, the effect of dams, pollution, and drinking water bases.

Our vulnerability to climate change can be assessed on the basis of the quantity and renewal potential of groundwater resources. The domestic situation is presented on the VGT 3rd Strategic Environmental Assessment (SKV) map and the explanation below (*Fig. 3*).

“In Hungary, due to the effects of climate change, the importance of the fight against extremes in water management is increasing. Without human intervention (passive adaptation), the maintenance of today's water-ecological economic-social conditions cannot be ensured in the future!” (*OVF*, 2022).

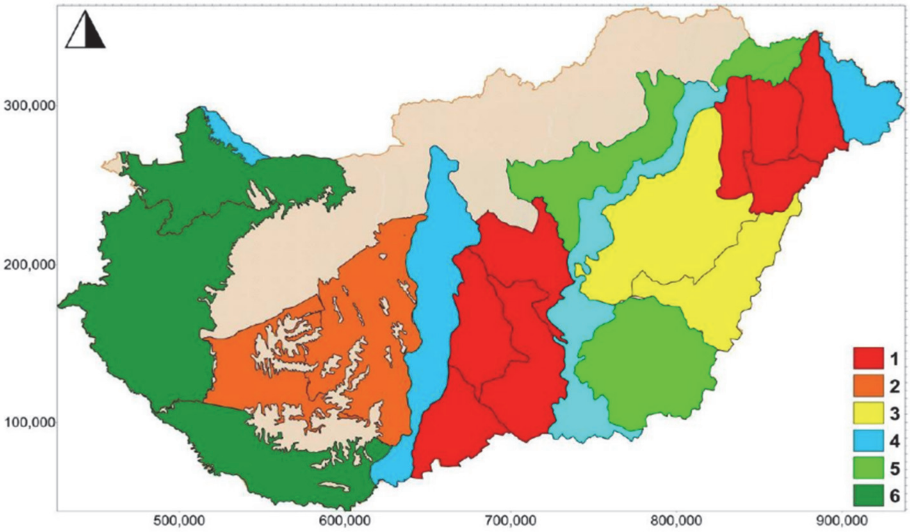


Fig. 3. The threat of groundwater resources due to climate change in the small villages of our country. *Source:* VIZITERV Environ Kft.

The goals set out in the Strategic Environmental Assessment are to create an integrated water management framework based on measurements, so that water damage prevention and water resource management activities can entirely fulfill their role by maintaining or improving ecosystem services (*OVF,* 2021). Water management strategies, action plans, and the proposals for adapting to the effects of climate change – including measures aiming natural water retention and adaption to climate change – are defined in the River Basin Management Plan Hungary 2021 (*OVF*, 2022).

4.2. Agriculture

The extreme water scarcity and heatwave of 2022 have had a significant impact on agricultural production and natural ecosystems. In Hungary, more than 1.4 million hectares of arable land were affected by drought damage (*MKR,* 2022*)*, and it was reflected in the number of agricultural damage claims in 2022 (*Fig. 4*).

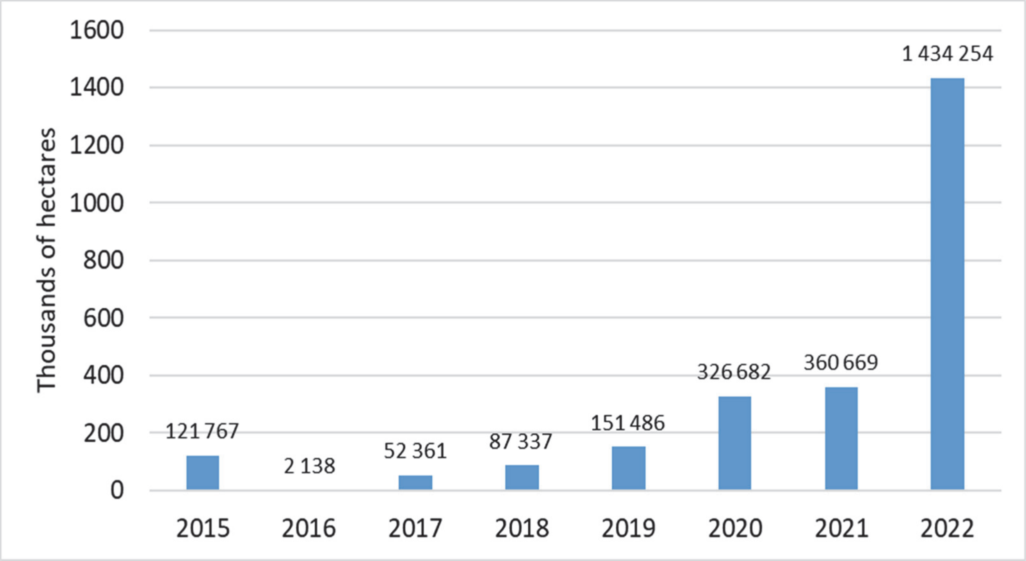


Fig. 4. The total area of drought-related agricultural damage claims between 2015 and 2022. *Source:* Lechner Knowledge Center, based on the Agricultural Risk Management System (MKR).

In connection with the 2022 drought, a new regional study over the operational area of the Trans-Tisza Region Water Directorate (TIVIZIG) located in the northern part of the Great Plain was performed by Zs. Hetesi and T. Bódi. They examined the change in the contiguous duration of rain-free days between 1964–1989 and 1990–2022 during the vegetation period, using the data of the 15 measuring stations of TIVIZIG. The alternative hypothesis of the research was that the distribution of extremely long (>25 days) rain-free periods differs between the two intervals.

The results of the F-test performed on the data sets with a confidence level of 95% are published here first, showing that a significant difference (increase) occurred in the length of rain-free days between the periods 1964–1989 and 1990–2022 (*Fig. 5*) in the northern part of the Great Plain, which must be taken into account when developing future drought prevention strategies.

