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H-1091 Budapest, Üllői út 25., Hungary
Phone: +36-(1)-201-7655,
Fax: +36-(1)-202-7244
Email: titkarsag@hidrologia.hu
Web: www.hidrologia.hu
Represented by: József VÁRADI,
Co-President of the Hungarian Hydrological Society

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Magyar Hidrológiai Társaság
1091 Budapest, Üllői út 25. IV. em.
Tel: +36-(1)-201-7655
Fax: +36-(1)-202-7244
E-mail: titkarsag@hidrologia.hu
Honlap: www.hidrologia.hu
A Kiadó képviselője: Váradi József, a Magyar Hidrológiai Társaság társelnöke

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Tartalomjegyzék

Címlapkép: A Magyar Tudományos Akadémia logója

Foreword

Two hundred years ago, on November 3, 1825, Count István SZÉCHENYI donated one year's income from his estates to establish a Hungarian scientific society. This act marks the founding of the Hungarian Academy of Sciences (MTA). Over the past 108 years, the Hungarian Hydrological Society has maintained a close relationship with the Academy in the field of water sciences. With a nationwide network covering all branches of water science, the Society has facilitated connections between researchers and practitioners. Members of the Academy and its various bodies have played a key role in this collaboration. With our cover page, featuring the coat of arms of the Hungarian Academy of Sciences, we honour the 200th anniversary of the founding of this esteemed institution.

We are pleased to present the 2025 English-language edition of the Hungarian Journal of Hydrology (HK), the official periodical of the Hungarian Hydrological Society (MHT).

This volume covers a number of professional topics. In addition to core hydrological themes, this issue also explores topics such as water policy, limestone caves, and peat bogs, reflecting the journal's commitment to professional excellence and innovation. We are confident that both our international and Hungarian readers will find these articles inspiring and thought-provoking.

In her article, "*Assessing the recharge of peat bogs in Northern Germany using various methods*," *Sára MOLNÁR*, a young researcher from the Budapest University of Technology and Economics, investigates groundwater recharge between 2018 and 2023 in two peat bogs in Schleswig-Holstein, Germany, using various simulation models.

The Buda Castle Cave, a natural limestone formation with over 800 years of history as man-made cellars, is the subject of the study by *Fanni GAZDA, Dávid FARKAS, Géza HAJNAL and Dénes SZIEBERTH: "Quantitative Drip Water Measurements in the Buda Castle Cave Using Classical and Modern Methods".* This research focuses on measuring drip water volumes and identifying changes compared to earlier data. It also explores the relationship between drip locations, water flow, and precipitation.

Bálint RÓZSA's article, "*The Role of Bilateral Memoranda of Understanding in Hungarian Water Diplomacy*", discusses how Memoranda of Understanding (MoUs) help foster professional cooperation between Hungarian institutions – such as the General Directorate of Water Management – and foreign partners, especially in countries that do not share transboundary water resources with Hungary. Since 2013, more than 50 such agreements have been signed.

The Hungarian Journal of Hydrology is committed to supporting the next generation of water professionals. In line with this mission, the YOUTH CORNER section offers high school students an opportunity to publish their research. We invite readers to support their efforts with respect and encouragement. The featured study, prepared for the 2024 Hungarian competition of the Stockholm Junior Water Prize, is by *Benedek SANTA, Márton FREI, and Zoltán BAROCSAI: "Improving the Water Retention Properties of Our Soils".* The article explores how different soil mixtures affect water retention capacity.

In the HISTORICAL SNAPSHOT section, *Gábor ALBERT* recalls the "heroic age" of Hungarian water management, associated with Imre Dégen, who served as President of the National Water Office. This period began 70 years ago and ended 50 years ago, offering a fitting moment to review Dégen's policy achievements and their lasting impact. The overview is based on bibliographic sources, archival materials, and personal recollections of his contemporaries.

The BOOK REVIEW section presents the book: "*Life from, for and to Water*" by *János J. Bogardi*, recommended by Springer as:

- A history of water quantity and quality for preserving healthy ecosystems,
- An inspiring personal account of various water resource projects,
- Motivation for those seeking a future profession or beginning a "water career".

In that section also featured is the book "*Hydrogeology of the Pannonian Basin"* by *István Almási and János Szanyi*, part of the "*Important Aquifer Systems of the World"* series by The Groundwater Project. The Pannonian Basin, shared by nine countries, is one of the world's most complex sedimentary aquifer systems.

We extend our thanks to the authors, reviewers, and editorial board for their dedication and support in bringing this English-language issue to life. Welcome to the English edition of the Hungarian Journal of Hydrology.

Veronika MAJOR
Editor-in-Chief

Assessing the recharge of peat bogs in Northern Germany using various methods

Sára MOLNÁR[1]

[1] Budapest University of Technology and Economics, Research Assistant (email: molnar.sara@emk.bme.hu)

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Abstract

Most peatlands in Northern Germany suffer from increasing water balance deficits and decreasing groundwater levels. According to recent studies, this is not only a local trend but is observed throughout the Northern Hemisphere. Ombrotrophic bogs function as natural lysimeters and are solely rain-fed, therefore the assessment of their groundwater recharge can be a great option for the water balance evaluation of their region. From the difference between their climatic and modelled water balance, deductions about external anthropogenic effects and climate change can be drawn. This study uses environmental tracers: isotopes and major ions for the estimation of the groundwater recharge. The tracers were analysed from groundwater samples from different depths, taken from two peat bogs in Schleswig Holstein with different characteristics. The water balance can be inferred from the groundwater recharge of recent years, estimated from the depth profile of environmental tracers. Different models were applied to simulate the recharge from 2018 to 2023, based on measured and collected data: a groundwater balance method based on climatic variables estimated a 193 mm/year recharge. The modelling by Hydrus 1D estimated 420 mm/year, the cumulative method estimated 240 and 280 millimetres for the two study areas, while the isotope model estimated 162 and 173 mm/year based on the concentrations of Oxygen-18 and deuterium. However, problems with the sampling can be inferred from the results, therefore conclusions must be drawn with caution.

Keywords

Peatland, hydrology, groundwater, water balance, recharge, ion-chromatography.

Észak-németországi tőzeglápok vízutánpótlásának értékelése különböző módszerekkel

Kivonat

Az észak-németországi tőzeglápok többségénél a talajvízszint csökkenése tapasztalható a növekvő vízháztartási hiány miatt, ami a legújabb kutatások szerint az északi félteke egészére jellemző tendencia. Az ombrotróf tőzeglápok természetes liziméterként működnek, vízutánpótlásuk pedig kizárólag a csapadékból származik, ezért a talajvíz utánpótlásuk értékelése kiváló lehetőség lehet a régiójuk vízmérlegének vizsgálatára. Az éghajlati jellemzőkből számított és a modellezett vízmérlegük különbségéből antropogén hatásokra és klímaváltozás okozta változásokra lehet következtetni. Jelen vizsgálat természetes nyomjelzőket: izotópokat és főbb ionokat vizsgál a felszín alatti víz utánpótlásának becslésére. A nyomjelzők Schleswig-Holstein tartomány két tőzeglápjának különböző mélységekből vett vízmintáiból kerültek elemzésre. A felszín alatti víz utánpótlását a természetes nyomjelzők mélység menti koncentráció változásából lehet megbecsülni a csapadék izotóp és ion koncentrációinak, illetve a talajt és a transzport folyamatokat jellemző különböző paraméterek ismeretében. A mért és becsült paraméterek felhasználásával így különböző modellekkel szimulálásra került a felszín alatti víz utánpótlása 2018 és 2023 között. Egy éghajlati változókra alapozott talajvízmérleg-módszer 193 mm/év vízutánpótlást becsült, a Hydrus 1D modellezése 420 mm/év értéket adott, a kumulatív módszer 240 és 280 millimétert becsült a két vizsgálati területre, míg az izotóp modell az oxigén-18 és deutérium koncentrációi alapján 162 és 173 mm/év értékeket adott. Az eredményekből azonban mintavételi problémákra lehet következtetni, így megállapításokat csak kellő körültekintéssel lehet tenni.

Kulcsszavak

Tőzegláp, hidrológia, talajvíz, vízháztartás, feltöltődés, ionkromatográfia.

INTRODUCTION

Wetlands are complex ecosystems, performing significant environmental and economic functions, providing numerous ecosystem services (*EPA 2003)*. They can store, filter and purify water, while they are modulating the atmospheric concentrations of some of the most dominant greenhouse gases (*Salimi et al. 2021*). Around 20 to 30% of the world's carbon pool is comprised in wetlands, making them a terrestrial ecosystem that has the highest carbon density (*Salimi et al. 2021*). If the layer of organic soil, built up from plant remains is thick enough (more than around 40 centimetres), then the wetland is called a peatland (*Price et al. 2023*). Ombrotrophic mires (bogs) are those peatlands that only receive water from precipitation and are therefore poor in solutes compared to minerotrophic mires (fens) that have groundwater and/ or surface water inflows as well (*Koster 2005*).

While wetlands, including peatlands are vitally important during climate change, they are among the most threatened ecosystems globally due to the rapid changes in climate and human activities, such as peat mining, land reclamation, the unsustainable degree of irrigation, agriculture, urbanization, drainage, and pollution. Although in general they are highly resilient to change – as they are fluctuating hydrologically between an aquatic and a terrestrial state every year – their ecosystem and functions are not flexible enough to adapt to all the additional changes and disturbances (*Salimi et al. 2021*). The altered hydrology and biogeochemistry of peatlands can lead to a higher rate of decomposition, carbon dioxide and methane emissions, and the release of nutrients instead of water purification (*Gutierrez Pacheco et al. 2021*). To mitigate the negative impacts on wetlands, monitoring and restoration projects are essential to assess their current state, identify the main threats, and implement management strategies to restore and conserve them. The first step is to quantify the recharge of groundwater and the sustainable yield with a high accuracy, which can provide a strong basis for sustainable groundwater management plans (*Sajil Kumar et al. 2021*). Recharge should be estimated with a method, which can be frequently updated, that is economical and easily feasible. A straightforward method for understanding groundwater flow is by tracing the movement of a dissolved substance through the groundwater. Environmental tracers, like major ions and isotopes are naturally present in groundwater, therefore the application of ion and isotope profile methods can be a great option for the estimation of point recharge (*Cook 2020*). The stable isotope and ionic composition of precipitation shows clear seasonal variations, which can be tracked through the groundwater column (*Yao et al. 2024*). This method can give a more accurate estimation than the groundwater balance method (*Sajil Kumar et al. 2021*), where the recharge is essentially the difference of total precipitation, groundwater inflow and outflow and potential evapotranspiration. This tracer technique was applied in the current study as well, following the example of several researchers, who have investigated solute and isotope concentrations to assess recharge mechanisms in different geological settings (*He et al. 2012, Joshi et al. 2018, Sreedevi et al. 2022*).

The aim of this study was to present an easily feasible method for the estimation of the yearly groundwater recharge in Northern Germany and to better understand the groundwater recharge of peat bogs in the area. Water rights are granted on the basis of outdated recharge estimations in the region, while there is already a huge pressure on groundwater and due to the increasing rate of evapotranspiration, the overall groundwater recharge is decreasing (*Wunsch et al. 2022*). The calculation of groundwater recharge in ombrotrophic (rain-fed) bogs can be a good proxy for regional groundwater recharge, because these bogs rely exclusively on atmospheric inputs (precipitation) and are largely insulated from direct groundwater contributions due to their perched, waterlogged nature. This allows them to act as natural rain gauges, capturing long-term precipitation patterns and evapotranspiration losses, which are primary components in estimating recharge (*Rydin and Jeglum 2013*). If the amount of yearly precipitation is higher than the evapotranspiration in the area of these bogs and their net recharge is positive, but their groundwater level is gradually decreasing, it can be inferred that the amount of water extractions from the connected aquifer is unsustainable. Therefore, two ombrotrophic bogs were chosen as study areas in the vicinity of Lübeck. The bog close to the municipality of Horst is located on a clearing of a forested area, far from roads, urbanisation or agricultural activities. The second sampling location on the other hand is located on the edge of Krummesser Moor, which is part of a water logging initiative by the city of Lübeck, focusing on raising the groundwater level to its original level to restore the once species-rich wetland, reduce greenhouse gas emissions, and support native biodiversity (*Lübeck.de 2022*). Over the past 20 years, measures such as closing inland ditches, and installing adjustable dams have been implemented to regulate water flow and improve habitat conditions, but further rewetting is still necessary. The area has now become a valuable ecological site and popular recreation destination, attracting bird enthusiasts (*Lübeck.de 2022*).

MATERIALS AND METHODS

The recharge of groundwater was calculated and modelled based on four different methods depicted in *Figure 1,* in order to reach more validated scientific conclusions on the basis of concordant data. It was important to choose models that describe the system and its representative factors well, that are based on the appropriate concept of tracer transport, and are calculating the behaviour of the tracer in the system correctly (*Leibundgut et al. 2009*). To model the transport of environmental tracers, a known or measured input and output of the same parameters (e.g. volume, concentration) is necessary as a function of space and time. Concentration time-series of solute and isotope concentration in precipitation was obtained from the weather stations at St. Jürgen and Wasserpfad, next to the Lübeck University of Applied Sciences (TH Lübeck). It was important to use several tracers, so that the possibility of the wrong understanding of the hydrological system - because of limitations or errors of a particular tracer or method - can be excluded (*Leibundgut et al. 2009*).

Sampling was carried out at Krummesser Moor and at a peat bog close to the municipality of Horst. Samples were analysed in the laboratory of the TH Lübeck (for solute concentrations) and at the laboratory of Hydroisotop in Schweitenkirchen (for isotopes). Input data for the recharge estimations were measured, collected and estimated based on literature and expert opinion or acquired from online databases. The flowchart of the study is depicted in *Figure 1.*

The study areas

The climate in the investigated region of Northern Germany is classified as temperate oceanic, with relatively mild temperatures (the average annual temperature is around 9 °C) and high precipitation levels (around 640 mm/year) throughout the year (*Climate 2024*). Two ombrotrophic bogs were chosen as the study areas of the study, located 18 kilometres from each other in Schleswig Holstein, which is the Northernmost state of Germany. A significant characteristic of these bogs is that they are perched above the local water table and rely entirely on precipitation for their hydrological needs, with no significant groundwater inflow (*Gajewski et al. 2001*). One of the study areas was at Krummesser Moor (*Figure 2/a*), to the South from Lübeck and to the Northwest from the lake of Ratzeburg, in an area surrounded by a larger (120-hectare) wetland. The second successful sampling was carried out close to the municipality of Horst (around 500 meters from Pinnsee) at a small peat bog in a clearing of a forested area, around 2 to 3 meters from a small lake (*Figure 2/b*).

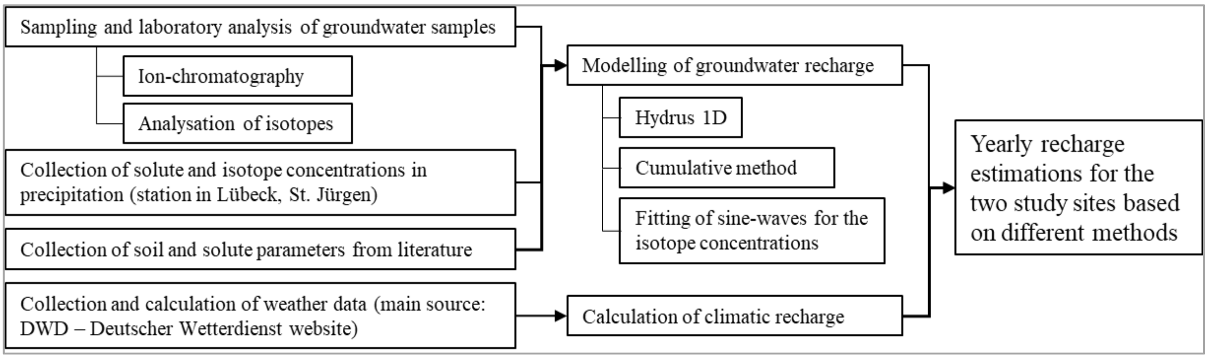

Figure 1. Steps of the groundwater recharge assessment of the study
1. ábra. A talajvíz-utánpótlási vizsgálat lépései

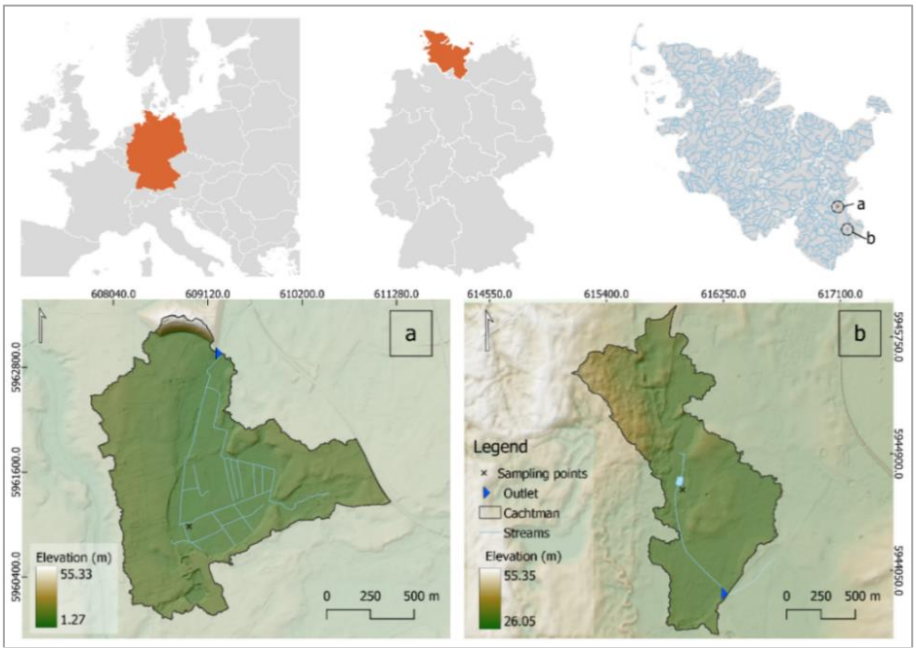

Figure 2. Map of the two study areas: Krummesser Moor (a) and the peatland near Horst (b)
2. ábra. A vizsgált területek térképei: Krummesser Moor (a) és a tőzegláp Horst közelében (b)

The soil in the study areas is primarily composed of peat, which is rich in organic matter and has a high water-bearing capacity. The vegetation of both study areas is predominantly composed of sphagnum moss. The topography of Schleswig-Holstein is characterized by a predominantly flat terrain, with low hills and occasional depressions. Glacial deposits, deformed by salt structures of the rising Permian and Upper Triassic are characterising the near-surface geology of Northern Germany. The "Lübecker Basin" was mainly formed during the Weichselian (Würm) Glaciation and its main inflow water stream is the Trave (*Grube and Lotz 2004*).

Around a quarter of the area of Northern Germany is affected by inland salinity, originating mainly from the upcoming of deep-seated salt waters from the pre-Tetriary sub-ground. Salty water reaches the shallow aquifer system at several locations in Schleswig-Holstein, thus salty springs and seashore salt grass also emerge across the region (*Magri et al. 2009*). *Grube and Lotz (2004)* investigated the distribution pattern and the origin of salinized water (>250 mg Cl/l) in the region. Intensive pumping in the 1970s resulted in the widespread drop of groundwater potential in the region, some depressions reaching 10 m below sea level. The decrease in the level of the groundwater table resulted in the mobilization of seawater and several pumping wells had to be abandoned. Since then, the situation has improved thanks to regulations, but in some parts the salinization is still increasing. It is important to note, that *Grube and Lotz (2004)* investigated a West-East cross section of geological layers between the Segeberg salt diapir and the Baltic Sea, which crosses 4.8 km north from Krummesser Moor. The thickness of the geological layers is very thin below the area and the salt diapir is less than 150 meters from the surface, which can potentially have an influence on the solute concentrations of groundwater at Krummesser Moor.

The investigated peat bog near Horst is in the watershed of Pinnsee. The lake does not have any in- or outflows above ground, it is purely fed by the precipitation in the catchment area and has a slowly decreasing water level (*Roehl 2023*). The interaction between the lake and the groundwater was investigated with the application of analytical element models by *Roehl (2023)*. Although the Pinnsee has no outflows on the surface, the calculated water balance indicated the presence of an outflow, prompting an investigation into the possibility of groundwater discharge. A surface water body, corresponding with the watershed was found, at the very location of the peat bog investigated in this study, near Horst. Therefore, there is a through flow, i.e. a lateral component in the groundwater flow at the peat bog, but it is much (around 50 times) smaller than the vertical gradient.

Sampling

The sampling equipment was a two-meter-long copper rod with small 1.5-millimetre openings on the last 5 centimetres and with a sharpened, closed ending. Inside the copper rod, there was a plastic tube (diameter: 0.5 cm), which was connected to a pump. The rod was inserted into the ground until the desired depth, after which the pump was turned on and a sample was collected when the pumped water turned visibly clear. After the collection of a sample (of 200 ml), the rod was pushed to the next desired depth, where the method was repeated after waiting for two minutes, to make sure that the water is no longer mixed, and it is coming from the desired depth. Due to the soil composition and the sponge-like behaviour of peat, the rod was easily pushed– and pulled - by hand until the desired depth. The sampling interval was 10 centimetres, and samples were collected from a 1-meter-deep column at Krummesser Moor (on the 3rd of May, 2023) and from 1.5 meters at Horst (on the 25th of June, 2023). The samples were taken to the laboratory and after filtration solute concentrations were measured by ion-chromatography. Samples from Horst were also sent to a laboratory for the analysis of isotopes.

As for Krummesser Moor, water temperature (10.7-15 °C), pH (decreasing from 6.6 to 5.8), electric conductivity (541-618 μS/cm), oxygen concentration (0.51-0.8 mg/l, 4.7-8.0%) and redox potential (175-200 mV) were measured on the field using a multimeter. From the fluctuations of the measured values between higher and lower peaks, it can be assumed that two years of recharge can be seen in the 1-meter-deep profile, as three lower and two higher peaks were observed, representing winter and summer concentrations. At the second sampling close to Horst, after the copper tube was completely pulled out, the tip of the rod was missing, thus the tube was open at its end. This gives a reason to treat the collected samples and the later acquired data with caution, as the depth where the tip has separated is not known and it is possible that the pump was not only sucking the water from the desired horizontal layer, but from a mixed water column below as well.

While the measured pH is similar to the measured values at Krummesser Moor, its range is considerably smaller (5.16 to 5.33). The electric conductivity was five times smaller compared to Krummesser Moor (91 to 112 μS/cm) and it was almost constant (excluding the first two samples). This could mean that the pumped groundwater was mixed indeed, but it cannot be unequivocally concluded simply from these values.

Laboratory analysis

Environmental tracers are powerful tools for understanding groundwater systems, offering insights into the origin, age, and recharge processes of groundwater. Unlike artificial tracers, which are less effective for slow or large-scale systems, environmental tracers - which are naturally integrated into the groundwater - provide a more accurate picture of the movement and aging of water (*Cook 2020*).

The transport of solutes through peat is controlled by the complex combination of physical factors and biogeochemical conditions. The latter is governed by the reactivity of organic matter and the presence of chemical species that are sensitive for redox reactions, like nitrate and sulphate (*Price et al. 2023*). As peat is a dual porosity medium, it has both mobile and immobile porosity. Solutes can get into the smaller pores with immobile porosity via diffusion from the solute flowing in the mobile region. The amount of these smaller pores is increasing with depth (*Price et al. 2023*). Tracers must be chosen carefully, considering the high complexity of peat. An ideal tracer for groundwater recharge assessments is soluble, mobile, relatively non-reactive, and easy to measure. Environmental tracer analysis typically assumes that their transport is primarily governed by advection, where substances move with the bulk flow of groundwater, rather than by diffusion or dispersion. In a relatively homogeneous aquifer, this results in the tracer progressively aging with increasing depth (*Cook 2020*).

Major anions (fluoride, chloride, nitrate, nitrite, sulphate), and cations (lithium, sodium, ammonium, potassium, calcium, magnesium) were measured from the groundwater samples by ion-chromatography (IC). While most of the anions are not sorbed and are not reacting with other molecules or the organic matter in the peat, cations usually are. Therefore, while the concentrations and depth-profiles were assessed for all measured ions, not all were further investigated and modelled. The only pre-treatment needed for the samples for the IC measurements was for the removal of particulates with filtration through a 0.45 μm filter (*Jackson 2000*). Oxygen-18 (^{18}O), which is an isotope of oxygen and deuterium (^{2}H) – an isotope of hydrogen – are commonly used as environmental tracers (*Cook 2020*) and these were measured in this study as well. Concentrations of both environmental isotopes show an observable pattern in precipitation, which can be approximated by sine waves. This seasonal isotopic signal can be used to evaluate the mean transit time of soil water (*DeWalle et al. 1997*).

At Krummesser Moor, most of the solute concentrations were unexpectedly high, which led to the assumption that the peat bog has an external input source, possibly a stream originating from the salt depositions close to the surface. As for the peat bog near Horst, the assumed small vertical gradient in the inflow can result in a slightly distorted profile of the investigated solute concentrations. This also means that the water might have been in contact with the aquifer before and it could have picked up some salts. The samples from the peat bog near Horst were analysed for isotopes as well, for oxygen-18 and deuterium. The range of the isotope ratios– measured by a dual-inlet stable isotope ratio mass spectrometer – was surprisingly small (-7.44 to -7.07‰ for $\delta^{18}O$ and -50.8 to -48.6‰ for $\delta^{2}H$). The isotope concentrations were stated in delta per mil notation (δ‰), with respect to the internationally accepted standard Vienna Standard Mean Ocean Water (V-SMOW) (*Wit et al. 2007*).

Collection of weather parameters

While rainfall can be measured in a reliable way, evapotranspiration depends on a great number of factors. Daily precipitation data was downloaded from the Deutscher Wetterdienst (DWD) website (*Wetter Und Klima 2023*) for the station of Grambek (station ID: 01736) 8 kilometres to the south-west from Horst, and Lübeck-Blankensee (station ID: 03086), 3 kilometres to the east from Krummesser Moor. The time series of precipitation was calculated for the sampling locations from the two station's data series based on their distance from the study sites. Yearly rainfall ranged from 490 to 870 millimetres per year in the 20-year period from 2003 and it shows a slightly decreasing trend. Calculations and modelling were carried out using five years of precipitation data from 2018. The time-series of daily evapotranspiration was calculated on the basis of the FAO Penman-Monteith equation (1), which requires several climatological and physical parameters (*Allen et al. 1998*):

$$ET_0 = \frac{0{,}408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0{,}34 u_2)} \quad (1)$$

Where: ET_0 = Reference evapotranspiration [mm/day], R_n = Net radiation at the crop surface [MJ/m^2 d], G = Soil heat flux density [MJ/m^2 d], T = Mean daily air temperature at 2 m height [°C], u_2 = Wind speed at 2 m height [m/s], e_s = Saturation vapour pressure [kPa], e_a = Actual vapour pressure [kPa], e_s-e_a = Saturation vapour pressure deficit [kPa], Δ = Slope vapour pressure curve [kPa/°C], γ = Psychrometric constant [kPa/°C].

These parameters were either measured at weather stations or they were calculated by empirical relationships from measured data. Relevant weather data was downloaded from the website of DWD (*Wetter Und Klima 2023*) and calculations were carried out on the basis of the guidelines of FAO (*Allen et al. 1998*). Potential evapotranspiration defines the amount of water that could be evaporated and transpired by plants if sufficient water is available (*Allen et al. 1998*). Since the investigated peat bogs are wet all year-round and their vegetation cover is not significantly fluctuating during the year, actual evapotranspiration is close to potential. One of the most straightforward methods to calculate recharge is based on the groundwater balance method and equation (2) (*Sajil Kumar et al. 2021*):

$$(P + G_{in}) - (Q + ET + G_{out}) = \Delta S \quad (2)$$

Where P = precipitation, G_{in} = groundwater inflow, Q = discharge, ET = evapotranspiration, G_{out} = groundwater outflow, and ΔS = change is storage. Due to the ombrotrophic nature of the bogs, groundwater inflow and discharge can be neglected. Since the sought parameter is the recharge (R) and not the change in storage, the equation can be simplified (*Hendrickx 1992*):

$$R = P - ET_p \quad (3)$$

An important input function for the physical models was the time series of isotope and solute concentrations in precipitation. Time series of concentration were provided for chloride, ammonium, phosphate, sulphate, sodium, potassium, calcium and magnesium in two-weekly intervals from a weather station in Lübeck, St. Jürgen (7 kilometres from Krummesser Moor and 23 kilometres from Horst). Monthly average concentrations were calculated, which can be seen in *Figure 4*, arranged according to the pattern of their seasonal fluctuations. The concentrations of phosphate were below the detection limit in the precipitation, thus these ions were excluded from further calculations. Data about the concentration of isotopes in precipitation were based on measurements that were carried out at the TH Lübeck station (Wasserpfad) between November 2017 and October 2022. These measured concentrations are depicted in *Figure 3.*

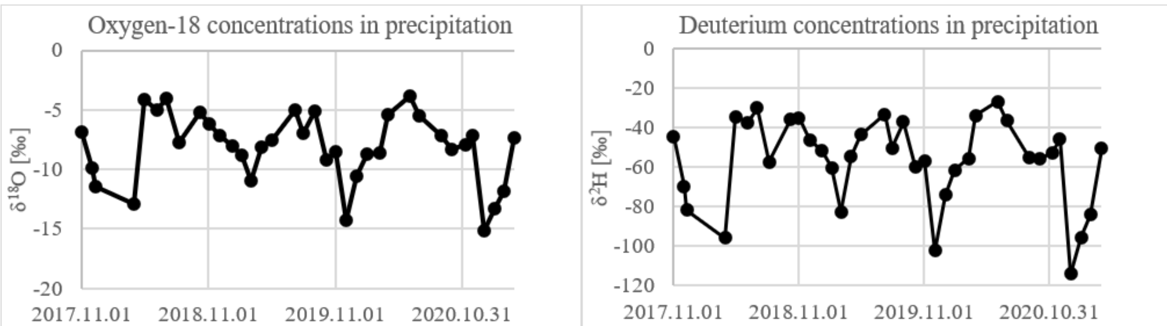

Figure 3. Concentration time series of the investigated isotopes, measured at the TH Lübeck station
3. ábra. A vizsgált izotópok csapadékban mért koncentrációjának idősorai a TH Lübeck állomáson

Sodium, chloride and magnesium appear with a high concentration in the precipitation in Northern Germany generally in the colder part of the year, possibly due to marine enrichment, the higher amount of storms and subsequently the elevated levels of sea spray in the air (*Keresztesi et al. 2019*). During the summer months, their concentration decreases almost to zero, as seen in *Figure 4*. These solutes might not be perfect tracers, since their concentration is high during the same period, when the evapotranspiration and thus the enrichment is low. Therefore, peak concentrations originating from higher winter concentrations might be neutralized by elevated concentrations due to enrichment. Calcium and ammonium behave in the opposite way, since their concentration is depleted in the precipitation during winter, and they appear with high concentrations during summer. These higher concentrations can be attributed to anthropogenic activities, such as industrial emissions, the use of fertilisers in agriculture, wind-blown soil dust or the presence of open quarries (*Keresztesi et al. 2019*). Ammonium could be a good tracer, as it appears with higher concentrations in the precipitation during summer, and it is also enriched at the same time due to the higher rate of evapotranspiration. However, it is a highly reactive compound, and it is converted in the water. Sulphate and potassium have three, less elevated peaks in a year. As *Figure 4* shows, they appear with higher concentrations during December and January in the winter, around April and May in the spring and around September in the autumn.

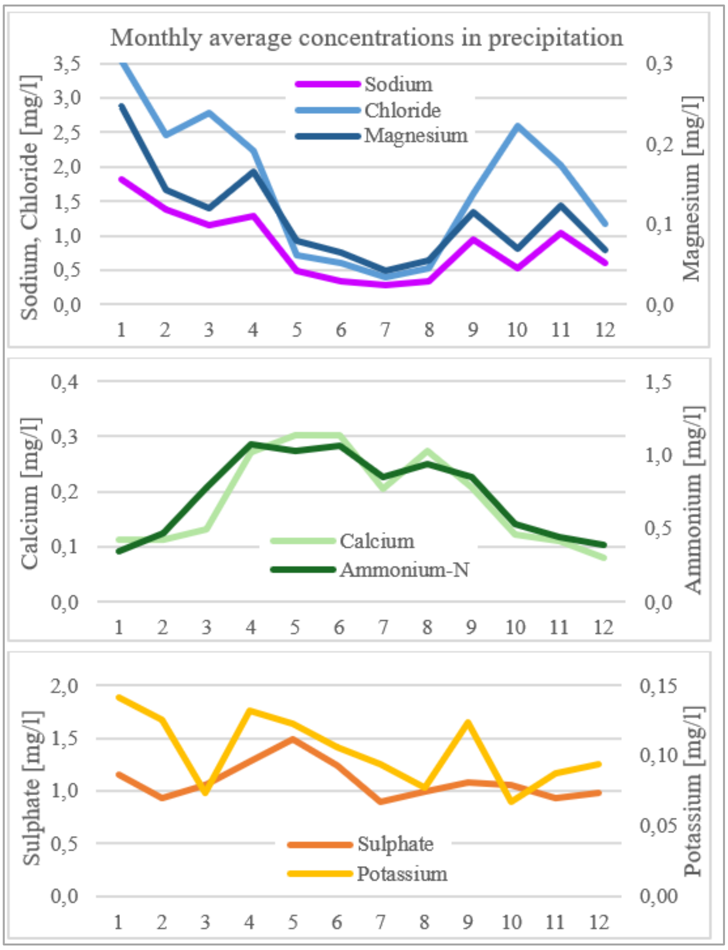

Figure 4. Monthly average concentrations of the investigated ions in precipitation
4. ábra. A vizsgált ionok csapadékban mért havi átlagos koncentrációja

Modelling with Hydrus 1D

A one-dimensional approach can be sufficient to represent the vertical flow and transport in peat bogs with variably saturated conditions in the profile. Hydrus 1D has the advantage that it is widely available, relatively simple and has a limited computational demand. It is commonly applied for the estimation of groundwater recharge in soils and for the evaluation of near-surface water balance (*Leterme et al. 2012*). With the available data, Hydrus 1D, version 4.17 (*Simunek et al. 2013*) was the best option to model the recharge and the movement of solutes.

In a simplistic manner, peat bodies can be divided into two parts vertically that have considerable differences in function and physical properties: the acrotelm and the catotelm. Consisting of moss and litter, the acrotelm is usually 30-50 centimetres deep and is the variably saturated upper layer of peat, where the rate of energy and matter exchange is considerably higher. Below it lies the saturated, generally more homogenous catotelm (*Whittington et al. 2021*). With the increased decomposition and compression and decreased pore size, the hydraulic properties of peat are also changing with the depth (*Price et al. 2023*). Two soil materials were defined in the simulated 150 cm deep soil profile, representing these two layers of the peat, which can be seen in *Figure 5*, together with the pressure head (which was set at the initial condition) along the modelled peat column. The depth of the acrotelm was defined on the basis of observations during the sampling process as 40 centimetres. It was not possible to pump water from the upper 10-20 centimetres of the peat, meaning that there was no water with free pressure in this layer. Therefore, this top zone was considered as an unsaturated layer with negative pressures, while in the saturated layer the pressure is increasing with depth.