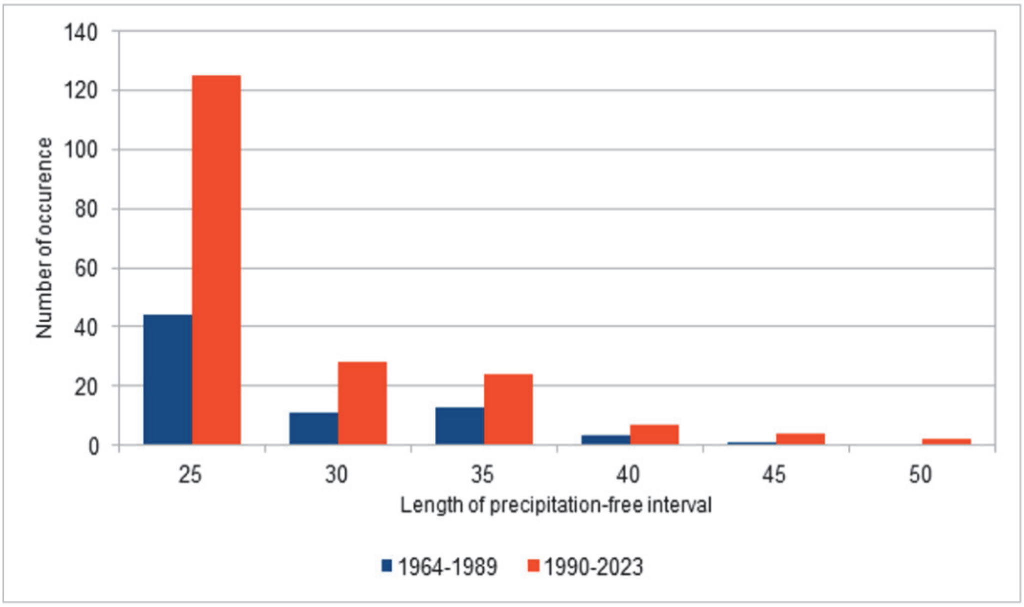


Fig. 5. Length of precipitation-free intervals (expressed in days) for the periods 1964–1989 and 1990–2023. *Source:* based on TIVIZIG measurements

Increasing the proportion of irrigated agricultural land and irrigation development are often mentioned as a way of "solving" the issue of water scarcity and drought damage in agriculture. *Fig. 6* illustrates the trends in agricultural water use between 2000 and 2020, showing that decreasing rainfall is associated with increasing irrigation water use.

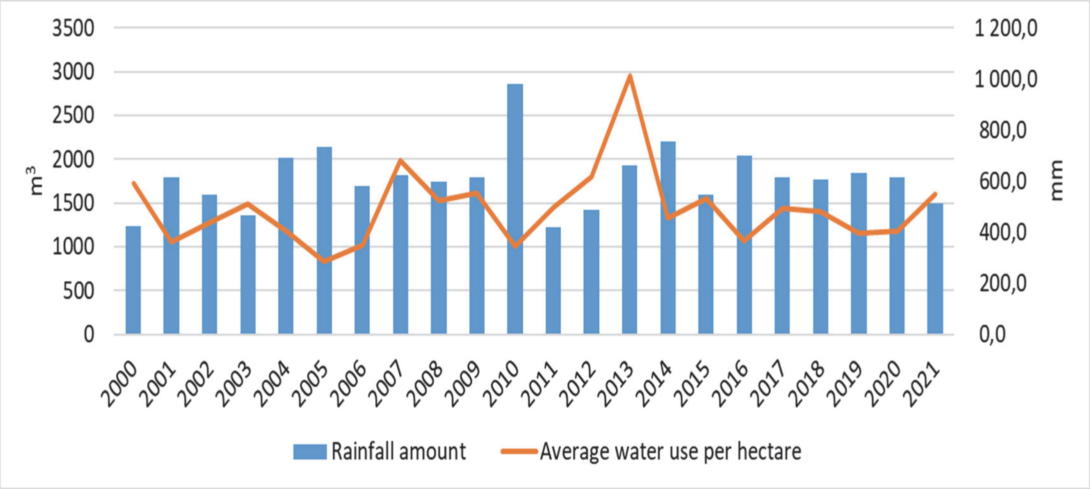


Fig. 6. Trends in agricultural water use between 2000 and 2021. *Source:* KSH data (KSH, 2022c).

However, it is important to stress that irrigation alone cannot solve the problem. As shown in *Fig. 7,* the proportion of irrigated land is orders of magnitude below the drought-affected area. Meeting the needs of the huge water demand of an intensive irrigation development – both in terms of area and water quantity – is not a realistic goal, especially if other conditions are kept unchanged.

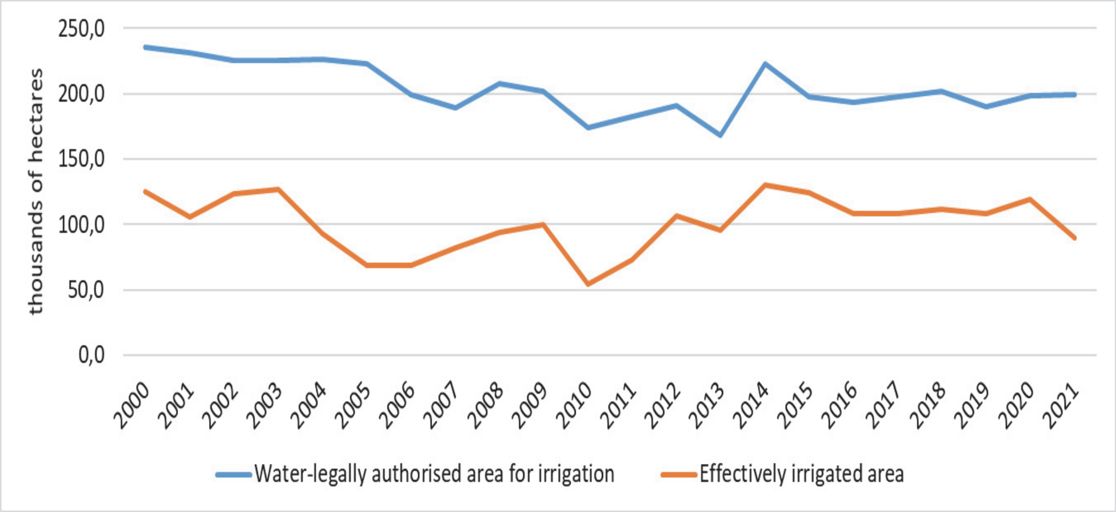


Fig. 7.: The extent of irrigated area between 2000 and 2021. *Source:* KSH data (KSH, 2022c).