	Depth [cm]	Pressure head [cm]
P 65 % BD 0,3 g/cm³ K_s 195 cm/day	10	-100
	20	0-10
	30	11-20
	40	21-30
P 75 % BD 0,1 g/cm³ K_s 35 cm/day	50	31-40
	60	41-50
	70	51-60
	80	61-70
	90	71-80
	100	81-90
	110	91-100
	120	101-110
	130	111-120
	140	121-130
	150	131-140

Figure 5. Main soil parameters and the pressure head of the modelled peat column
5. ábra. A tőzegláp paraméterei és nyomásmagassága a modellezett talajoszlop mentén

To understand and model the hydrological functioning of a peat bog, its hydraulic properties need to be known. Hydrological models like Hydrus require the parameters from the soil water retention curve (SWRC) and also the hydraulic conductivity function for the modelling of the water and solute transport under unsaturated conditions (*Menberu et al. 2021*). Values for the necessary parameters were chosen carefully in order to represent the study sites the best, based on literature, the site visits and expert opinion. In Hydrus 1D, the Richards's equation (4) is used to model the movement of water through soil:

$$\frac{\delta\theta}{\delta t} = -\frac{\delta q}{\delta z} = \frac{\delta}{\delta z}\left[K(h)\frac{\delta h}{\delta z} - K(h)\right] - S \qquad (4)$$

Where: θ = Volumetric water content - estimated based on literature (*Price et al. 2023, Whittington et al. 2021*), z = Vertical coordinate, q = Water flux, t = Time (time passed from the start of the modelling in days), S = Sink term representing root water uptake, $K(h)$ = Soil hydraulic conductivity function (depending on the pressure head "h") - estimated based on literature (*Price et al. 2023*) and expert opinion

The relationship between soil moisture and hydraulic conductivity is described by the Van Genuchten equations (5; 6) (*Van Genuchten 1980*):

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha\cdot h|^n]^m},\ h < 0 \\ \theta_s,\ h \geq 0 \end{cases} \qquad (5)$$

$$K_r(h) = \frac{\left[1-(\alpha\cdot h)^{n-1}\cdot[1+(\alpha\cdot h)^n]^m\right]^2}{[1+(\alpha\cdot h)^n]^{\frac{m}{2}}} \qquad (6)$$

Where = θ_s: Saturated water content [-] - estimated based on literature (*Price et al. 2023*) and expert opinion, θ_r = Residual water content [-] - estimated based on literature (*Price et al. 2023*) and expert opinion, α, m, n = Empirical parameters [1/L], [-], [-] - defined based on literature (*Menberu et al. 2021*), S_e = Effective water content [-] - calculated based on the water content, K_s = Saturated hydraulic conductivity [L/T] - defined based on literature (*Menberu et al. 2021*), K_r = Relative hydraulic conductivity [-] estimated based on literature (*Price et al. 2023*) and expert opinion, $K_k(h_k)$ = Unsaturated hydraulic conductivity at pressure head h_k [L/T]

Some further parameters had to be defined for the modelling of solute transport: l = Tortuosity parameter in the conductivity function [-] - a dimensionless parameter, defined based on literature (*Gharedaghloo et al. 2018, Weber et al. 2017)*, ω = Mass transfer coefficient for peat [-], defined based on literature (*Rezanezhad et al. 2016*), BD = Bulk density [-] (the quotient of the dry mass and the total volume) - defined based on expert opinion, D_L = Longitudinal dispersivity [cm] - As its rate was not known, it was a calibration parameter, *Fract* = Fraction of adsorption sites in contact with mobile water [-] - defined based on expert opinion, D_W = Molecular diffusion coefficient in free water [m^2/s] - defined based on water temperature and literature (*Holz et al. 2000*), α = Mass transfer coefficient for solute exchange between mobile and immobile liquid regions [1/day] - defined based on literature (*Genuchten and Wierenga 1976*).

The chosen and defined values for the parameters are listed below in *Table 1*.

Table 1. Calculated or chosen water flow and solute transport parameters
1. táblázat. A vízáramlást és az oldott anyag transzportot leíró számított és választott paraméterek

Water flow parameters		**θ_r [-]**	**θ_s [-]**	**α [1/cm]**	**n [-]**	**K_s [cm/day]**	**l [-]**	**$\theta_{im,r}$ [-]**	**$\theta_{im,s}$ [-]**	**ω_W**
Depth [m]	0-0.4	0.3	0.65	0.05	1.39	195	0.8	0.4	0.7	0.6
	0.4-1.5	0.25	0.75	0.02	1.42	35	2	0.35	0.75	0.6
Solute transport parameters		**BD**	**D_L [cm]**	**initial conc, (mobile)**		**initial conc, (immobile)**		**Fract [-]**	**D_W [m²/s]**	**α [1/day]**
Depth [m]	0-0.4	0.3	0.5	listed in *Table 2*		listed in *Table 2*		0.3	$1.607 \cdot 10^{-9}$	0.4
	0.4-1.5	0.1	0.5	listed in *Table 2*		listed in *Table 2*		0.25		

2001 days were simulated from the 1st of January 2018 until the second successful sampling date (25th of June 2023). The 'Dual-porosity (mobile – immobile, water content mass transfer)' model was chosen as the hydraulic model. Therefore, the Van Genuchten parameters were defined for the mobile and immobile regions as well, together with an exchange factor, as listed in *Table 1*. The hysteresis option – which describes the difference between wetting and drying – was not chosen, since the investigated peat bogs are wet all year round and there is a considerable impact only in case the peat becomes dry (*Simunek et al. 2013*). Boundary conditions had to be chosen that represent the modelled 5-year- long period well. The upper boundary condition was set to the 'Atmospheric Boundary Condition with Surface Layer' option, where the time-series of daily precipitation and the calculated evapotranspiration had to be provided. Since the aim was to model a situation, where the rainwater either evaporates or percolates (so there is no significant runoff), ponding was defined as zero. The lower boundary condition was set to 'Constant Pressure Head'. Longitudinal dispersivity (D_L) was a calibration parameter during the modelling, since its rate was not known. The best fit of the modelled concentrations to the measured ones was reached with it being defined as 0.5 cm.

The upper boundary condition for the solute transport was set as a 'Concentration Flux', which was the time-series of the concentration of major ions in precipitation. The lower boundary was set as 'Zero Concentration Gradient'. The initial conditions were set in the liquid phase concentrations for every modelled ion, which describes the amount of the solute's mass per the volume of water. Observation points were set at every 10 centimetres of the modelled peat column. After running the model, the most recent results for the observation points were taken for the peat bog near Horst, while for Krummesser Moor results for the 1948th modelled day (the day of the sampling: 3rd of May 2023) were considered.

Cumulative Method

A simple model was built in Excel to model the movement of major ions from the precipitation through the peat columns. Since the tracer – in this case the ions – is entering the peat perpendicular to the flow direction throughout the whole cross-section of the column, dispersion can be neglected (*Leibundgut et al. 2009*). The x-axis is the flow direction, while the concentration gradients in the y and z directions equal zero. Assuming that the tracer enters the column at x = 0, the solution to the transport equation of *Leibundgut et al. (2009)* is the following:

$$C(x,t) = \frac{M}{Q} \cdot \frac{x}{\sqrt{4\pi D_L t^3}} exp\left[-\frac{(x-vt)^2}{4D_L t}\right] \quad (7)$$

Where: M = The mass of the injected tracer [g], Q = Volumetric flow rate through the column [m³/year], x = Distance travelled by the tracer (depth) [m], D_L = Longitudinal dispersivity [m], t = Transit time [days], v = Velocity [m/year].

The mass of the injected tracer can be calculated from the amount of precipitation and the ionic concentrations in precipitation. Calculations were carried out in monthly intervals up until four years before the sampling dates. Effective porosity (which directly influences velocity) and longitudinal dispersivity functioned as calibration parameters and were being changed – in a range based on expert opinion, taking all the properties of the sampled peat into account – to find the best fit between the measured and modelled profile. The range was between 0.65 to 0.80 for porosity, based on literature about sphagnum peat (*Price et al. 2023*) and the observations during the sampling. In the calibration process the dispersion parameter (P_D) was used instead of D_L, which is calculated by equation (8):

$$P_D = \frac{D_L}{vx} = \frac{\alpha_L}{x} \quad (8)$$

Evaporation causes the enrichment of solutes in the soil during rainfall and after infiltration in shallow groundwater (*Sreedevi et al. 2022*). Due to evapotranspiration, recharge is around 2.5 to 3.5 times lower than the amount of precipitation in the area, which results in the enrichment of ions in the infiltrated water. In the top layer the rate of enrichment varies due to the fluctuation of the evapotranspiration between the summer and winter period. To include the process of enrichment in the modelling, a factor was introduced. The cumulated calculated concentrations at each depth were multiplied by an enrichment factor. At the bottom of the modelled peat column, the factor was calculated by the equation (9) from the yearly precipitation and evapotranspiration (*Leibundgut et al. 2009*):

$$Enrichment_{bottom} = \frac{1}{\frac{P_{yearly} - ET_{yearly}}{P_{yearly}}} + Factor \quad (9)$$

A factor could be added to the calculated enrichment, so that the amount of enrichment can be increased for those ions, where it plays a bigger role. At the surface, it was possible to add an enrichment factor or leave it at zero. From the surface until the bottom of the column, the rate of the enrichment was interpolated between the two given factors. While the rate of the enrichment is almost constant below one meter, on the surface its factor can vary between one and five. While ions get enriched due to evapotranspiration, isotopes are quasi-insensitive to evaporation. Therefore, the concentration of isotopes in the investigated peat column was calculated with a different model.

Modelling for isotopes

Małoszewski et al. (1983) applied a sine-curve analysis for the seasonal variations in precipitation and subsurface sources of the concentrations of isotopes. From this analysis, a model is described to determine subsurface water transit times. The sine-curve theory can also be used to describe soil hydraulic diffusivities (*DeWalle et al. 1997*).

A seasonal sine-curve model was fitted to the measured oxygen-18 and deuterium concentration fluctuations by using periodic regression analysis:

$$\delta(z) = \delta_A \cdot e^{z/d} \cdot sin(\omega \cdot z + \varphi_0) + \delta_{00} \quad (10)$$

$$f(z) = f \cdot e^{z/dv} \quad (11)$$

Where: δ_A = Amplitude, z = Depth of the sample [m], d = Attenuation factor, δ_{00} = A quasi-constant isotopic value, f = Frequency corresponding to the seepage velocity, ω = Angular frequency (ω=2πf), φ_0 = Variable, describing the phase shift, calculated as:

$$\varphi_0 = arcsin\big((\delta_0 - \delta_{00}) \,/\, \delta_A\big) \quad (12)$$

Where: δ_0 = the isotope value at t=0, δ_A, f, d, δ_0, δ_{00} and d_v can be fitted either manually or via several standard optimizing methods.

RESULTS AND DISCUSSION

In this section, the results of the climatic recharge calculation, the modelling by the cumulative method, by Hydrus and by the isotope model are described.

Groundwater Balance Method

From the time-series of precipitation and the calculated evapotranspiration, monthly rates of recharge were derived. The average yearly rainfall in the investigated period between January 2018 and June 2023 was 621 millimetres, while the evapotranspiration was 428 millimetres. The yearly recharge ranged between 36 millimetres (in 2018) and 317 millimetres (2021), with an average of 193 mm/year in the investigated period. The fluctuation of the monthly precipitation and evapotranspiration is depicted in *Figure 6*. The periods when evapotranspiration exceeds precipitation are in the growing season, which results in the lowering of groundwater tables.

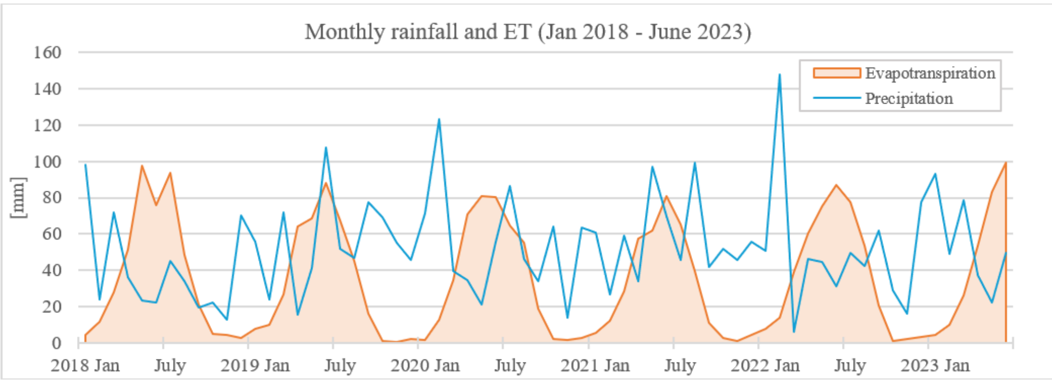

Figure 6. Monthly rainfall and evapotranspiration (ET) of the study area for the climatic water balance
6. ábra. Havi csapadékmennyiség és evapotranspiráció (ET) a vizsgált területen

Modelling with Hydrus 1D

Initially, the goal of the modelling with Hydrus was to reproduce the measured concentration profiles and determine the soil and solute parameters and the recharge. However, since there was a problem with the sampling at the peat bog near Horst (which was either the mixing of the sampled water column due to the dislocation of the tip of the sampling tube, or the not fine enough sampling resolution – or both), the aim of the modelling changed. It is also possible, that the solute concentrations in the peat are influenced by a lateral groundwater flow. As for Krummesser Moor there must be an external stream and/or groundwater inflow indicated by the high level of the measured concentrations. Therefore, the following modelled concentration profiles demonstrate how does the concentration change in the peat column based on the precipitation, the calculated evapotranspiration and the ionic concentration inputs from the rainfall with the chosen soil and solute parameters. The results show how would an ombrotrophic bog's depth profile look like with the defined characteristics.

The modelling results were the most sensitive to the initial concentration and to the longitudinal dispersivity (D_L). The initial concentrations had to be set for every ion, which are listed for the mobile region (which equal the average measured concentration for every ion) and immobile region as well in *Table 2* for the peat bog near Horst. As for the dispersivity, different values were tried. *Figure 7* depicts how does the modelled chloride concentration start to deviate from the given initial concentration and how does it start to show the actual concentrations by depth, while applying the dispersivity that gave the best fit for the modelled concentration depth profile. The modelled concentrations are reliable for every depth from around two years after the start date of the modelling (1st of January 2018).

Table 2. Initial concentration of solutes for the modelling
2. táblázat. Az oldott anyagok kezdeti koncentrációja a modellezéshez

Horst	Initial concentration (mobile) [mg/l]	Initial concentration (immobile) [mg/l]
Chloride	6.5	6
Sulphate	0.3	0.28
Ammonium	2.9	2.5
Sodium	4.7	4.5
Potassium	2.2	2
Calcium	11.8	11.5
Magnesium	2.3	2.5

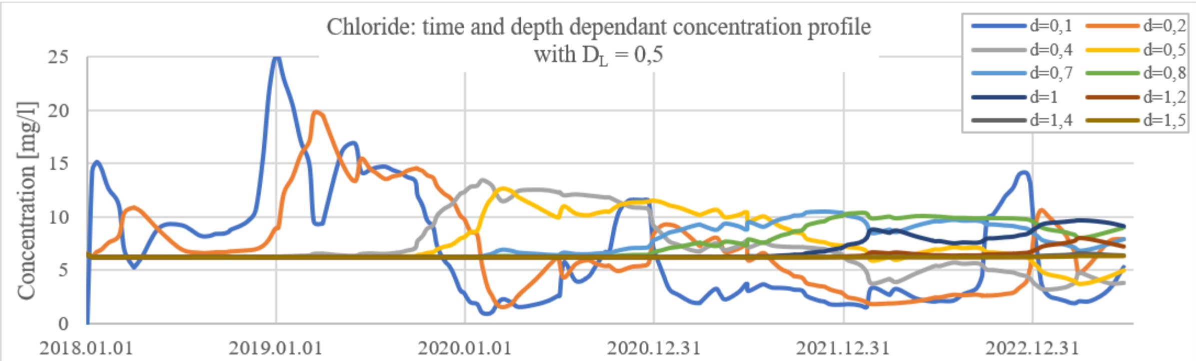

Figure 7. Concentration time series of chloride in the groundwater at the observation points of the investigated soil column at Horst. 'D_L' [cm] is the longitudinal dispersivity and 'd' [m] is the depth below the surface.
7. ábra. A horsti talajvíz megfigyelési pontokon modellezett kloridion koncentrációinak idősorai. A 'D_L' [cm] a hosszirányú diszperzivitás, 'd' [m] pedig a felszín alatti mélység

Figure 8 depicts the modelled chloride concentrations based on the different longitudinal dispersivities. While the modelled concentrations are around the measured ones, the modelled results have a much wider range. The Root Mean Square Error (RMSE) for the measured and modelled concentrations is 1.44. The most likely reason for this is the error during the sampling process and the mixing of the sampled groundwater column. On the other hand, the modelled concentration profile depicts the seasonal variation of chloride well. Based on the fluctuations, the modelled 1.5-meter-deep peat column contains 2.5 years of recharge assumed on the basis of the 3 positive and 3 negative peaks. This would indicate a yearly recharge of around 420 millimetres if the porosity is considered as 70%. The modelled concentration profiles of the other ions also show the same number of peaks.