Water abstraction for irrigation – calculated on the water deficit of about 1.8–2.2 billion cubic meters of the total irrigable area – can have a significant negative impact on the water flow of rivers at low water periods. In the long term, about 1.5 billion cubic meters of water scarcity and resulting water demand can be expected on the Great Plain (*Jung*, 2022). This amount cannot be replaced from rivers in low water periods; hence, solutions stocking water from the rivers at high water periods are necessary, such as water retention in the landscape and by using artificial structures.

Irrigation or its development is indeed necessary in the case of certain crops (e.g., vegetables), this is the only way to satisfy conditions for their (further) cultivation. However, in the case of field crops, other solutions must also be implemented for the successful adaptation to changing circumstances.

5. Current decision support and planning tools

Geographic Information Systems (GIS) have become a widely used tool for complex analysis and planning tasks involving a wide range of data and spatial relationships. In Hungary, IT systems in various sectors connected to water management (water, nature conservation, agriculture, disaster management etc.) use GIS solutions for everyday tasks. Besides this, GIS is a very efficient tool to solve specific, multi-sectoral problems, permitting easy integration of cross-sectorial data and the expertise.

Data from remote sensing images has become a key in recent decades in several application areas, while rapid development in aerial remote sensing techniques has also enabled high-resolution and high-precision analyses. Aerial photographs and the derived orthophotos, as well as surface and terrain models produced by laser scanning (LIDAR) and other technologies are the cornerstones of any water management planning (*Szabó et al.*, 2017; *Uuemaa et al.*, 2018; *Demelezi et al.*, 2019; *Nagy et al.*, 2020; *Csatáriné et al.*, 2020).

Furthermore, the increasing amount of data yielded by different earth observation satellite systems (e.g., NASA/USGS Landsat missions, https://www.nasa.gov/mission_pages/landsat/main/index.html; ESA/EU Sentinel missions, https://sentinels.copernicus.eu/web/sentinel/home), open data policy, and the decades of available archives of imagery provide a unique opportunity to understand the past and present of a given area. Among others, the nature and condition of vegetation, changes in land cover, extent of surface water, and soil moisture content can all be observed and measured by satellite data, studying a single time or time series of images (*Csornai et al.*, 2007; *Mucsi* and *Henits*, 2011; *van Leeuwen et al.*, 2020; *Kozma et al.*, 2022).

In the light of the above, it can be stated that data-driven planning of water retention can most effectively be achieved through systems integrating GIS and remote sensing tools. The following provides an insight into the solutions currently available for this purpose.

5.1. The Agricultural Risk Management System (MKR)

The fundamental objective of MKR is to provide a unified system for mitigating the economic impact of adverse weather events on agricultural production and to manage compensation for damages (*Act CLXVIII of 2011,* https://net.jogtar.hu/jogszabaly?docid=a1100168.tv). The system handles a complex and multifaceted database, facilitating the work of all actors and processes involved in the compensation process, namely farmers' damage reporting, claims and payments of compensations, insurance, and official controls. MKR also plays a major role in decision-making at management and executive levels (*Nádor et al.*, 2018; *NAK*, 2020).

In 2012, the former Institute of Geodesy, Cartography and Remote Sensing (FÖMI) joined the national project for MKR development; the Lechner Knowledge Center (LTK) took over its tasks in 2019. LTK contributes to the effective operation and development of the system by achieving and processing high- and medium-resolution optical satellite images to map and monitor the extent and temporal/spatial frequency of certain phenomena caused by extreme weather events in agricultural areas. LTK produces the following maps and databases:

- operational inland excess water maps for specific dates and periods,
- inland excess water frequency maps,
- drought maps maps indicating anomalies in the values of vegetation indices to characterize crop conditions, and
- drought frequency maps (see more details in Section 5.2).

These data are regularly uploaded to the central database of MKR and shared with other relevant institutions.

5.2. Mapping drought, crop condition, and inland excess water

Mapping of agricultural crop conditions, resulting from more than a decade of research and development in Hungary, plays a fundamental role in drought damage assessment, (*Csornai et al.,* 2006, 2007). Thanks to the continuous research and development activities, crop conditions or drought maps have been improved and adapted to the technologies and data sets currently available and produced in a routine manner for operational use.

Originally, the mapping was based on the processing of medium-resolution MODIS satellite images, as at the launch of the MKR in 2012, the 250 m resolution images of the MODIS sensors (https://modis.gsfc.nasa.gov/about/) on NASA's Aqua and Terra satellites provided the fastest available and openly available data for this task. The maps consider a time series of optical images from more than 20 years within a given period of the year, typically August, depending on the weather. The spatial resolution of the maps is 250 meters, i.e., one pixel covers an area of approximately 6.25 hectares. Therefore, the maps are not suitable for field-level analyses at typical Hungarian parcel sizes but can be used to identify regional variations.

Besides assessing and estimating the damage in a given year, the long time series (20 years) of satellite data provides an opportunity to produce a drought frequency map (*Fig. 8*) as well, an indicator of high importance for a long-term adaptation to the phenomenon. The map shows a percentage of drought-affected years for each pixel over a 20-year period.