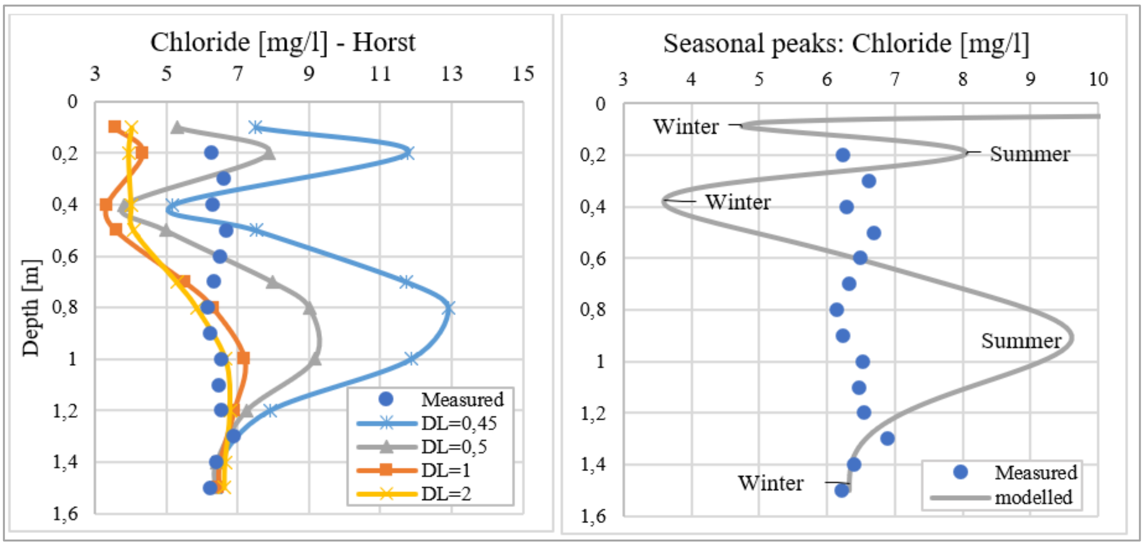

Figure 8. Modelled concentration profile of chloride at Horst with different dispersivity parameters
8. ábra. A kloridion modellezett koncentrációprofilja Horstnál különböző diszperzivitás paraméterekkel

Similarly to the results of the cumulative method, the reduction of sulphate can be assumed from the modelled concentration profile with Hydrus. On the bottom of the modelled column, the modelled concentrations approach the measured ones, but this is only due to the lower boundary conditions and the initial concentration. Since chemical reactions that could represent the reduction of solutes were not applied in the model, the modelled sulphate concentration in the peat and groundwater column are occasionally more than 10 times higher than the measured, reduced ones and they change based on the input concentrations from the rainfall and the set soil and solute transfer parameters.

Ammonium and sodium behave in a similar way to chloride in the model. While the range of the modelled concentrations is significantly wider than of the measured ones, they provide an estimate of the fluctuations of the measured profile well. The longitudinal dispersivities that give the best estimate are D_L=0.45 and D_L=0.5, which can be seen in *Figure 9*. The difference in the range is most probably due to problem with the sampling device during the sampling, where the samples belonging to certain depths got mixed with water pumped up vertically. However, the fact that the model was run based on the presumption of a continuous input of solute concentrations from the precipitation, and it stayed around the average of the measured concentrations after modelling 5 and a half years of recharge proved that the bog near Hort is indeed ombrotrophic and it does not have any significant secondary groundwater input sources.

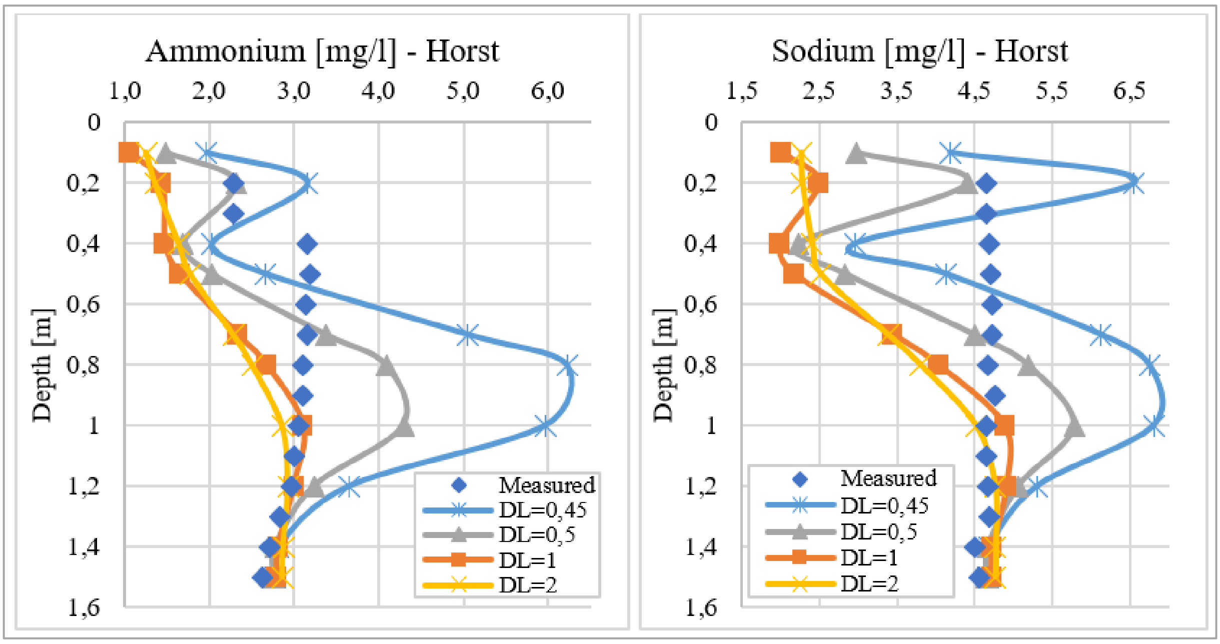

Figure 9. Modelled and measured concentration profile of ammonium and sodium at Horst with different longitudinal dispersivity (D_L) parameters

9. ábra. Ammónium és nátrium modellezett és mért koncentrációprofilja Horstnál különböző longitudinális diszperzivitás (D_L) paraméterek mellett

Potassium, calcium and magnesium profiles are underestimated by the model. These are the same ions which were not estimated well with the cumulative method. Cations are not as good tracers as anions in general, as they react with the organic material content of the peat and with other compounds more frequently. However, it is more likely, that the real explanation for the discrepancy is that these cations also have an additional input source aside from the rainfall.

The amount of yearly recharge was evaluated based on the propagation of the modelled concentration profile. However, this method would only be reliable if the modelled concentration profile would provide a good estimate of the real concentrations of the peat and the measured values – which was not the case in this study. These results would indicate a recharge of 250 to 300 millimetres per year.

While the modelled concentrations were in the range of the measured values in the case of the samples from Horst, for Krummesser Moor it was not possible to reach the range of the measured solute concentrations. As mentioned before, this is because the peat bog at Krummesser Moor has an additional inflow aside from the precipitation. By simply using the precipitation and the ionic concentrations in the precipitation as an input, the range of the modelled concentrations is 5 to 10 or even more times lower than the measured concentrations, even if the initial concentration is set as the average of the measured values.

Cumulative Method

As a result of the calibration process, the velocity – and thus recharge – was 240 mm/year for Krummesser Moor which is 320 mm/year when porosity is considered (which was considered as 0.75). As for Horst, the velocity (and recharge) was 280 mm/year, which is 370 mm/year taken the porosity of 0.76 into consideration. The calculated velocity, which takes the porosity into account visualises the recharge that belongs to one year in the soil column.

The dispersion parameter and the two enrichment factors (on the surface and at the bottom of the peat column) were changed for each ionic compound separately. The surface enrichment should have been between 1 and 5, and around 2.5-3.5 in the bottom. To match the range of the measured concentrations with the modelled ones, the factor of enrichment had to be out of this range for some of the ions, mostly for the cations. In these cases, the enrichment factor only conceals the discrepancy between the measured and modelled concentrations. A high enrichment factor therefore mostly implies an external source and means that the solute does not only originate from precipitation.

The results of the model prove that there must be an external input (stream or groundwater) at Krummeser Moor. Ionic concentrations are ten times higher in some cases than at the peat bog near Horst and the results of the simulation do not correlate with the measured concentrations. Therefore, it was only possible to match the range of the measured concentrations with the model by adding a factor with a high value. The factor – which was originally meant to represent the enrichment – was only in a reasonable range for ammonium and potassium. Assumptions can be made that groundwater indeed comes to the surface from a layer with salt depositions around Krummesser Moor.

As for the peat bog near Horst, the modelling results matched the range of the measured concentrations for chloride (RMSE: 0.50), sulphate (RMSE:1.77), ammonium (RMSE: 0.25) and sodium (RMSE: 0.34). The factor had to be increased for potassium (RMSE: 0.27), calcium (RMSE: 0.83) and magnesium (RMSE: 0.35) to a degree which cannot be explained with the enrichment from evapotranspiration (the calculations of the RMSE were carried out using the modelled calculations with these high enrichment factors). Therefore, it can be assumed that these cations have an additional, external input source, possibly from the direction of Pinnsee.

Chloride concentrations in the rainfall are mostly between 0 and 2 mg/l and they increase up to 6-8 mg/l around 2-3 times during the colder part of the year. Two additional concentration peaks were observed during the period of 2016-2022 with 20 and 14 mg/l (these peaks cannot be observed from *Figure 4*, only from the full time-series of chloride concentrations in the precipitations, since the figure only shows the average monthly concentrations). The range of the concentration of chloride at the peat bog near Horst matches this interval when the enrichment by evapotranspiration is considered, therefore the factors chosen to represent it are also in a reasonable range. As for Krummesser Moor, the measured values in the top layer could be explained by enrichment, which is also shown by the chosen surface enrichment with the value of 4, but deeper in the ground it increases in a way that a factor that is 5 times higher than the expected enrichment had to be chosen to fit the measured concentrations. This implies an external source for chloride at Krummesser Moor. Since the measured concentrations at Horst are in a very small range, it was only possible to estimate them with a high P_D value. Therefore, the modelled concentrations don't show the small variations that the measured values do. The factor of enrichment and the chosen calibration parameters for chloride are listed in *Table 3* and the measured and modelled depth-profile of the solute is depicted in *Figure 10*.

Table 3. Chosen calibration parameters for chloride
3. táblázat. A kloridion koncentrációjának modellezéséhez használt kalibrációs paraméterek

Calibration variables	**Chloride**	
	Krummesser Moor	**Horst**
v [m/year]	0.24	0.28
Porosity [-]	0.75	0.76
v_p [m/year]	0.32	0.37
P_d	0.1	0.15
Enrichment: surface	4.0	0.9
Enrichment: bottom	15.52	2.75

Peat is a highly reducing environment, where sulphate is also reduced and converted into hydrogen sulphide. This chemical process cannot be modelled on the basis of solute transport. In case of Krummesser Moor, sulphate levels are completely reduced below 60 centimetres below the surface, while the model keeps an elevated concentration. In the case of Horst, sulphate is reduced throughout the whole sampled column, thus the modelled results overestimate the concentrations. Sulphate concentrations in the rainfall (mostly between 0.5 and 2.0 mg/l) are also significantly lower than in groundwater (*Scheytt 1997*), which can give an additional explanation for the difference in the multitude of the sulphate levels at the two different study sites, since Krummesser Moor has an external groundwater and/ or stream input according to the assumptions made on the basis of the data. Furthermore, sulphate commonly has dry depositions and it can be enriched by fertilizers, thus results of models that only use the concentrations in precipitation as an input are not necessarily reliable for the anion, even if they include chemical reactions (*Scheytt 1997*).

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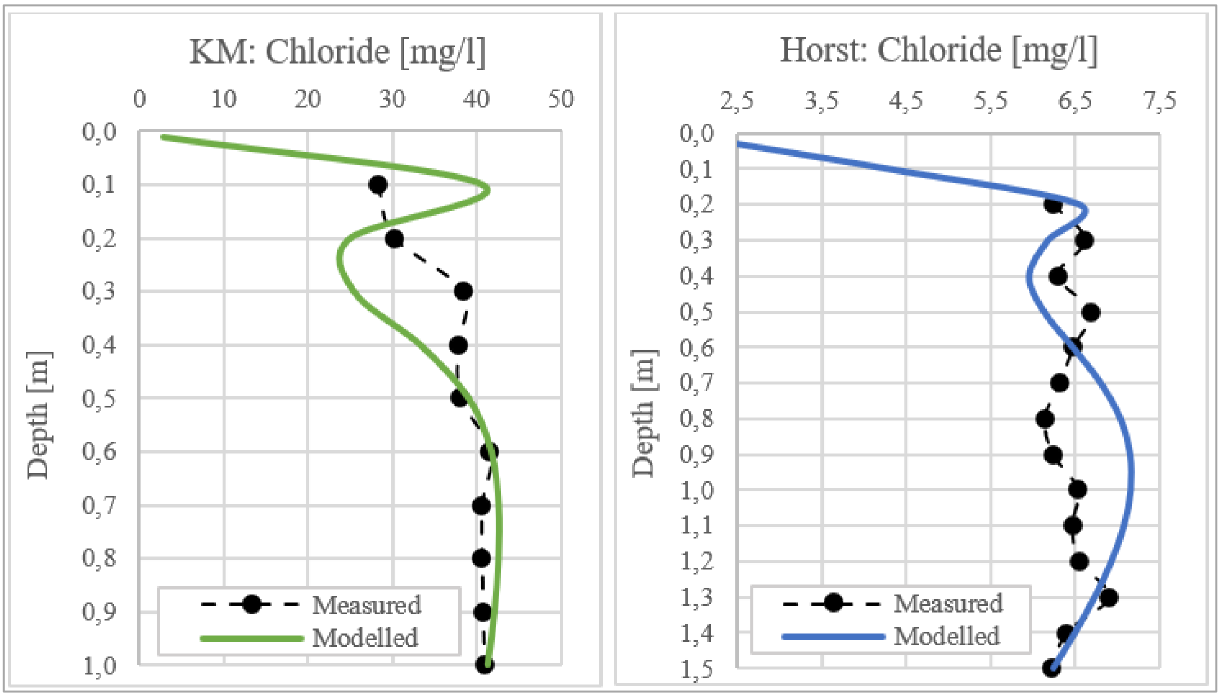

Figure 10. Measured and modelled concentration profile of chloride at Krummesser Moor (KM) and at the peatland near Horst with the cumulative modelling method
10. ábra. A kloridion mért és modellezett koncentrációprofilja Krummesser Moor-nál (KM) és a Horst melletti tőzeges területen, a kumulatív modellezési módszerrel

As for the concentration of ammonium, the upper 30-40 centimetres in the soil are still controlled by atmospheric processes, therefore the model can approximate the measured concentrations well. Below this top layer, reactions start to happen and the model deviates. In the case of Krummesser Moor, a high ammonium concentration is maintained based on the model, but in reality – and also according to the samples – the concentration is lowered due to the degassing of ammonium, but as the process of nitrification decreases with depth due to the reduction of oxygen availability (this process was measured during sampling as well), it reverts to an elevated level where conditions are favourable for the accumulation of ammonium. Since the model does not include chemical reactions, the concentration stays high. Aside from the lowered concentration in the transition zone, the model gives a good estimate of the concentration profile of ammonium, with reasonable enrichment factors. The first two peaks in the top layer are also matched with the model. As for Horst, the model gives a good estimate for the measured concentrations and the calibrated enrichment factors are also reasonable.

The chosen calibration parameters for ammonium are listed in *Table 4* and the measured and modelled depth-profile of the solute is depicted in *Figure 11*.

Table 4. Chosen calibration parameters for ammonium
4. táblázat. Az ammónium modellezéséhez választott kalibrációs paraméterek

Calibration variables	**Ammonium**	
	Krummesser Moor	**Horst**
v [m/year]	0.24	0.28
Porosity [-]	0.75	0.76
v_p [m/year]	0.32	0.37
P_d	0.01	0.08
Enrichment: surface	2.4	1.5
Enrichment: bottom	3.02	2.75

Sodium concentrations are around 10 times lower in precipitation, then in groundwater in the region (*Scheytt 1997*), which explains why the enrichment factor had to be increased significantly for Krummesser Moor to match the measured concentrations, with the assumption of the external input source. At Horst, the model matched the range of the measured concentrations and the chosen enrichment factors are also reasonable.

High potassium concentrations (>3.0 mg/l) can be an indicator for anthropogenic effects (mainly agricultural use and fertilizers), as its level is naturally very low both in precipitation and in groundwater (*Arbačauskas et al. 2023*). This explains why the factor had to be slightly increased above the expected enrichment in the case of both sites to be able to match the range of measured potassium concentrations. This also means, that in the case of this solute, the factor does not indicate a high enrichment by evapotranspiration, but a moderately high additional input.

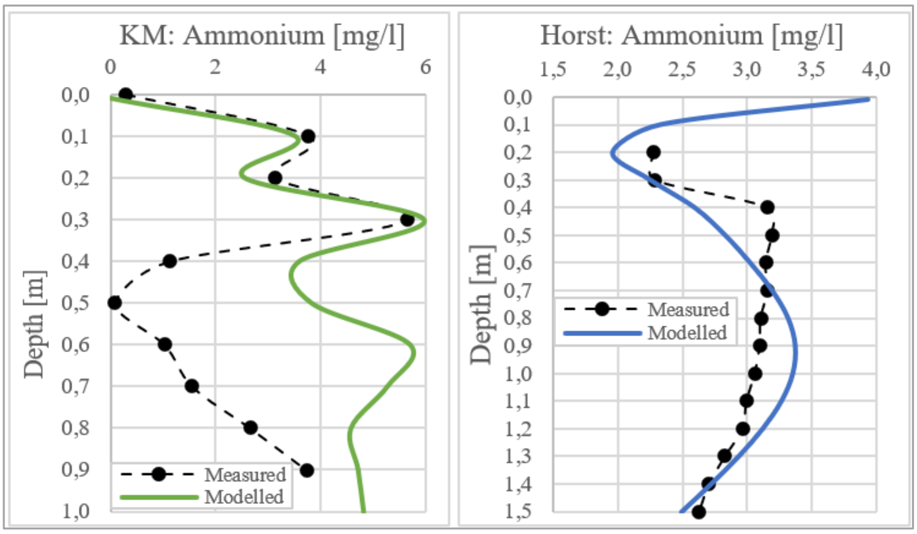

Figure 11. Measured and modelled concentration profile of ammonium at Krummesser Moor and at the peatland near Horst
11. ábra. Az ammónium mért és modellezett koncentrációprofilja Krummesser Moor-nál (KM) és a Horst melletti tőzeges területen, a kumulatív modellezési módszerrel

Calcium concentrations are also significantly lower in precipitation (around 0.1 to 0.4 mg/l), than in groundwater and it can have high agricultural inputs (*Scheytt 1997*). This explains why the factors had to be increased for both study sites. It again leads to the conclusion that Krummesser Moor must have an external input source, but in this case the peat bog near Horst also must have an input of calcium from somewhere else as well, probably from the groundwater from the direction of Pinnsee.