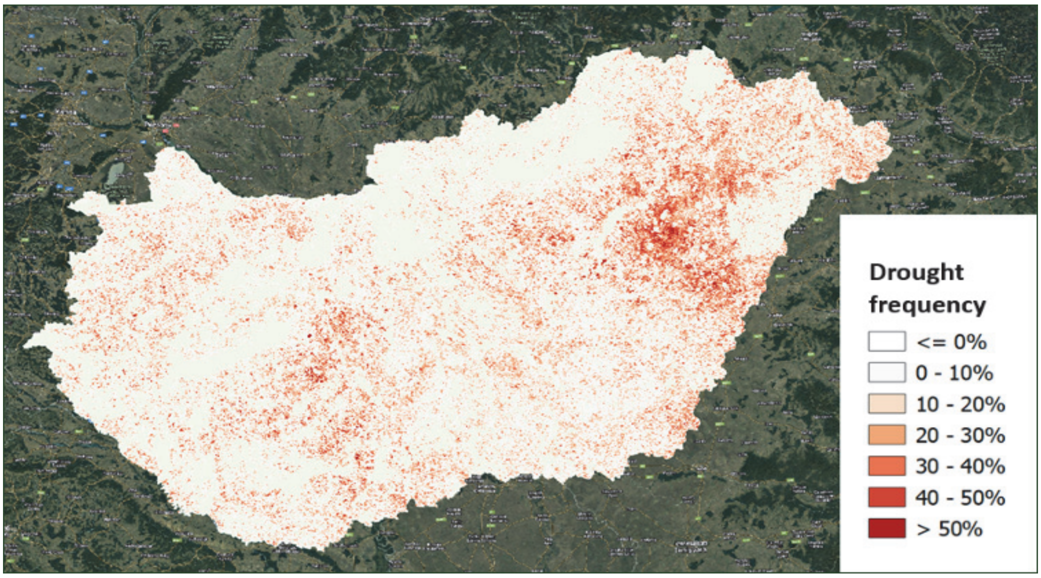


Fig. 8.: National drought frequency map for the second half of August (based on a time series of MODIS satellite images between 2003 and 2022). *Source:* LTK.

In 2021, *Birinyi et al.* (2021) conducted a drought sensibility study on maize fields based on time-series of medium-resolution MODIS images, and from 2022 onwards, methodological developments of crop condition mapping based on high-resolution Sentinel-2A and 2B satellite images have also been started (*Birinyi et al.*, 2022a, 2022b, 2022c). Multiple different spectral indices are calculated from the values measured at different wavelengths, providing information on photosynthetic activity, leaf water content, or the amount of green biomass, thus enabling a complex assessment of local vegetation conditions.

LTK experts also use openly available high-resolution Sentinel-2 and Landsat 8/9 satellite images for operational inland excess water mapping. The spatial resolution of these images allows observations at a sufficient level of detail. The workflow requires high-level expert control for the fine-tuning of mapping thresholds to provide status maps for a given day over the affected areas. Clouds can constitute a major hindrance in the availability of optical images. Depending on the availability of cloud-free imagery, period-integrated inundation maps are also created based on several images taken at different times. The longer-term study of the damage event's impact is ensured by processing satellite images acquired on different dates: a first one as early as possible after inundation, and another several weeks later. The combination of the two produces a so-called persistent excess water map, which provides an adequate characterization of the waterlogging situation in a given area over longer periods. These maps are only made for agricultural areas eligible for area-based payments (SAPS) at a resolution of 10 or 30 meters, depending on the sensor. The categories of the map provide information on the extent of open water surfaces, vegetation standing in water, and waterlogged soil (i.e., saturated with water).

Similarly to the drought frequency map, regularly updated relative inland excess water frequency maps are also provided by LTK. The methodological developments of LTK's predecessor institution, FÖMI, resulted in flood and inland excess water maps for parts of the country and, in certain years, for the whole country, starting from 1998 (*Nádor et al.*, 2018). The most recent map was made by integrating the yearly maps produced in the period of 1998–2021 showing the number of times a certain area was inundated or waterlogged during the study period (*Fig. 9*).

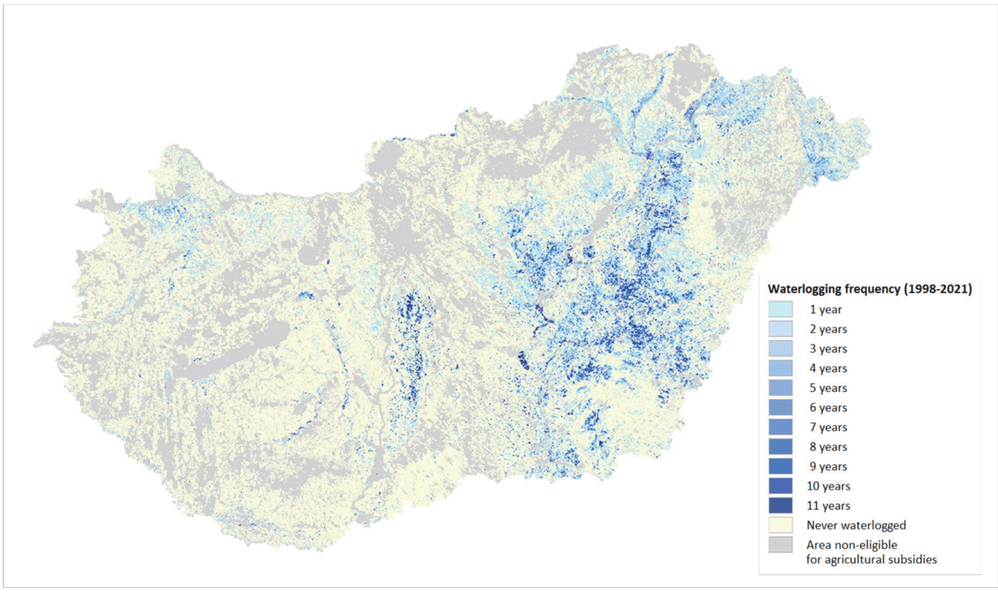


Fig. 9. Country-wide inland excess water / waterlogging frequency map (1998-2021). *Source:* LTK.