The case and behaviour of magnesium is similar to calcium, but the extent of the external input is presumably smaller, as the factors are 2 to 4 times smaller. The magnesium concentration of the precipitation is also similar to calcium, ranging between 0.1 and 0.3 mg/l.

The extent of the concentration peaks of the measured values does not show a general increasing or decreasing pattern with depth. However, the modelled concentration profile does, as the extent of both the positive and negative peaks are decreasing with depth. This is probably due to the dual porosity in peat, which is not considered in this model. In reality, smaller pores hold onto groundwater like a sponge and the main flow is only through the bigger macropores.

Isotopes

For oxygen-18, the recharge is 162.54 mm/year with an RMSE of 0.048, while for deuterium the result is 172.79 mm/year with an RMSE of 0.376. The fitted sine-curves can be seen in *Figure 12* for both isotopes.

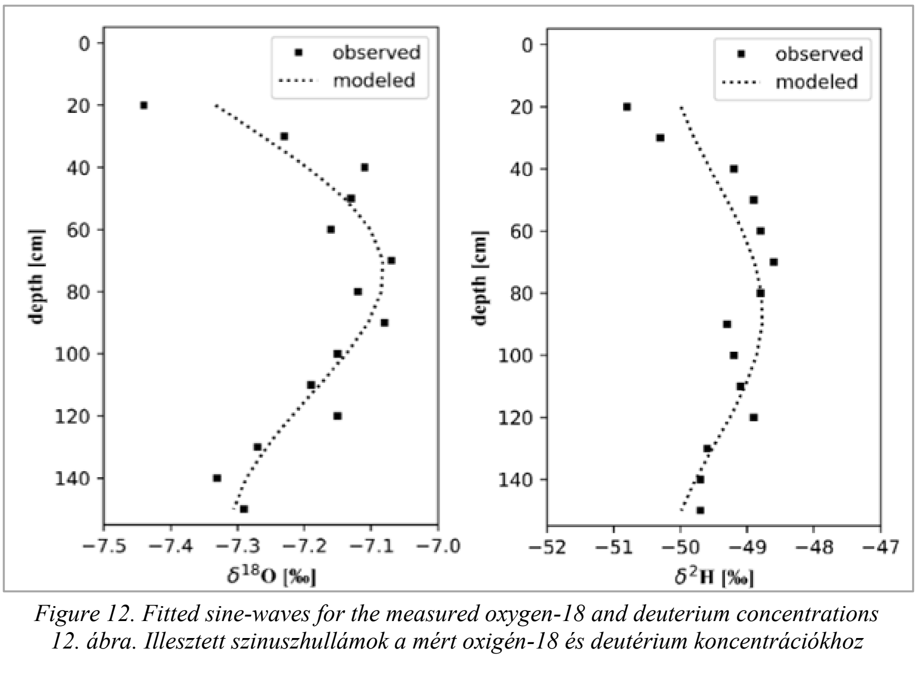

Figure 12. Fitted sine-waves for the measured oxygen-18 and deuterium concentrations
12. ábra. Illesztett szinuszhullámok a mért oxigén-18 és deutérium koncentrációkhoz

Discussion

The estimates of groundwater recharge gained with the different methods varied greatly. Results are summarized in *Table 5*. The calculated climatic water balance must be treated with caution as well, as the calculated evapotranspiration depends on many factors. These factors are either measured or estimated, therefore the margins of error can superimpose upon each other. While the values of soil parameters were chosen with great care, the reliability of recharge estimates could be improved by defining the necessary parameters based on the analysis of peat samples from the investigated locations. Ideally at least those parameters should be measured to which the model results are sensitive: the ratio between mobile and immobile pores, their respective water content and porosity. Dual porosity can influence the flow and the spreading of water and solutes and therefore also the estimate of recharge made with these methods to a high extent. While its effect was considered in Hydrus and its required additional parameters were set, they were only estimated on the basis of observations.

Table 5. Final estimations of groundwater recharge based on different methods
5. táblázat. A különböző módszerekkel becsült felszín alatti víz utánpótlás értékei

Study site	Recharge estimations [mm/year]					
	Calculated	Modelled				
	Climatic recharge	Cumulative method	Hydrus		Isotopic model	
			Method I	Method II	O18	Deuterium
Krummesser Moor	193	240	-	-	-	-
Peatland near Horst		280	420	250-300	162.54	172.79

CONCLUSIONS

While the inaccurate or not precise parameterisation of the soil and solute can result in inaccurate recharge estimates, the main problem in this study was with the sampling method and the sampling locations. Due to the shortage of time, samplings could not be repeated. Results of the modelling were greatly underestimating the measured concentrations at Krummesser Moor, which means that the peat bog must have an external input source. This posed a problem to this study, because only those peat bogs are representative for the regional recharge from precipitation that are ombrotrophic. Moreover, it was found from literature that around the site there is a layer with salt depositions close to the surface, which can potentially influence solute concentrations. As for Horst, the area seemed suitable, although according to ongoing research there might be lateral groundwater inflow in the direction of the investigated peat bog from Pinnsee (*Roehl 2023*). However, results of the modelling by Hydrus 1D do prove that the bog is ombrotrophic, and that the extent of this lateral inflow component is probably negligible.

It is also possible, that the chosen sampling resolution was not fine enough. If a porosity of 75% and a yearly recharge of 200 mm is assumed, then one meter of peat would hold four years of recharge, thus a full yearly cycle of winter and summer peaks would have had to be found in a 250 mm thick layer. The sequence of peaks in this case is very small, therefore a much smaller sampling resolution would be required: 2 to 2.5 centimetres, instead of the applied 10 centimetres, to have a more reliable estimate of every seasonal peak by at least 5 points.

To make estimates of groundwater recharge would be vitally important for sustainable groundwater management and for the calculation of sustainable yield, as a base for the provision of water rights. Ion and isotope profile methods are indeed promising options, but the acquirement of their input data – the sampling process – must be optimized and executed precisely and sampling locations must be chosen with greater care.

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THE AUTHOR

SÁRA MOLNÁR finished her bachelor's degree as a civil engineer in 2021 at Budapest University of Technology and Economics (BME). Her topic was the "Model study of habitat-based restoration of the lower Danube in Hungary". She continued her studies in an Erasmus Mundus master programme in applied ecohydrology and studied at universities in Portugal, Poland, Germany and Belgium. She wrote her master thesis at the Technical University of Applied Sciences Lübeck, which provided the basis of this article. She is currently pursuing her PhD at BME while working as a research assistant.

Quantitative drip water measurements in the Buda Castle Cave with classical and modern measurement methods

Fanni GAZDA[1,3], Dávid FARKAS[1], Géza HAJNAL[1], Dénes SZIEBERTH[2]

[1] National Laboratory for Water Science and Water Security, Budapest, Hungary
[2] University of Technology and Economics, Faculty of Civil Engineering, Department of Hydraulic and Water Resources Engineering, Budapest, Hungary
[3] Corresponding author (email: gazdafanni@edu.bme.hu)

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Abstract
The study of cave waters is important for the preservation of the Castle Cave, which lies underneath the Buda Castle Hill. The objectives of this research were to carry out quantitative measurements of drip water and to identify the changes from previous observations. This study also aimed to investigate the relationship between drip water locations and drip water and precipitation data. The present study employed self-made tipping bucket gauges and ad hoc drip water measurements. Correlation analysis was carried out on the values measured at the two drip locations and on the drip water and precipitation time series. Annual drip water volumes were calculated, and the results were compared with past measurements. The results indicate that there is a strong correlation between the two drip locations, and both have a weak connection to precipitation. The annual drip water volume has possibly increased compared with past data, based on the study period. Further research with longer measured data and water chemistry tests is needed to determine the origin of the cave waters.

Keywords
Buda Castle Cave, drip water, monitoring, precipitation, correlation analyses.

A budai Várbarlang csepegővizeinek mennyiségi mérése klasszikus és modern mérési módszerekkel

Kivonat
A budai Várhegy alatt húzódó Várbarlang állagmegőrzése szempontjából fontos a barlangi vizek vizsgálata. A kutatás fő céljai a csepegővíz mennyiségi mérése és a korábbi megfigyelésekhez képest bekövetkezett változások feltárása voltak. A célok közé tartozott továbbá a csepegővíz mérési helyek, valamint a csepegővíz- és csapadékadatok közötti kapcsolat vizsgálata. A méréseket saját készítésű billenőedényes mérőműszerekkel és ad hoc helyszíni mérésekkel végeztük. Korrelációvizsgálatot hajtottunk végre a két helyszínen mért csepegővíz értékeken és a csepegővíz és csapadék idősorokon. Az éves csepegővízmennyiségeket kiszámítottuk, és az eredményeket összehasonlítottuk a korábbi mérésekkel. Az eredmények azt mutatták, hogy a két csepegőhely közt erős, azonban a csapadékkal csak gyenge lineáris kapcsolat van. Az éves csepegővízmennyiség a korábbi adatokhoz képest a vizsgált időszak alapján valószínűleg nőtt. A barlangi vizek eredetének megállapításához további kutatások szükségesek hosszabb mérési adatokkal és vízkémiai vizsgálatokkal.

Kulcsszavak
Budai Várbarlang, csepegővíz, monitoring, csapadék, korrelációvizsgálat.

INTRODUCTION

The problems of stability and wetness in the Buda Castle Cave have been mentioned in a wide range of literature (*Szontagh 1908, Horusitzky 1937, Scheuer 1986, Hajnal 2003, Hajnal and Farkas 2011*) over the last century, and scholars at the Budapest University of Technology and Economics have been actively researching the Castle Cave for the past 40 years. Consisting of natural limestone formations and artificial corridor systems, the cave system is located underneath the Buda Castle Hill in Budapest, Hungary (*Figure 1*). The area above the Castle Cave is an area of great administrative, economic, cultural and touristic importance, furthermore this landscape is part of the UNESCO World Heritage Sites. In recent years, there have been several projects in the area – such as the development of the government quarter – making it even more important to study and monitor the underground areas, which are particularly important for the preservation of the surface. Despite this, there were very few measurements available until recently.

The hydrology of the Castle Cave was first researched in the 1970s by *Kessler (1971)*. The investigations continued in the 1990s, and a comprehensive study of the hydrogeology of the Castle Hill was accomplished by *Hajnal (2003)*. The latest measurements were carried out between 2008 and 2010 when water levels in the wells were investigated, pumping tests were performed, and water quality parameters were studied (*Hajnal and Farkas 2011*). Since then, the measurements have been suspended. However, recently, in the area of the Great Labyrinth (in Hungarian: "Nagy Labirintus"), the amount of water seeping into the cave appears to have reached an unprecedented level during the studied period. The infiltrating water caused some weathering and rock fall – mostly at the roof of the cave – that has recently become more common. It can be concluded that a detailed investigation of the water conditions in the cave is necessary for the preservation of the Castle Cave. To achieve this goal, cave waters, including drip waters need to be measured to determine if they are increasing and to discover the reasons for these changes. Accordingly, the study introduced in this paper had three primary aims: (1) to install and operate instruments suitable for cave conditions, that measure drip water at several locations with high temporal resolution, (2) to compare the drip water intensity time series at two locations, (3) to correlate precipitation time series and drip water intensities, and (4) to investigate the changes since the previous measurements.

STUDY AREA

The plateau of the Castle Hill is estimated to be about 405 000 m^2. The total area of its sides and slopes is approximately 750 000 m^2. The longitudinal axis of the plateau is 1 500 m, the total length of the hill is 2 000 m. The width of the plateau varies between 450 m and 120 m. The eastern and south-eastern parts of it are bordered by the steep valley side of the Danube, while the western, south-western and southern sides are bordered by the Ördögárok (*Krolopp et al. 1976, Scheuer 1986*). The average height of this erosion terrace-island, which has been transformed by sliding and degradation, is 154-159 m, with a maximum height of 169 m a. s. l. The plateau gradually decreases towards the south with levels of 149, 144-134, 119-114 m a. s. l. (*Scheuer 1986*). (All of the altitude units are in meters above the Baltic Sea level.)

Figure 1. The location of the Buda Castle Cave in Budapest, Hungary (Map data: Open Street Map, Google Satellite)
1. ábra. A budai Várhegy elhelyezkedése Budapesten, Magyarországon (Térképadatok: Open Street Map, Google Satellite)

Stratigraphy, tectonics, cave formation

To this day, the Várkert thermal, installed in 1938 at the south-east end of the hill, provides the most information about the stratigraphy and geology of the mountain (*Figure 2)* (*Horusitzky 1938*). On Castle Hill, the Triassic dolomite bedrock is covered by Upper Eocene–Lower Oligocene Buda marl (*Horusitzky 1938*). The next geological unit is the Oligocene Tardi Clay Formation, which is followed in the stratigraphic sequence by the Oligocene Kiscelli Clay Formation (*Scheuer 1986*). There are no traces of young rocks from the Tertiary period in the area, probably due to the erosion of the Miocene and Pannonian layers (Scheuer 1986). In the Polgárváros area, the next layer is an approximately 0.5-1.5 m thick fluvial alluvium, consisting of cobble gravel, sandy gravel, and clayey gravel, deposited by the Ördögárok stream (*Krolopp et al. 1976, Scheuer 1986*). Above the sediment layer, or where it is absent, there is a valley bottom layer, typically consisting of silt and clay. Hot springs, which had a significant lime ($CaCO_3$) content, emerged in the Buda Hills in the Upper Pliocene, forming freshwater limestone deposits at the site of the Castle Hill. In some places, loess settled on the limestone, but most commonly, the limestone is covered by anthropogenic fill (*Hajnal 2003*).

Until the Pleistocene, the area of Castle Hill was similar to its surroundings: the Triassic carbonates were covered by young Tertiary sediments. The present form of the Castle Hill was formed thanks to the freshwater limestone deposits and the incision of the Danube and the Ördögárok. Although the Ördögárok valley is of tectonic origin, there is no evidence of a fault on the other (eastern) side (nor has there been any vertical movement along the fault in the Ördögárok valley), so the Castle Hill cannot be considered a faulted mountain. The surface formation was primarily influenced by the limestone cover, which is significantly harder than the Buda marl. The limestone withstood erosion and denudation, protecting the layers below it, and thus the Castle Hill gradually rised above its surroundings (*Leél-Őssy et al. 2011*).

There are several theories about how the caves in Castle Hill formed. According to *Cholnoky (1936)*, the Castle Hill was directly connected to the Szabadság Hill during the Oligocene epoch and the streams rushing down from there carved out the cavities under the freshwater limestone. Others believed that the warm spring water could no longer rise through its own sediment – freshwater limestone – so it sought a path at the surface of the Buda marl, where it abraded the lower layers of limestone and the looser layers beneath the limestone (*Horusitzky 1938, Kerekes 1940*). The presence of corrosion marks on the walls of the caves also supports this theory. Another theory (*Kadič 1942*) suggests that surface water from precipitation dissolved the cavities through cracks and gaps in the limestone.

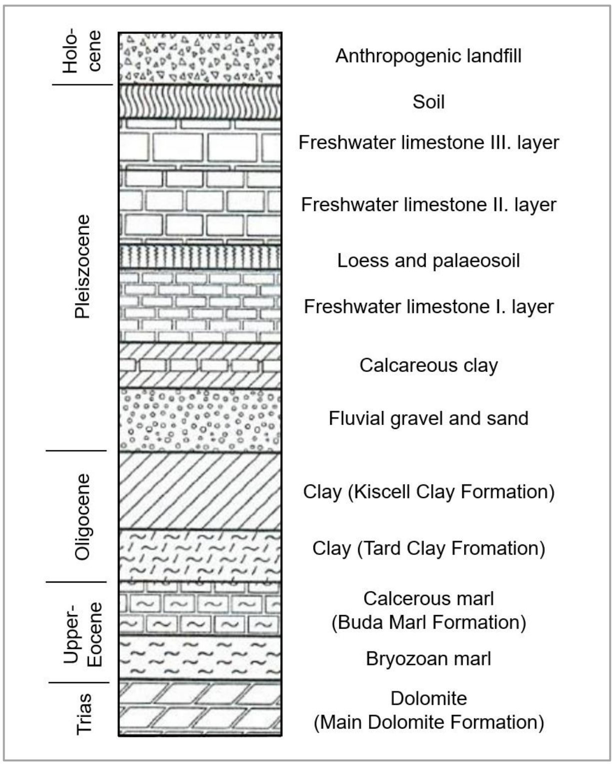

Figure 2. The stratigraphy of the Buda Castle Hill (Hajnal 2003, after Horusitzky 1938)
2. ábra. A budai Várhegy rétegsora (Hajnal 2003, Horusitzky 1938 alapján)

The calcareous tuff caverns of the Castle Cave were originally irregular, low-lying formations, which people have historically sought to shape for their own benefit. If the limestone was hard, it was hollowed out at the bottom. If it could be carved, they were extended towards the roof and the sides. The latter were often walled up and the roof was supported by pillars (*Kadič 1942*). Wells were dug to collect water that seeped into the cavities, often with air shafts from the roof to the surface. To the best of our present knowledge, caves of natural origin are found only under the Polgárváros. The total floor area of the connected cave cellars is about 18 000 m^2, and the total area of the individual caves is about 4 000 m^2 (*Hajnal 2005*). Part of the connected cellar system is called the Great Labyrinth. At present, the Great Labyrinth can be divided into three parts based on the operator. The southern part is rented by an entrepreneur, the northern part is operated by the Danube-Ipoly National Park Directorate (DINPI) and the third part consists of the Hospital in the Rock. This study was carried out in collaboration with the Duna-Ipoly National Park Directorate on the northern area of the Great Labyrinth (see the study area on *Figure 3*).

Hydrogeology

According to the classical hydrogeological classification, there is no contiguous body of groundwater on the plateau of the Castle Hill. In the travertine beneath the anthropogenic fill, karst water flows through fractures. Since this layer is on average 5-8 m thick, it is not karst water in the classical sense. Because of the variability of the limestone and its various structural appearance, it can also be present in varying quantities, for example, in capillary networks but also in cavities of a few cubic metres. The water that runs down into the one- to two-metre-thick fluvial alluvium beds beneath the limestone also does not form a contiguous water body. The wells in the labyrinth are fed by water collected in separate, small sumps (*Hajnal 2003*). These are recharged by rainfall and by the losses from utilities. This could be proven by stable isotope measurements (*Czuppon et al. 2022*) but so far this was proven with other methods. The calculations of *Hajnal (2003)* revealed that water from utility losses plays a dominant role compared to precipitation in terms of the amount of water that seeps in.