5.3. Mapping crop conditions in the extremely dry year of 2022

5.3.1. Drought maps derived from MODIS sensor data

In 2022, responding to the extremely dry weather, LTK started to produce MODIS-based crop condition maps from May on and uploaded them to the MKR central system twice a month until the end of August. To respond quickly, the first maps provided information for all eligible agricultural areas included in LPIS, but later, when claim data became available, the maps were re-generated with bare soil or stubble parcels excluded from the analysis. In total, LTK provided 13 country-wide MODIS-based maps to the MKR from May to August 2022 (*Fig. 10*).

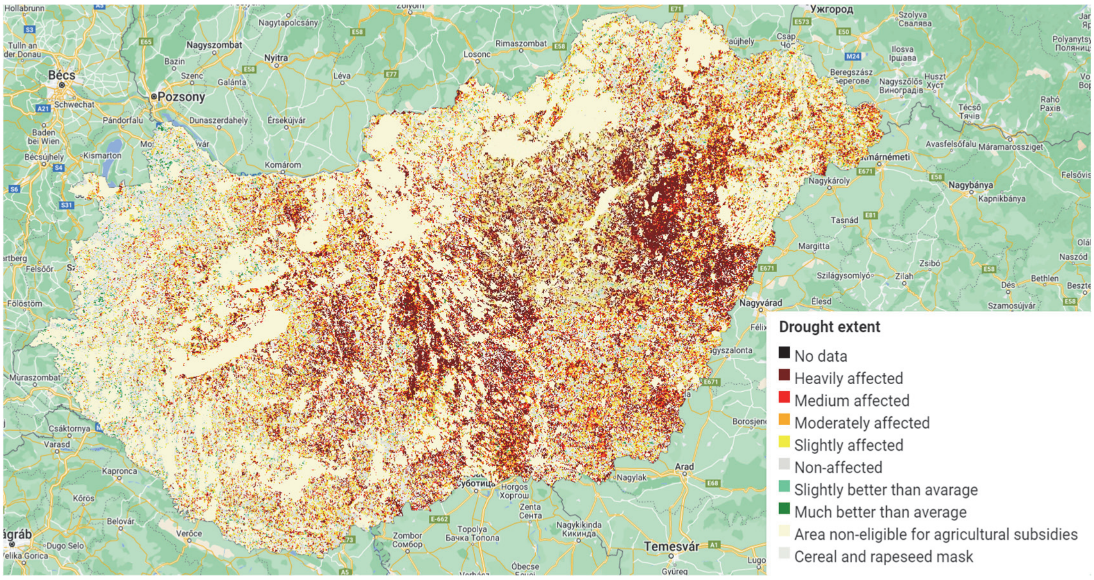


Fig. 10. Drought extent in the first half of August, 2022. *Source:* LTK.

5.3.2. Development of high-resolution crop condition maps

In 2022, LTK experts developed a methodology for integrating high-resolution Sentinel-2 (A and B) satellite imagery in crop condition mapping *(Birinyi et al.*, 2022c). These satellites of the European Union (EU) and European Space Agency (ESA) provide optical images with spatial resolutions of 10, 20, and 60 meters every 2-3 days, which could be used to significantly increase the level of detail of resulting maps. It is a promising direction for the MKR in laying the foundation for parcel-level or even more detailed drought mapping, and the results could also contribute to supporting data collection for the new

Common Agricultural Policy (CAP) (*EU Regulation 2021/2115,* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R2115). However, the method requires further validation to prepare the operational use of results.

The most significant outcome of this research is the ability to provide high-resolution crop condition maps, specific in terms of location, time, and crop type. The underlying methodology is based on the integrated analysis of multiple different spectral indices including three vegetation indices, a moisture content index, and a yellowness index. The map identifies six condition categories depending on the number of indices showing values worse than those typical for the given crop in similar periods in previous years in the given area. The results were shared with the National Food Chain Safety Office (NÉBIH) for four different periods and two agricultural crops (maize and sunflower) during the summer of 2022 to assess operational application. Besides this, ground truth was also collected by LTK experts in five locations in August 2022 over 250 sample points for quantitative validation and fine-tuning. Although detailed investigations are still ongoing, field visits and expert feedback so far indicate that the categories correspond well to plant conditions observed on the field (*Fig. 11).*