Previous measurements

Historical data on drip waters is highly scattered in time and space, so few conclusions can be drawn from them, as indicated by *Hajnal (2003)*. At the time of the 1 885 surveys, only the drip sites were determined, no other measurements were made (*Rétiné 1994*). The identification of drip sites was a very difficult task based on the past descriptions, as street names and house numbering changed several times over the span of more than 100 years, and several inaccuracies were noted in the texts (*Hajnal 2003*). The study performed for the Tunnel drainage also identified several drip sites (*Szontagh 1908*). A thorough, more detailed study was only carried out in the 1970s (*Kessler 1971*). At that time, six measurement points were recorded, but today it is only possible to clearly identify five of them (*Hajnal 2003*). The method of these measurements was the following: one m^2 plastic sheet was placed under the drip points and the drip rate was measured through an opening in the middle of the sheet once a week from February to May 1971. By analysing the measured values, it was found that the individual measuring points responded differently to precipitation (*Kessler 1971*).

METHODS

In this study, the drip water in the Castle Cave was measured continuously using tipping bucket gauges at two locations, but additional ad hoc measurements were also carried out. The measurement locations are indicated on the map in *Figure 3*. This map was based on the laser scanning survey by the BURKEN Ltd. The methodology of these measurements is described in the following chapters.

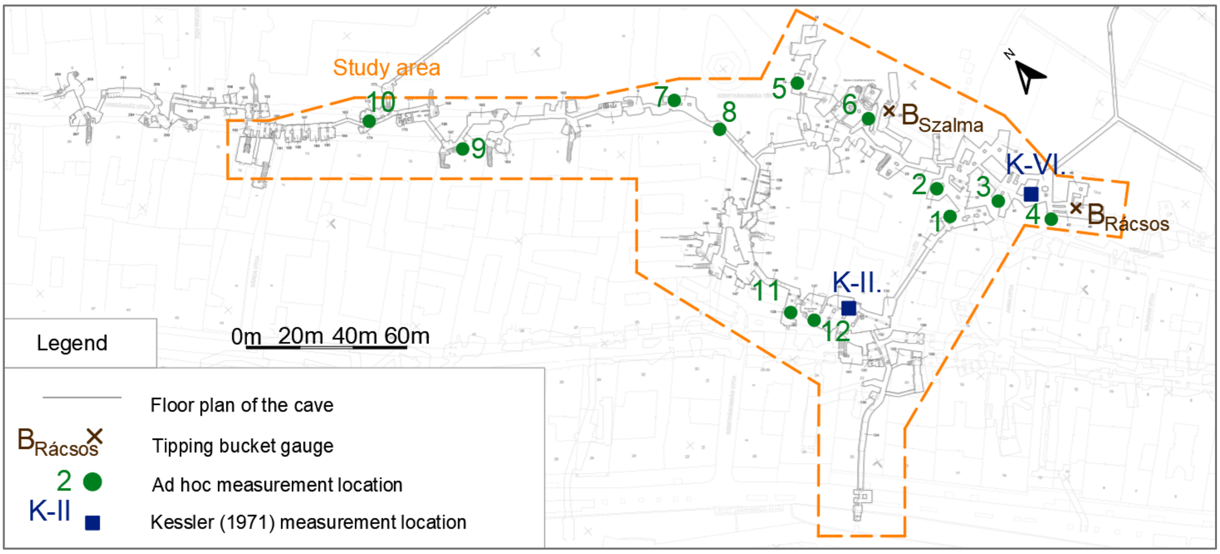

Figure 3. Measurement locations in the Great Labyrinth (base map by Havasi (2011) based on Burken Ltd. survey (2010); measurement points added by the author)

3. ábra Mérési helyszínek a Nagy Labirintusban (Havasi (2011) által készített áttekintő térkép a Burken Kft. (2010) felmérése alapján, saját mérési pontokkal kiegészítve)

Tipping bucket gauge measurements

The drip water measurements required an instrument that was low power, as access to the cave required prior arrangement and it was only possible on a monthly basis and the devices were left unattended for the time interval between the readings. In addition, it was necessary to obtain high resolution data. Therefore, a version of the drip water measuring instrument, which is currently under development, was built and adapted to the conditions of the cave. The device is based on the designs of *Tóth (2016)* and *Nagy (2021)* in their diploma theses, but it has been modified to enable self-powered operation. The assembled measurement device is based on a tipping bucket rain gauge, consisting of a funnel, a two-armed tipping bucket and a Reed-relay. The funnel directs the precipitation into one half of the tipping bucket, and when the tipping bucket is filled up, the device tilts over, closing the circuit momentarily. The hardware consists of an Arduino Pro Mini microcontroller, a DS3232 clock and an SD card reader module located on the motherboard. The power supply is secured by an 18650 1600 mAh lithium iron phosphate battery. As for the operation principle, the instrument is asleep by default. When the circuit is closed (tipping occurs), the Arduino microcontroller detects an interrupt on one leg, wakes up and increases the tipping count. If more than 10 minutes have elapsed since the previous recording, it writes the number to the SD card, then resets the count to zero and returns to sleep. The instrument was calibrated, using a burette. Based on the calibration measurements of the tipping bucket gauge, the average volume of the tipping bucket was found to be 4.6 cm^3, but the range of the measurements was relatively large, from 4.3 to 4.9 cm^3. Considering the observations of *Nagy (2021)*, this was probably owing to some waterdrops remaining in the buckets after the last tipping. Based on this assumption, the calibrated value was accepted, as this could also happen to the device after installation.

The instruments were installed in the Castle Cave after a visual inspection of the cave and an assessment of the drip water intensities. When considering the placements, the previous measurement locations and the securement of uninterrupted operation were also taken into account. After selecting the locations, a tarpaulin was placed over the funnel of the tipping bucket gauges, which collected water from a larger area into the instruments. Two measurement devices were placed in the Buda Castle Cave on the 8th of January 2024 on the "Szalmacseppköves" and "Rácsos kút" drip locations (*Figure 4*).

Figure 4. "Szalmacseppköves" and "Rácsos kút" drip water measurement location in the Buda Castle Cave
4. ábra. "Szalmacseppköves" és "Rácsos kút" csepegővíz mérési helyek a budai Várbarlangban

As the data was processed, the measurement times were rounded to the nearest minute and the tipping count was converted to water volume by multiplying it by the calibrated volume and dividing it by the area of the tarpaulin. The time passed from the (n-1)th to the nth measurement was calculated and the volume was divided by the elapsed time (in minutes). The resulting value was assigned for each minute between the (n-1)th and nth measurement according to *Eq. 1*.

$$i_{t_{n-1}+1} = i_{t_{n-1}+2} = \cdots = i_{t_n} = \frac{V_{t_n}}{(t_n - t_{n-1}) \cdot A} \quad (1)$$

Where:

- $i_{t_{n-1}+1}\left[\frac{ml}{s \cdot m^2}\right]$ – is the intensity value (or specific drip yield) one minute after the time of the (n-1)th measurement,
- $V_{t_n}[cm^3]$ – is the water volume calculated as $V_{t_n} = c_{t_n} \cdot V_{cal}$, where c_{t_n} $[-]$ is the tipping value at the nth measurement and V_{cal} $[cm^3]$ is the calibrated volume of the tipping bucket,
- t_n $[s]$ – time at the nth measurement,
- A $[cm^2]$ – is the area of the tarpaulin.

After the intensities were calculated in such way for each minute, the hourly values were also calculated from them.

This measurement provided data with high temporal resolution. However, as groups of tourists regularly visit the Castle Cave, it was not possible to establish an extensive, continuously operating drip water monitoring network. Therefore, ad hoc measurements were essential to obtain information on drip water intensity over a larger cave area and determine the amount of drip water over the whole study area.

Ad hoc field measurements

The ad hoc field measurements were carried out in September 2024. On the first occasion, on 18 September, the dripping from the roof of the cave was observed and measuring buckets were placed at high-intensity points. The measurement locations were marked in *Figure 3* and numbered 1-12. The classical, most simple measurement method was used, where the drip water was collected in a bucket for a set time. During the field measurements, the time was recorded after placing the measuring buckets. At the next site visit, the volume of water collected in the measuring buckets was measured and the elapsed time was recorded. The drip water yield was calculated as the water volume divided by the elapsed time. At first, the measurements were carried out for one and a half to two hours, then the subsequent three measurement lasted for one week. The reason behind this is that it was not easy to schedule and perform the measurements at once, as it required more time (two hours), and the weekly measurements allowed for the measurement of the mean value over time. Due to the measuring containers overflowing in many places in a week, another short measurement of approximately one hour was conducted on the 8th of October. Overall, this resulted in a total of five drip water yield values per measurement location.

During the measurement process, the wet or dripping areas were identified on the roof of the cave and similar areas (based on dripping intensity) were delineated around each measurement location. These areas were later used for the annual drip volume estimation (*Table 2.*).

Correlation analysis

A simple correlation analysis was performed on the hourly data from the two drip locations using linear regression, to examine the similarities in drip water behaviour across the cave. Another one of the study's objectives was to investigate the origin of drip water by comparing it with precipitation data and searching for connections between them. The ten-minute automated weather station data from the Meteorological Data Repository of *HungaroMet Nonprofit Zrt. (2024)* was used. The Station Number 44121, in District II in Budapest, lies the closest to the Castle Cave, and according to *Hajnal (2003)*, the precipitation on the Castle Hill correlates well with the measurements of this station. The connection between the precipitation and drip water intensities was studied using linear correlation. The temporal resolution was decreased as it can be more difficult to explore the relation between time series with high temporal resolution and they also may be subject to larger bias and errors. Therefore, the analysis was executed on the daily precipitation sums and the daily average drip water intensities. The precipitation data was shifted by 1,2, … n days (maximum of five months), and the correlation coefficients were determined for each data pair using linear regression. The highest correlation coefficients and the shifted day value belonging to them were determined.

RESULTS

The tipping bucket gauge measurements resulted in a 10-minute temporal resolution drip water intensity data. The two time series were correlated to each other and also with precipitation. The ad hoc measurements were used to calculate an estimate of annual drip water volume. These are introduced in the following sub-chapters.

Measured drip waters

The result of the tipping bucket gauge measurements can be seen in *Figure 5.* The dotted line indicates that there was a gap in the measurements. From April to August, the devices needed to be repaired. At the "Rácsos kút" drip location, the specific drip water yield was around 140 ml/h m^2 at the beginning of the measurements in January 2024, but it has decreased to 50 ml/h m^2 by the end of March. In the middle of August, it was approximately 70 ml/h m^2 and it has been decreasing since, although it has less steepness than that of the time series at the beginning of the year. At the last reading, it was around 40 ml/h m^2. The „Szalmacseppköves" measurement location had a much lower drip water intensity of about 18 ml/h m^2 in January and 4.7 ml/h m^2 in October, about 1/8 of those at the „Rácsos kút".

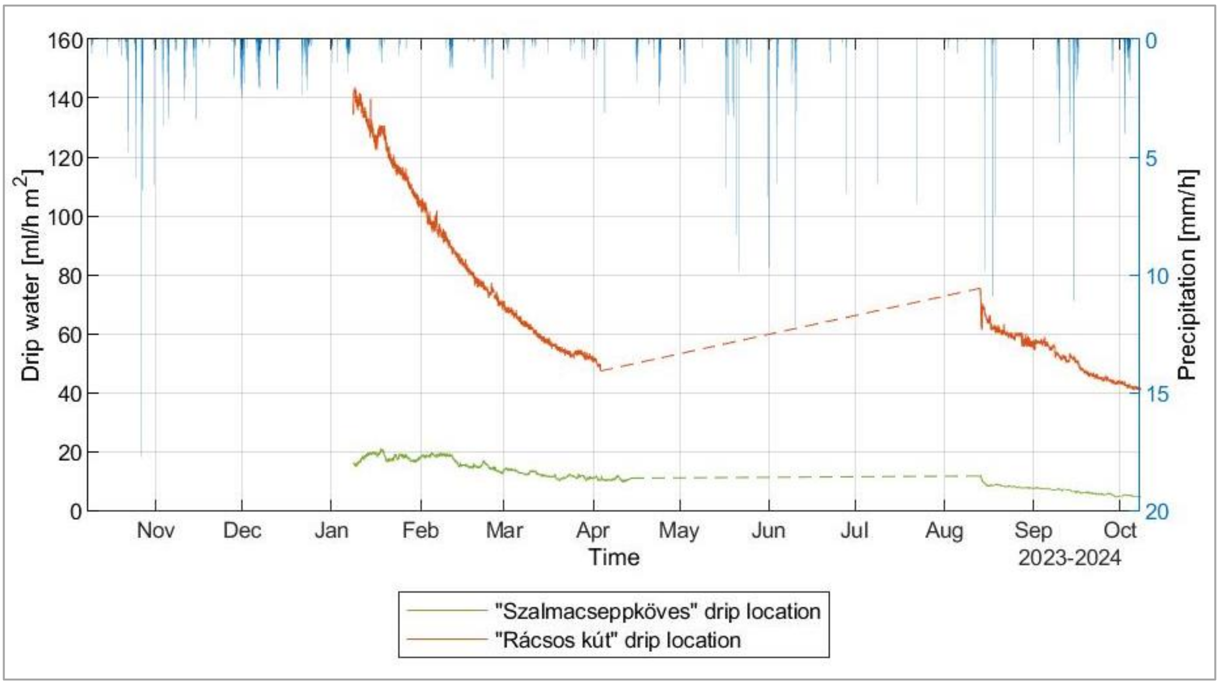

Figure 5. The drip water measurement data from the two tipping bucket gauges in the Castle Cave
5. ábra. A Várbarlangban lévő két billenőedényes mérőműszerrel mért csepegővíz intenzitás adatok

The calculated drip water yield for each ad hoc measurement point is shown in *Figure 6*, where the change in values over time can also be observed in the consecutive columns for each location. The measurements, when the measuring bucket overflowed, are marked with "+" in the figure. This means that there was a higher drip water yield than these values during the measurement interval, but there is no information on how high it was. In some cases, the measuring bucket may have been moved at some point during the measurement interval, as it was not in its original location at the time of measurement. These were not included in *Figure 6* and these 'displaced' values also with the 'overflowed' ones, were not considered in the following calculations introduced in the next chapter.

Correlation analyses on drip water intensities and precipitation

The correlation analysis was conducted on the time series data of drip water intensities and precipitation presented in *Figure 5.* The data from the two drip water locations correlates well, with a correlation coefficient of 0.87 (*Figure 7*).

The resulting maximal correlation coefficients and the shifted day (lag) values belonging to them are shown in *Table 1.*

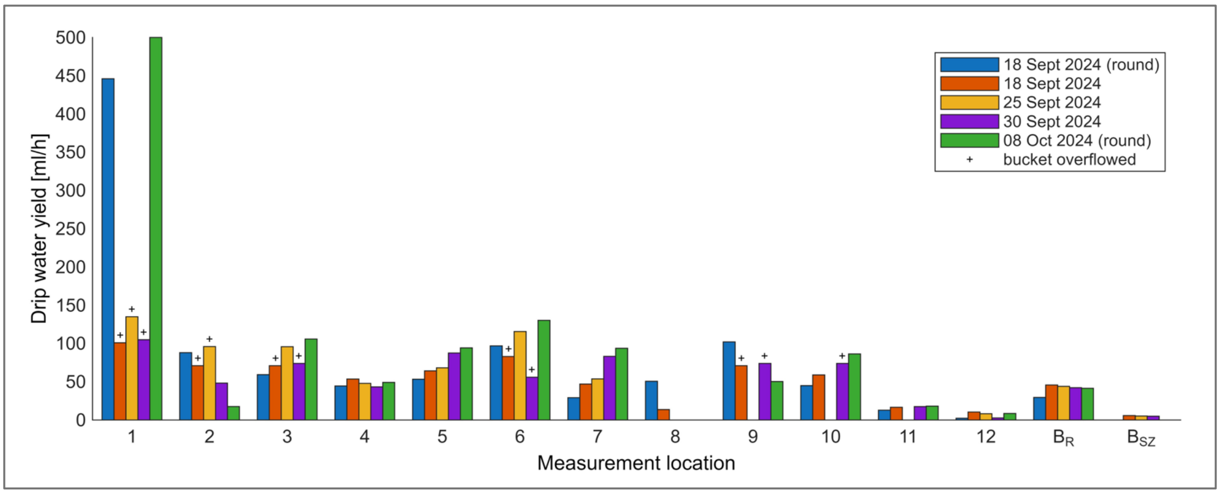

Figure 6. Drip water yields from the ad hoc (Nr. 1-12) and tipping bucket gauge (B_R and B_{SZ}) measurement locations
6. ábra. Az ad hoc és a billenőedényes mérésekből származó csepegéshozamok az egyes mérési helyeken

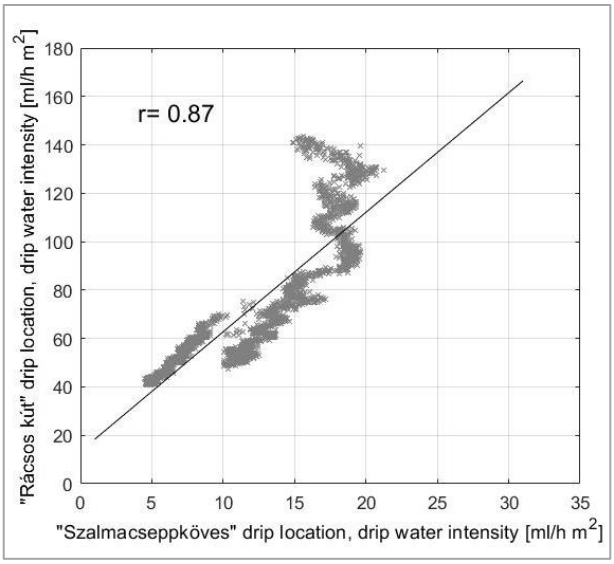

Figure 7. Correlation between the drip water intensities at the two tipping bucket gauge measurement locations
7. ábra A két billenőedényes mérési hely csepegés intenzitás adatsorai közti korreláció

Table 1. Correlation coefficients between the drip water intensities and precipitation
1. táblázat. A csepegővíz intenzitások és a csapadék közötti korrelációs együtthatók értékei

Drip location	Szalmacseppköves Jan 2024 - Apr 2024	Szalmacseppköves Aug 2024 - Okt 2024	Rácsos kút Jan 2024 - Apr 2024	Rácsos kút Aug 2024 - Okt 2024
R [-]	0.34	0.35	0.40	0.36
Lag [days]	48	88	41	88

Due to the good correlation, the "Szalmacseppköves" and "Rácsos kút" drip locations in the Castle Cave have very similar correlation coefficient values to the same shifted precipitations for the interval since August, and they also have a lot of similarities before April.

The correlation analysis with precipitation revealed only weak connections. Since the correlation analysis could only be performed on data from two locations, these findings are less generalizable to the entire study area. While this study did not confirm the origin of cave waters, it partially contributed to our understanding of their relation to precipitation. It can be assumed, that there is no strong linear correlation between the drip waters and precipitation. In karstic areas this is to be expected, as there does not need to be a connection between daily precipitation and infiltration. After all, the relationship between precipitation and infiltration is not linear, it is much more complex, even in non-urbanised areas. Since the methods usually applied to karst areas are not relevant in the Castle Cave due to the urbanisation of the area, further studies could be conducted with other methods capable of exploring non-linear relationships.

Estimation of annual drip water amount in the study area

As the measured intensities ranged across several magnitudes and the spatial variety of the drip waters was considerable, a minimum and maximum estimate of the drip water for the whole study area (3 700 m^2) was calculated. First, the minimum value was estimated directly from the measured drip water yield (Q_n [ml/h]). It was assumed that the measuring buckets collected most of the drip water in a one m^2 area. Thus, during the calculation of the lower estimate, the measured value was considered as a specific drip water yield defined for a unit area of one m^2. Next, the maximum estimate was also calculated using specific drip water yields, but these were acquired from the measured drip water yields using a different empirical ratio (r_{emp} [-]) for each area. The ratios were determined based on the visual inspection of the wet areas and considering the spatial distribution of drip water around each measuring bucket. The area of a measuring bucket was 0.07 m^2, which is approximately 1/14 of the unit area, therefore these empirical ratios ranged between 1 and 14. The minimum and maximum specific drip water yields and the empirical ratios for each area can be found in *Table 2*. The minimum and maximum specific drip water yields were multiplied by the area assigned for each measurement location (A_n [m^2]) and the annual drip water quantity (V [m^3/year]) was calculated. This evaluation method is summarized in *Eq. 2* and *Eq. 3*.

$$V_{min,annual} = \sum_{n=13}^{n=1} Q_n \cdot 10^{-6} \cdot 365 \cdot 24 \cdot A_n \quad (2)$$

$$V_{max,annual} = \sum_{n=13}^{n=1} Q_n \cdot r_{emp} \cdot 10^{-6} \cdot 365 \cdot 24 \cdot A_n \quad (3)$$

Table 2. Calculation of annual drip water volume from ad hoc measurements
2. táblázat Az éves csepegővíz mennyiség kiszámítása az ad hoc mérésekből

Measurement location	A $[m^2]$	q_{min} $[ml/h \cdot m^2]$	r_{emp} $[-]$	q_{max} $[ml/h \cdot m^2]$	$V_{min,annual}$ $[m^3/year]$	$V_{max,annual}$ $[m^3/year]$
1	103	473	3	1 419	427	1 280
2	256	51	5	257	115	575
3	283	65	1	65	162	162
4	161	48	1	48	67	67
5	45	74	2	147	29	58
6	66	114	4	457	66	264
7	111	61	1	61	60	60
8	40	13	1	13	5	5
9	157	51	1	51	70	70
10	45	52	2	104	21	41
11	63	14	1	14	8	8
12	360	6	7	45	20	143
13. (entrance)	31	6	1	6	2	2
				$\sum$	**1 051**	**2 735**

The calculation resulted in a total of 1051 m^3/year minimum and 2 735 m^3/year maximum drip water for the studied 3700 m^2 area of the Great Labyrinth. This can be compared to *Kessler's (1971)* and *Hajnal's (2003)* calculations, as they calculated the amount of water infiltrating to the Great Labyrinth (GL). *Kessler (1971)* calculated based on drip water measurements in 1971, *Hajnal (2003)* determined the infiltration based on water balance calculations, proportional to each area on the Castle Hill, for several intervals between 1971-2000 (although some years were missing). For the comparison, the average of his calculations was used. To be able to compare the exact values, the results of *Kessler (1971)* and *Hajnal (2003)* were divided proportional to the total area of the current measurements $V_{annual,GL\text{-}part}$. As they both examined all 18 000 m^2 of the Great Labyrinth, their calculated drip water volumes for a year were divided by 18 000/3 700=4.86, as the currently measured area is about 1/5 of their study area. Their results are compared with the current calculations in *Table 3*. The past calculations of *Kessler (1971)* and *Hajnal (2003)* are between the current minimum and maximum estimates, showing good agreement. As they are closer to the minimum estimate, the drip water volume per year has probably increased. It should be noted that a source of weakness in this study which could have affected the annual drip water volume estimates is that although the ad hoc measurements covered the study area, they were limited to a few occasions.

Table 3. Comparing calculated annual drip water volumes to previous studies
3. táblázat. A korábbi tanulmányokban található éves csepegővíz mennyiség összehasonlítása a számított értékekkel

Study	Time interval	A $[m^2]$	$V_{annual,total}$ $[m^3/year]$	$V_{annual,GL-part}$ $[m^3/year]$
Kessler (1971)	1971	18 000	7 300	**1 504**
Hajnal (2003)	1971-2000	18 000	7 382	**1 517**
Current Min.	2024	3 700	1 051	**1 051**
Current Max.	2024	3 700	2 735	**2 735**

SUMMARY

This study was carried out with the primary objective of the preservation of the priceless historical and cultural assets of the Buda Castle District, by assessing the water conditions in the underlying Castle Cave. Drip water measurements with tipping bucket gauges and ad hoc field tests were performed. Two self-made, low-cost and low-power tipping bucket gauges were placed in the Castle Cave. The measured drip water intensity ranged from 4.7 to 140 ml/h m^2. The drip water intensity at the two locations were analysed using linear regression and a strong connection (R=0.87) was found. Both drip locations have a weak connection to precipitation, so other impacts (such as losses from utilities) should also be examined. The ad hoc field measurements resulted in highly varying drip water intensities, and the spatial distribution was also variable. Thus, minimum and maximum estimates were calculated for the annual drip water volumes. According to the estimates, the drip water volume in the studied area is at least 1 051 m^3/year and it can be up to 2 735 m^3/year. The previous calculations of annual drip water volumes of *Hajnal (2003)* and *Kessler (1971)* were proportionally calculated for this part of the Great Labyrinth and those values also fall into this range, with 1 517 and 1 504 m^3/year. Consequently, it can be assumed that the drip water volumes during the study period have increased since the past measurements. In the future, longer measurement data would be helpful to analyse the factors affecting the drip waters so that more assured conclusions could be drawn about the changes since the past measurements. In addition, water chemistry tests would be essential to ascertain the origin of the cave waters.

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THE AUTHORS

FANNI GAZDA is a civil engineering student at the Budapest University of Technology and Economics. She started her studies as a BSc student in 2021 and currently studies at the Specialization in Hydraulic Engineering. She has participated in the Scientific Student Competition (TDK) three times and received the Palatin Joseph Prize of the university in 2024. She was granted the University Research Scholarship in 2024/2025. Additionally, she is working as a research assistant at the National Laboratory for Water Science and Water Security.

DÁVID FARKAS graduated from the Budapest University of Technology and Economics as a civil engineer in 2015. He was a PhD (2015-2018) student at the Department of Hydraulic and Water Resources Engineering, from 2018 he was a research assistant, since 2022 he is an assistant professor. He has been a member of the Hungarian Hydrological Society since 2009. Member of the Hungarian Chamber of Engineers since 2020.

GÉZA HAJNAL graduated from the Budapest University of Technology and Economics (BME) as a civil engineer in 1993, and he received a degree as a certified engineering teacher in 1994. In 2002, he obtained a PhD degree. Since 2008, he is an associate professor at the Department of Hydraulic and Water Resources Engineering, and between 2017 and 2020, he held the position of the head of department. His main research interests are hydrogeology and water balance calculation. He has been awarded the Bolyai János Research Fellowship twice (2004-2006, 2008-2010) for his research in hydrogeology. In 2020, he defended his dissertation in Literature at the University of Pécs.

DÉNES SZIEBERTH obtained his degree in chemical engineering in 1997 and his PhD in 2000. Since completing his studies, he has been working at the Department of Inorganic and Analytical Chemistry at the Budapest University of Technology and Economics, where he has been an associate professor since 2011. His original field of expertise is the modeling of chemical reaction mechanisms. He has conducted research as a scholarship holder at several universities (Kaiserslautern, Leuven, Antwerp, Edinburgh, Sendai, Turin). Since 2014, his interest has turned to karst waters. In addition to water analysis, his main research interests include measurements and sampling in underwater caves and the design of unique instruments.

Wet area from drip water near measurement location Nr. 12 (Photo by Fanni GAZDA)
Vizesedés a 12. mérési helyszín környezetében (Gazda Fanni fotója)

Role of Bilateral Memoranda of Understanding in the Hungarian Water Diplomacy

Bálint RÓZSA[1]

[1] economist, free-laced expert (email: balint.rozsa@outlook.com)

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Abstract

This paper explores the role of bilateral Memoranda of Understanding (MoU) in Hungary's water diplomacy, focusing on the creation of over 50 agreements signed in large numbers between 2013 and 2024, although cooperation in the field of water management had been established even before the period under review. These MoU's primarily aim to foster professional cooperation between Hungarian institutions, such as the General Directorate of Water Management, and their counterparts in various countries, in general those without shared water resources with Hungary. This is an original research, which delves into the historical context and motivations behind these agreements, highlighting their significance in promoting export and political relations rather than addressing the fragmentation of Hungary's water governance system, but touching upon that matter. While MoU's provide a flexible framework for cooperation without the binding obligations of formal treaties, they also present limitations, such as a lack of enforcement mechanisms and clear ownership, which can hinder effective implementation. The thesis suggests that for complex projects requiring clear obligations, formal treaties may be more appropriate. Future research directions include a detailed analysis of economic relations, educational and scientific collaborations, and a comparative study of similar programs in Europe. Overall, this work contributes to understanding Hungary's international water governance and diplomacy, emphasizing the need for better coordination among institutions involved in water management and clear definition of intended purpose when assigning resources.

Keywords

Bilateral Memorandum of Understanding, water diplomacy, sustainable water resources management, Budapest Water Summits, non-binding agreements, water scarcity, legal frameworks, transboundary water management, export strategy.

A Magyar Vízdiplomácia kétoldalú együttműködési megállapodásainak jelentősége

Kivonat

Ez a tanulmány a kétoldalú együttműködési megállapodások szerepét vizsgálja Magyarország vízdiplomáciájában, a leginkább 2013 és 2024 között aláírt több mint 50 megállapodás alapján, bár a vizsgált időszak előtt is születtek együttműködések a vízügy területén. Ezek az megállapodások elsősorban a magyar intézmények – például a Vízügyi Főigazgatóság – és a különböző (többnyire Magyarországgal közös vízkészletekkel nem rendelkező) országok – intézményi megfelelői közötti szakmai együttműködést hivatottak elősegíteni. A kutatás tárgya e megállapodások történelmi kontextusának és motivációinak vizsgálata, kiemelve jelentőségüket az export és a politikai kapcsolatok előmozdításában, amihez csak érintőlegesen kapcsolódik a magyar vízügyi irányítási rendszer széttagoltságának kérdése. Míg ezek a megállapodások rugalmas keretet biztosítanak az együttműködéshez a hivatalos szerződések kötelezettségei nélkül, ugyanez korlátokat is támaszt, hiszen például ebben a konstrukcióban hiányoznak a számon kérhető végrehajtási mechanizmusok és az egyértelmű felelősségvállalás. Mindez akadályozhatja a hatékony végrehajtást. A cikk utal rá, hogy az egyértelmű kötelezettségeket igénylő összetett projektek esetében a hivatalos államközi szerződések szükségessé válhatnak. A javasolt jövőbeli kutatási irányok kitérhetnek a gazdasági kapcsolatok, az oktatási és tudományos együttműködések részletes elemzésére, valamint a hasonló európai programok összehasonlító vizsgálatára. Összességében ez a munka hozzájárul Magyarország nemzetközi vízügyi szerepvállalásának megértéséhez, és hangsúlyozza a vízgazdálkodásban érintett intézmények közötti jobb koordináció szükségességét, a források allokálásakor meglévő világos célkitűzés fontosságát.

Kulcsszavak

Kétoldalú együttműködési megállapodás, vízdiplomácia, fenntartható vízgazdálkodás, budapesti Víz Világtalálkozók, nem kötelező érvényű megállapodások, vízhiány, jogi keretmegállapodások, határokon átnyúló vízgazdálkodás, exportstratégia.

INTRODUCTION

The subject

- For about a decade (from 2013 to 2024) Hungary signed more than 50 bilateral MoU's (Memorandum of Understanding) with focus on water resources, mainly with distant countries for promoting professional cooperation between Hungarian institutions (prominently the General Directorate of Water Management), organisations and their equivalents in the other countries. The current research is concentrating on the history and the motives behind these paperworks, and subsequently the chosen form of cooperation. Beyond the history, the fact, that these states commonly do not have shared water resources with Hungary is raising various questions, worth to explore.
- What does the character (MoU's with no legal consequences) of these cooperations indicate?
- What is the afterlife of these initiatives? Where is the focus? Is it on the act of signature or is it on actual implementation?
- Is export promotion a purpose of these instruments (MoU's) in the water industry and are they serving as diplomatic tools for opening markets or are there rather different goals (i.e. water management knowledge and experience can be key to doors of politics)?

- Is there a gap of any kind when we consider implementation, shall that be financial, institutional, human, or just the lack of political will?
- Are the resources used efficiently - even if limited - for supporting the sector and its export?
- The recent improvements in the Hungarian water governance system (i.e. restructure of ministry responsibilities and organization) gives an extra topicality to the subject and is raising the question: what is going to happen to this activity in the future?

Photo 1. Minister of Foreign Affairs and Trade Péter Szijjártó and Saudi Minister of Environment, Water and Agriculture Abdulrahman Abdulmohszen A. al-Fadley in Riyadh on October 21, 2020. (MTI/KKM/Kkm/M. Király)
1. kép. Szijjártó Péter külgazdasági és külügyminiszter és Abdulrahman Abdulmohszen A. al-Fadley szaúdi környezetvédelmi, vízügyi, és mezőgazdasági miniszter találkozója Rijádban 2020. október 21-én (MTI/KKM/Kkm/Király M.)

Connections to other areas

When we try to answer the above main questions, there are several others that we cannot go by. Who are the partners? Are there patterns existing, that connect them in terms of politics, economics, natural resources (especially water) or culture? Where does the background of Hungary put the country on this map? Beyond our own motives why is Hungary a desirable partner for these countries to sign an MoU in water management?

Resources, means of study

For presenting the background and to create an analysis that aims to find patterns, some of the memoranda and implementation reports were used. Occasionally references to legislation and the National Water Strategy were included. I use recent studies about the current (and changing) setup of the Hungarian water governance and some older ones for depicting the historical background. There is a big emphasis on interviews with water professionals and ministry officials. Additionally, I reach out for publicly available statistical data from international organisations like World Bank, UNDP, UNEP etc.

MEMORANDA OF UNDERSTANDING AS A TOOL IN (WATER) DIPLOMACY

Emerging role of water in diplomacy

Water

Water is a vital resource of a multifunctional nature, central for all life, economic and social development. The hydrological cycle is essentially contributing to sustainability and the stability of the environment. Due to the direct and indirect consequences of the intense economic growth and the worldwide ignorance of environmental destruction, currently we experience a degradation of the biosphere, climate change and pollution (a triple planetary crisis) transmitted through and impacting mostly water, water habitats and water resources.

There is an interesting duality present in the availability of water resources: While the industrialized world takes abundant water resources for granted, on parts of our planet access to even the primarily needed water-quantity means a daily struggle. 26% of the world's population lacks access to safe drinking water (*Kőrösi 2023*). Also important to note that the most water-stressed parts of the world, that have the lowest capacity in resilience and are hit most seriously by climate change, have the most limited possession of the resources necessary for adaptation. Interestingly the modernization and economic growth in the "Global West" while having greatly contributed to climate change, also provided the financial resources and technological innovations to bail out climatic disadvantage and eventual resource scarcity. Unfortunately, the Global South is deprived of these (*Cziko 2016*).

Security

Water both as a sensitive and complex global common, tends to force international actors to engage in long-term cooperation because – as quite early the 1977 Mar del Plata congress recognized – water availability is one of the greatest security challenges of our times (*Grafton at al. 2023*). This finding was underlined later in several instances, ranking water even as No1 security risk (*Davos World Economic Forum 2015*).

Water as a strategic resource can have a Ianus face depending on the hand directing its flow.