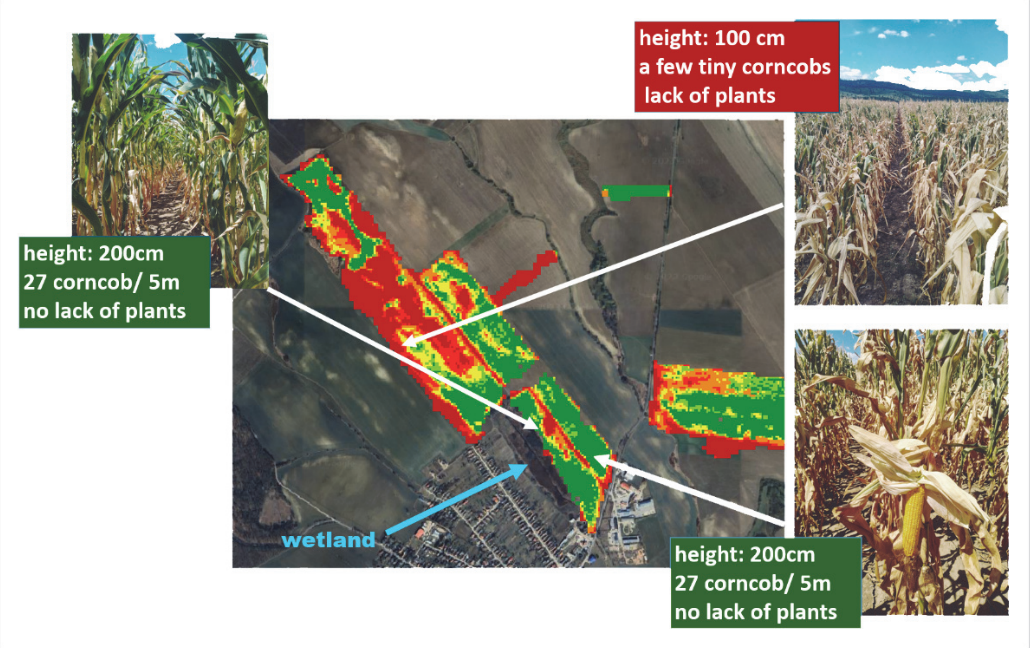


Fig. 11. Pattern of the high-resolution crop condition map and its correlation to on-the-spot observations. *Source:* LTK.

Fig. 12a and *12b* introduce some map extracts on the example of maize.

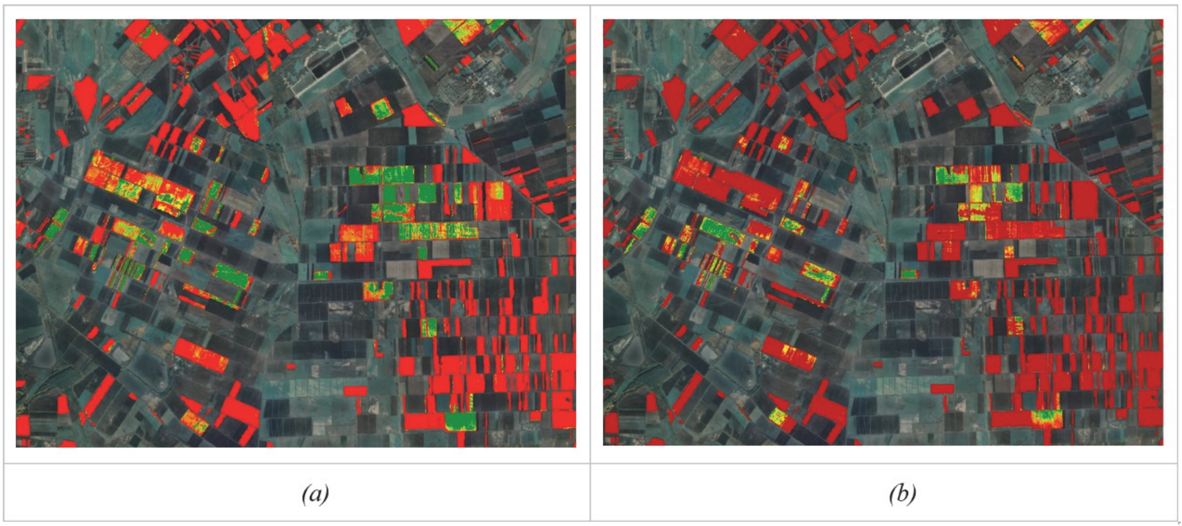

(a) *(b)*

Fig. 12. Illustration of the high-resolution crop condition map: maize fields in the surrounding area of Karcag, on July 3, 2022 (a) and July 23, 2023 (b). Crops in worse condition than in previous years appear in yellow, those in much worse condition in red. *Source:* LTK.

5.3.3. Soil moisture data from space

In addition to damage assessment and monitoring, satellite sensors can potentially be used for forecasting, considering that soil moisture (among other factors) at any given time has a significant influence on subsequent plant conditions.

Passive microwave sensors (e.g., SMOS mission https://earth.esa.int/eogateway/missions/smos; SMAP mission https://smap.jpl.nasa.gov/mission/description/) can be used to monitor soil moisture status from space (*Eswar et al.*, 2018*; Remote Sensing Special Issue,* 2023). Although the spatial resolution of these data is small, at the same time they provide frequent revisits. For example, the processing chain of NASA's SMAP (Soil Moisture Active Passive) satellite, operating since 2015, provides modeled soil surface and subsurface moisture values with a spatial resolution of 9 kilometers almost every day. Besides the “usual” summer drought period, these data also contribute to monitoring the increasingly frequent "spring drought" events to a great extent (*Fig. 13*). The latter are the consequence of the decrease in winter precipitation and the lack of slowly melting snow cover. *Fig. 13* illustrates the phenomenon on SMAP soil moisture values for February 2022, when the soil was significantly drier compared to the same period of the previous year, especially in the country's eastern regions.

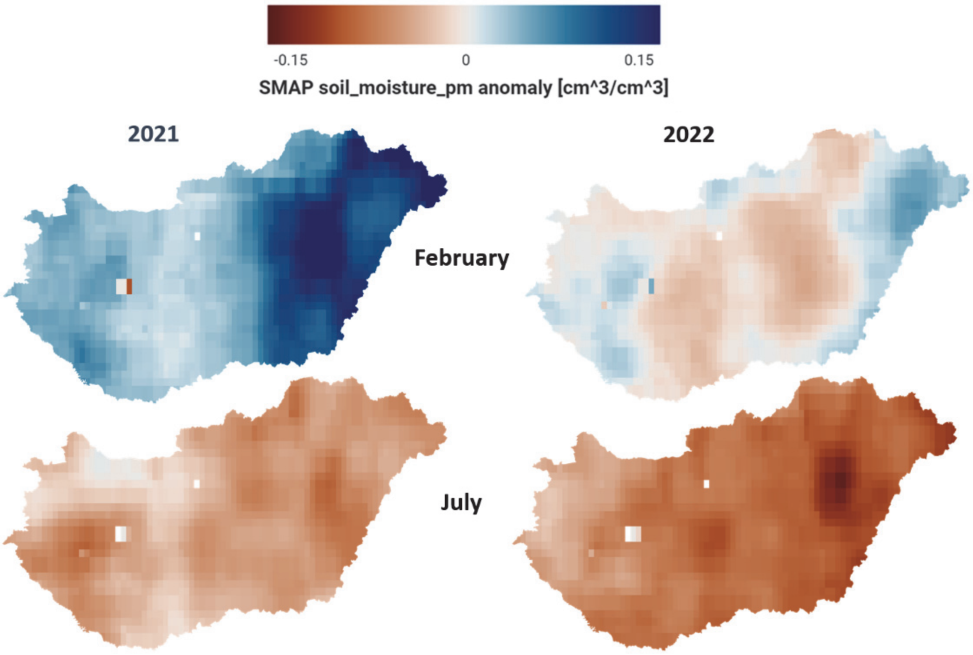


Fig. 13. Soil moisture anomalies based on SMAP data in late winter and summer in 2021 and 2022. *Source:* NASA, SMAP / Google Earth Engine / LTK.

When comparing SMAP soil moisture of the years 2021 and 2022, the difference in moisture deficit is striking between the western counties (e.g., Zala), covered with forest mosaic, and the eastern half of the country, predominantly composed of arable lands (e.g., Jász-Nagykun-Szolnok county), especially in early spring 2022. Although this difference had largely disappeared by August 2022, the conditions under which agricultural crops could develop during the main growing period were spectacularly different (*Fig. 14*).

When used carefully and thoroughly, the above methods and instruments can support the reconsideration of the current practice and the development of a more sustainable, integrated, and water-efficient land management with consideration of all ecosystem cascade services that human life is based on.

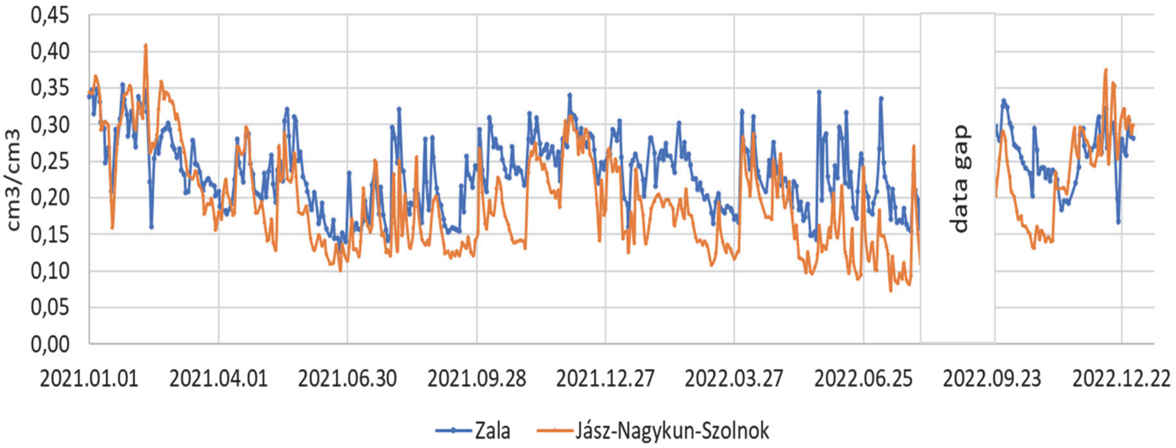


Fig. 14. Time series of SMAP surface soil moisture data for years 2021 and 2022 for two Hungarian counties (Zala and Jász-Nagykun-Szolnok) showing significantly different moisture conditions. *Source:* LTK, based on SMAP data.

6. Summary, recommendations

According to the "Global Risk Report 2023" released by the Davos World Economic Forum, "Climate action failure" stands on the first and the second places of global risks overall (*WEF*, 2023).

In order to adapt to the extreme weather effects expected in the Carpathian Basin, it is crucial to introduce sustainable land and water management by restoring the relationship and ensuring proper balance and efficient fluxes among precipitation, soil conditions, vegetation, crops and water, nutrients, and evaporation (*O.Lakatos et al.*, 2022).

6.1. Soil health

6.1.1. No till

In order to heal the framework of soil conditions–vegetation–crop and water–nutrients–evaporation, the first necessary step is the wide-scale introduction of soil-conserving cultivation techniques, including the abandonment of plowing as much as possible.

The essence of the method is that with the mindful use of cover crops and the absence of plowing, a deeper, structured layer is formed in the soil, permitting the retention of a larger amount of precipitation and a deeper penetration of rainwater into the soil, making it capable of retaining up to 100% more rainwater (*Hetesi*, 2019).

6.2. Land cover change, mulching in agriculture

6.2.1. Buffer strips, installation of agro-forestry systems

Buffer strips are areas of natural vegetation cover (grass, bushes, or trees) at the margin of fields, arable land, transport infrastructures, and water courses. They can have several different configurations of vegetation types, varying from grass-only to different combinations of grass, trees, and shrubs. Due to their permanent vegetation, buffer strips offer good conditions for effective water infiltration and slowing down surface flow; they, therefore, promote the natural retention of water. They can also significantly reduce the amount of suspended solids, nitrates and phosphates originating from agricultural run-off. Buffer strips can be located in riparian zones, or further away from water bodies as field margins, headlands, or even within fields (e.g., beetle banks). Hedges across long, steep slopes may reduce soil erosion as they intercept and slow down surface run-off water before it builds into a damaging flow, particularly where there is a margin or buffer strip alongside (NWRM website, http://nwrm.eu/measure/buffer-strips-and-hedges).

6.3. Water management by creating place for it with a mosaic landscape structure

Where the potential evaporation is greater than the available precipitation, there is no harmful water, only water that has no place. The problems of inland excess water and drought are largely caused by the fact that the current water management approach is territorially minimized, as there is literally no place for water.

Water replacement must be built on spreading floods and retaining inland excess waters. It requires a mosaic landscape structure and a management practice that matches landscape features. Mosaicism means that water replacement and the formation of local waterlogging can be solved by re-creating temporary or permanent wetlands in areas that are essentially not suitable for agricultural cultivation. A dominant proportion of these areas was originally waterflow or largely water-affected land.

Landscape use oriented at water buffering (i.e., acquiring excess water and returning it in a natural way) could also save the conditions for arable farming. As an estimate, 2/3 of the current production can be secured by the extensive transformation of arable land.

A reasonable territorial compromise can be a solution to the problems that have arisen, during which nearly half a million hectares of land along the Tisza – least suitable for intensive production – would be returned to the landscape, for sustainable landscape management. The Tisza valley, therefore, does not need artificial reservoirs but hundreds of thousands of hectares of flood plain (*Balogh*, 2022; *Murányi* and *Koncsos*, 2022).

A few thoughts on irrigation: replenishment of water-deficient areas can be solved primarily from the low water flow rivers. Due to the characteristics of our country, we currently do not have areas suitable for water reservoirs where we could retain and store large amounts of irrigation water. Reservoirs in the river bed, e.g., above Tiszalök, and the existing reservoirs, such as Lake Tisza, are not primarily used to hold back large amounts of water, but rather to provide a short-term buffer and to enable gravity water withdrawals. If the water from these reservoirs were to be used for irrigation during a prolonged period of water shortage, gravity water extraction above Tiszalök would be impossible.

Withdrawal of irrigation water can significantly affect the small water yield of rivers in an unfavorable direction, with the totality of irrigable areas requiring approximately 1.8–2.2 billions of cubic meters based on their calculated water deficit. Looking at the long-term processes, we can expect a water deficit of around 1.5 billion m^3 in the Great Plain of Hungary, and consequent water demand. This quantity cannot be replenished from the water of the rivers during low water periods. Artificial and landscape water retention is therefore necessary, which mainly taps the high water flows.

6.4. Data-based planning

Besides global and local weather conditions and their variability, several interacting factors influence water balance in the landscape and its hydrological extremes (e.g., drought, inland excess water), such as:

- surface and groundwater conditions and their changes,
- topography, morphology (runoff, water retention),
- soil conditions (water storage capacity, drought sensitivity, etc.),
- type of land cover (evaporation, cooling capabilities, erosion prevention, etc.),
- type of land use and cultivation (soil conservation, soil structure retention, preventing soil degradation, erosion control, etc.),
- hydrology of the area, water balance, water quality,
- the 'history' of the landscape, both in terms of hydrology and land-use change (the key to solving water retention issues is often rooted in this),
- other current landscape characteristics (e.g., built-up areas, land reclamation, the impact of water works and water management, etc.),
- ownership tenure,
- regulatory regime, legislative framework,
- data policy,
- et cetera.

Therefore, mapping damage events related to climate change and their consequences, modeling and identifying areas at risk and development of adequate solutions require the close cooperation of several disciplines and areas of expertise, including governmental and non-governmental organizations and people working to solve local problems, including farmers.

To develop strategies on both local and national levels, it is essential to acquire a thorough understanding of all these factors, and to carry out conscious planning based on all relevant data and knowledge.

So far, data collected in various sectors by research institutes, measurement networks, or field surveys have resulted in the establishment of large specific information systems, e.g., in the fields of water, meteorology, soil, nature conservation, forestry, land registry, land parcels, etc. In certain areas, though, there is a need for further surveys and mapping activities; for example, a unified national inventory of grasslands and wetlands would serve climate policy as well as agricultural and nature conservation efforts to a great extent.

Besides this, several professional and research institutes build in their practice the multi-purpose use of airborne data (LIDAR, hyperspectral or orthoimages) and medium- and high-resolution satellite images, mainly those freely available from the European Space Agency (ESA) and NASA to solve national and regional or local tasks.

Together with the databases and processing methods mentioned above, the long-time series of remote sensing images can provide a solid basis for trend analysis, anomaly detection, and modeling. All of these data and techniques should play a significant role in the long-term strategic development of climate change adaptation, responding to and monitoring of ad hoc phenomena (e.g., force majeure), and for revealing cause and effect relationships.

Numerous research institutes are at the forefront of state-of-the-art data processing, with machine learning and artificial intelligence algorithms being applied by almost all national research and R&D laboratories with expertise in meteorology, soils and water management, land cover and land use monitoring, ecology and vegetation research. With this experience, these laboratories and institutes can effectively contribute to the preparatory studies for a strategy or to solve specific problems of smaller regions.

In connection with the above, we draw attention to all the research on landscape history, as well as to the proposals of organizations, people, and farmers working on local issues; those, by involving invaluable local knowledge, offer reasonable solutions for the questions about where and how to preserve the water in the landscape.

So, the data and expertise are given, but harmonized use of them faces many difficulties.

Droughts and floods, among many other phenomena, are the "output products" of a complex, systemic problem, which is global climate change, combined with often inappropriate land use practices. Responding to these phenomena requires complex thinking, greater interoperability of information systems, and closer cooperation between disciplines, local farmers and land users. An integrated decision support system can hardly develop in the right direction (or fast enough) with an insufficient stream of information or without mutual feedback among underlying information systems and disciplines. For instance, assessment of crop conditions and payment of compensations should be integrated with the analysis of satellite imagery along with soil and meteorological conditions and compensation claims. Likewise, delineation and management of areas suitable for water retention should be based on landscape characteristics and integrated with water management and land consolidation.

Currently, in Hungary, the low degree of interoperability – mainly due to the rigid data policy – constitutes a major hindrance for rapid response and effective solutions for situations resulting from the climate crisis.

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