Its uneven distribution and increasing scarcity can lead to tensions and conflicts between countries. Quite often water has been used as a weapon. The continuous supply of water and control of water bodies was used as a coercive tool or has been simply diverted, shut. That has often led to water disputes, water conflicts, having disrupting effect on the weak and often resulting in migration of people or degradation of land. “Many of the wars of the 20th century were about oil, but wars of the 21st century will be over water unless we change the way we manage water” (*Global Water Forum 2013*). Predicted Ismail Serageldin, vice president of World Bank, seeing that the worlds policymakers lack long-term perspectives in the management of water and for preserving social stability, the governments are reluctant to recognise shortages, that eventually can lead to devastating consequences. Summarizing the role of water from security perspective safe and sufficient drinking water and proper sanitation is vital for human (human security) thus the availability of this is a strong factor of social stability. Ecological stability and rich biosphere provide vital ecosystem services and prevent environmental degradation (environmental security) thus contribute to resilience against natural hazards, economic development, eventually to national security. However, since water creates a worldwide strategic interdependence due to the relation of water and climate, there are no “national solutions” for most of the water problems. Institutionalised international solutions and water management mechanisms are essential and the character of water also provides the opportunity for promotion of good water governance: “the range of political, social, economic and administrative systems that are in place to regulate development and management of water resources and provisions of water services at different levels of society” (*Baumgartner and Pahl-Wostl 2013*).

Despite of its currently relative abundant supply Hungary’s position in terms of water is highly vulnerable to outside activities and climatic factors. This puts water to a priority position in Hungarian foreign political considerations and also motivated the country for centuries to accumulate experience in efficiently managing water supply and treatment, irrigation methods, inland navigation. In connection with this, it is obvious why is the domestic capacity of water industry and water engineering too, vital for the security of the country and why is important to provide export opportunities for the Hungarian water sector in times when the domestic investment is temporarily limited.

Water diplomacy

The increasing scarcity of this special resource at the same time requires and provides new types of foreign political tools. As Csaba Kőrösi in a presentation said, a zero-sum game with a global common inevitably leads to the destruction of that global common (thus eventually to a negative sum game). Water diplomacy aims to create an additional benefit by common use of the water resources, making everyone interested in cooperation. Water diplomacy is not only focusing on shared water resources, resolving and preventing conflicts, but is also addressing various aspects of water management to promote cooperation between countries based on the use of water resources. Water diplomacy is building on the unificating character of water that derives from the vulnerability and vital importance of this special resource. Utilising water as a creator of peace and cooperation is what water diplomacy aims for, for bringing parties on a common ground (*Körösi 2023*).

Concerning Hungary as a small player, water diplomacy provides a unique opportunity to become visible in the international stage, focusing its resources to a niche area within the globalised international relations.

Water diplomacy toolset

The toolset that water diplomacy uses, includes negotiation and dialogue, facilitating communication on sharing and managing water, sharing hydrological data, and providing transparency in water management for building trust and cooperation. It encourages shared projects in infrastructure development (dam construction, water treatment facilities, irrigation systems, flood protection dykes) that benefit all parties involved, knowledge exchange and training to develop water management expertise. Broad stakeholder consultation, including academic and professional contribution is part of the essence of water diplomatic solutions. Last but not least it creates legal framework by developing and operating international agreements, treaties and institutions that govern water sharing and management.

Conclusion

By contributing to conflict prevention, cooperation and regional stability, economic integration, more efficient and sustainable water use practices and providing improved access to water, water diplomacy is a powerful, yet soft and friendly tool in improving relationships of countries.

Saying this, we must point out that water diplomacy is not just about government-to-government relations. Non-governmental organizations, private sector, and civil society can also play an important role in promoting water cooperation. Here must be mentioned public diplomacy that can use water and the tools of water diplomacy as a powerful diplomatic PR tool, because of the importance and unifying character of this resource.

If we think about the growing number of Hungary’s MoU’s in water management, it’s important to see that water diplomacy will likely have a growing importance as water scarcity becomes a growing challenge in the future as a result of climate change and population growth in the developing world. Endeavours in water-based cooperation and sustainable water management practices should serve a future, where water is a source of peace and development. Existing and future technological solutions in engineering, data collection and monitoring can facilitate these cooperations.

Photo 2. Signature of the Hungarian-Pakistan MoU in water management in Islamabad - Ambassador István Szabó and Muhammad Ashraf, Secretary of State for Water Resources (mfa.gov.hu)
2. kép. A Magyar-Pakisztáni vízügyi megállapodás aláírása Islamabadban - Szabó István nagykövet és Muhammad Ashraf vízkészletekért felelős államtitkár (mfa.gov.hu)

Role of MoU's in international diplomacy and the evolution of relations

What can be the reasons for choosing a soft, legally non enforceable cooperation form such as Memorandum of Understanding's in the diplomacy practice? How do these MoU's fit in the legal framework of international water management cooperation?

In the past few decades, there has been an increasing trend of both states and international organizations using this instrument, in bilateral or even multilateral relations, including fields like trade, environment, human rights, culture, etc. While MoU's were a rare phenomenon in the first half of the twentieth century, their number has increased exponentially in recent times (*Poast et al. 2010*).

Non-binding

International cooperation is an essential element of our age when globalization puts national sovereignty in a new context. MoU's are written and non-binding paperwork that are meant to regulate cooperation in issues where a treaty is either unnecessary, infeasible, or the parties involved do not want to create binding obligations. The "Agreements between two or more parties to do or refrain from doing an act or acts in the future." A shared course of action, a shared desire to collaborate on a specific issue or set of issues or establishing a framework for cooperation. They are not meant to be treaties with a different name, still they are not completely independent of treaties, frequently containing references to treaties and using treaty language. Depending on the depth of the agreement, an MoU can take on many forms, sometimes presenting concrete terms of agreement and conclusion statements, or in other cases serving as a mere "gentleman's agreement". The extent to which MoU's are related to treaties often impacts their role and success in effecting the actual cooperation.

Framework

Signing an MoU can establish a solid foundation for future partnerships and collaborative efforts. By defining areas of mutual interest and outlining potential joint initiatives. This can be in relation to almost anything: trade relations, drug enforcement, scientific research, or other matters. Additionally, MoU's facilitate communication and information exchange between the involved parties.

Flexible

MoU's provide a framework for cooperation without the rigid obligations associated with a treaty. This flexibility can be very attractive and allows parties to explore potential partnerships without a long-term commitment. In some cases, a successful MoU can pave the way for a more formal agreement in the future. MoU's can form an agreement (not in legal terms) without being a formal treaty and express the understanding with intent to eventually follow up with a treaty or maybe to avoid it in the event of undesired intention.

Perspectives

MoU's are applied in various fields of international diplomacy. They can be used to foster collaboration on scientific research projects, establish cultural exchange programs, promote trade and economic cooperation, or address common environmental challenges. If a temporary MoU isn't successful, parties can simply neglect to renew it, and no harm is done. On the other hand, completion of a successful MoU can lead to the natural progression of more formal agreements or treaties. By fostering dialogue and building trust, MoU's play a significant role in international relations.

Limitations

Despite of being a valuable tool for international diplomacy, MoU's have inherent limitations. Most significantly because of the non-binding nature, deviation from the paperwork cannot have legal consequences (unlike more formal treaties). If a party violates the terms of an MoU, there's no legal mechanism to enforce compliance. So can cooperations easily fail or commitments go unfulfilled if parties are less motivated.

Wording of the paperwork can be often ambiguous or vague or lack the specific details of a formal agreement. This ambiguity can lead to misunderstandings or different interpretations by the involved parties. Additionally, MoU's typically focus on creating a framework for cooperation rather than outlining specific actions or deliverables. What comes useful for initial discussions, might not be enough for complex projects, requiring clear goals and timelines.

Conclusion

In conclusion, MoU's offer a valuable tool for initiating cooperation and building trust. However, their limitations, particularly the non-binding nature and lack of enforcement mechanisms, need to be carefully considered when choosing this approach in international diplomacy. For complex projects or situations requiring clear obligations and enforcement, a formal treaty might be a more suitable option (*Csaba 2024*).

HUNGARY – Background, engagement and interest of Hungary in international water relations

Historical background

Focus areas on the history of Water governance in Hungary

The special location in the Danube Basin is so determining in several aspects, but perhaps it played the most crucial role in shaping water management practices in Hungary (*Fleischer 2013*). From the earliest times on, it had an ever-changing but never decreasing importance that helped the water management sector in the country to be as developed and versatile as it is today. Since the earliest times, the country went through several periods when different water-management practices were applied, different water-related challenges were in focus and different water governance paradigms (*Allen 2003*) were followed.

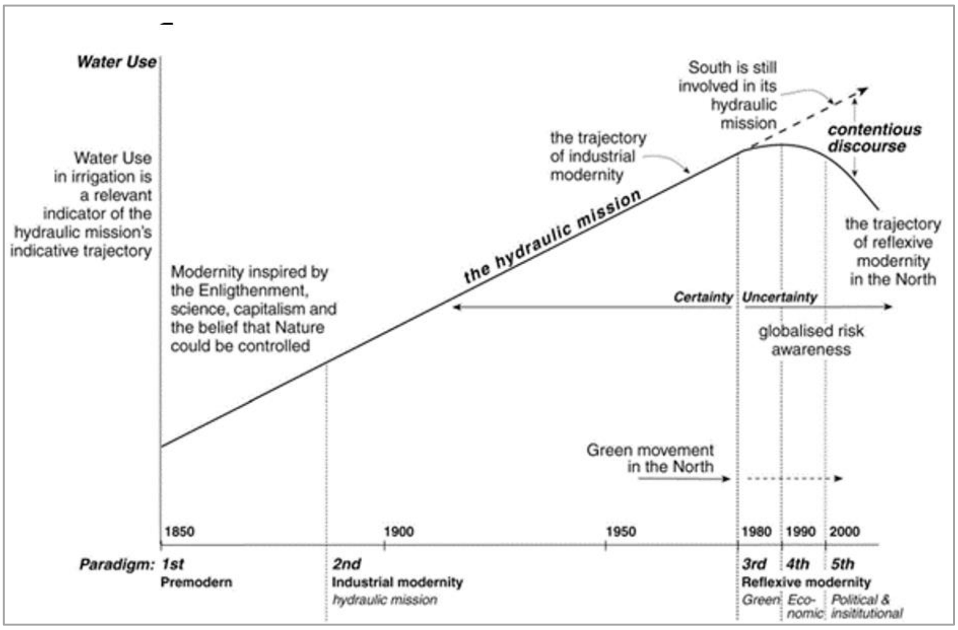

Figure 1. Hydraulic mission and neo-liberal modernity in water sector (Allen 2003)
1. ábra. Küldetéses vízügy és neo-liberális fordulat a vízgazdálkodásban (Allen 2003)

The stages of development in water governance (in Hungary and other developed countries), are reflecting the challenges, developing countries are facing currently, exacerbated by the impacts of climate change (*Nováky and Bálint 2013*).

Concluding: Hungary as a developed country, has a long and intense history in managing water resources. It not only has a wide range of versatile experiences in water engineering, research, and innovation, but also a strong capacity in building water and wastewater related structures. In whichever stage a country is while managing of its water resources (shall that be on the intensive track or in the realization of natural risks), the water sector of Hungary is very likely in the position of offering engineering, industrial or institutional solutions (*Kovács 2024*).

History of foreign relations with focus on water

Beyond all that, its special location makes Hungary extremely sensitive to the issue of shared watercourses, thus to the problems of water diplomacy in general. Post world war Hungary has a very strong hydrographical dependence, which is very often characterized by the ratio of 95% of our waters coming from foreign countries. While this is a much more complex relationship that is by far not accurately expressed through this sole figure as *Tamas Fleischer (2013)* points out in a study exploring opportunities in water use Hungary's dependence on surface waters from beyond its borders is no question (*Statista 2024*). The situation also highlights the importance of water diplomacy, international relations, for understanding interrelationships and addressing water-budget issues effectively. The sensitive approach towards water-matters and the rich experiences make the country a desirable partner to others, when facing water-related challenges and Hungary's image in the field is just strengthened by its repeating engagement in forward-looking efforts like the creation of the SDG's, the embracement of sustainability problems through the Budapest Water Summits, Planet Budapest Expo and as organizer and participant of other international events. While water diplomacy is a fairly new notion, water was a common factor of the countries international relations from early times on.

Initiated by VITUKI (Research Center for Water Management, founded in 1952), – largest research centre and information base of Hungarian water management – Hungary built a number of overseas projects in Algeria, Nigeria and elsewhere together with a foreign company called TESCO (International Technical Scientific Cooperation Office). Through these projects VITUKI have brought Hungarian water knowledge to the market for a fraction of the international price, funding a reputation that outlasted the institution itself *(Major 2024)*.

VITUKI's involvement in the UN and other professional organisations and institutions (including the UNESCO IHE Delft Institute for Water Education), participation in the UNESCO International Hydrology Decade has contributed to the international standing of the Hungarian water knowledge. Later Hungary was among the first signatories of the two determining international water conventions, the UN watercourses agreement (United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses) and the UNECE Water Convention (Convention on the Protection and Use of Transboundary Watercourses and International Lakes). Both of them emphasize the same principles in transboundary water management and by the participation in their formation the country affirmed not only its commitment to international cooperation and responsible management of shared water resources but also its position in international water governance. Over time the general principles of modern water-law (equitable and reasonable utilization, prevention of transboundary harm, and the exchange of information among riparian states) due partly to these overarching international agreements strongly shape international relations.

Budapest water summits (BWS) and the Planet Expos

From the year 2013, Hungary organised 3 events (2013, 2016, 2019) of the BWS under the umbrella of the UN. These summits, driven by UN member states growing concern for global water challenges and the need for international cooperation, played a significant role in shaping global water policy discussions and served as a platform for international collaboration in the field of water.

The BWS-s created an excellent opportunity for Hungary to emphasize its capabilities and background in development of water economy and creation of water policy and to enhance international relations along these themes. Starting from 2013 (with only a few of such paperwork existing previously) Hungary signed a range of non-binding international paperwork MoU's with countries which whom it does not share any transboundary waterbodies.

Past 2019 there was no subsequent Water Summit organised, but Hungary remained engaged in water-related and sustainability issues. In the last year with President Áder in office the Planet Expo has been introduced as an international sustainability fair. While water might not be always the lead subject of the individual Expos (in 2023 it was agriculture and food supply chain), it is a most determinate factor of sustainability, thus a steady subject on these events. So are representing the Planet Expos a continuation in the signature of MoU's.

Photo 3. Sándor Pintér (Hungary) and Karim Hasni (Algeria) signing on Planet '21 (www.mfa.gov.hu)
3. kép. Pintér Sándor (Magyarország) és Karim Hasni (Algéria) aláírása a Planet '21-en (www.mfa.gov.hu)

Institutionalisation of water in Hungary

Despite the international recognition and the extensive list of professional and diplomatic achievements during these years, water management has struggled for long to earn an adequate representation within the state administration. While responsibilities and competencies related to water management were present across various levels of the state's organization, the majority of powers and administrative duties in this regard are carried out by the Government and its affiliated bodies. Each branch of power plays a dedicated part in water management, whether it be in the realms of water extraction, water conservation, or prevention of water-related damages. Furthermore, Parliament participates in water-related endeavours by means of legislation and the implementation of the National Environment Programme. However, division of tasks and responsibilities even within the Government structure were very much fragmented and the separate voices/parts, did not form a harmonious whole. The very same structure has limited the communication and proper coordination between the involved stakeholders. Recent changes in government structure (i.e. concentrating more and more water management areas at one place even if this is the ministry responsible for energy management) eventually might support the implementation of the MoU's. However, it has not happened yet, and current ownership of the MoU's is rather based on personal commitment then on institutional setup.

This is a critical obstacle as the signature of the MoU's point towards a cooperation in various policy and water governance issues with the possibility of creating export-potential. Both presumes the involvement of organisations either from the side of government and the public sector or from sectoral or connecting non-governmental organisations.

Priorities of the Hungarian foreign economy

Improving international position- Opening to the South (Tarrósy and Solymári 2022) and East (Shishelina 2022)

In the 2010's Hungary announced the "Opening to the South" and the "Opening to the East". Historically there is a repeating endeavour from the side of Eastern-European countries to develop their relations with the Global South, especially with Sub-Saharan Africa (SSA). However, the previous focus from ideological solidarity (supporting liberation movements, offering educational scholarships as soft power strategy) shifted towards a more pragmatic approach (*pragmatic solidarity*). The post-communist era saw a re-evaluation of Hungary's foreign relations, prioritizing economic cooperation and leveraging education as a tool for fostering long-term relationships with these countries.

From the perspective of pragmatic solidarity, the improvement of relations with the global south (and especially SSA) has a significant role based on the position of these countries in geopolitics and economics, because of their rich natural resources and their emerging markets. This shift towards engaging with the Global South shows a recognition of the region's potential in contributing to global economic growth and political stability. However, as we can experience with some of the MoU's in focus, actual political and economic stability is very strongly impacting the eventual successes of once positively started initiatives (see the MoU wit Sudan). The need for sustainable policies and a commitment to multilateralism further highlights the South's importance in global affairs, especially in climate change and EU-Africa relations. The focus on SSA within Hungarian foreign policy, emphasizing education and economic cooperation, illustrates the region's role in fostering long-term international relationships.

The Opening to the East, policy of Hungary shows numerous similarities. Likewise, it was initiated after 2010, and by reinitializing the relations built during the communist times it aims to diversify the country's foreign relations and economic partnerships beyond its Western focus that was predominant (and in most part still is) for two decades after 1990. This strategic paradigm is driven by the same pragmatic approach to address economic challenges related to resources, mainly energy (gas, gasoline, and electricity supplies) and acquiring markets for Hungarian products. By developing relations with countries in the East, including Russia, Central Asian states, Turkey, and China (more recently India), Hungary seeks to secure economic benefits and enhance its energy security. The policy also reflects Hungary's intention to play a more significant role in global geopolitics by establishing stronger ties with key Eastern economies and political entities. The policy includes significant engagement with Turkey, demonstrating the multi-vector nature of the country's foreign policy by balancing its relations between the East and the West. This approach enhances Hungary's global position and intends to secure tangible benefits for its citizens, reflecting a consistent trend towards pragmatism in its international relations.

In this regard the water-management MoU's are tools that enhance Hungary's multi-vector foreign policy creating professional cooperation in political level, which can possibly serve export endeavours.

Hungary's current export strategy – a more economical approach

Hungary is one of the most export-oriented economies of the EU with 81.2% of the GDP deriving from export. The export-potential indicator (currently 13th in the world ranking according to *The Observatory of Economic Complexity trade ranking (2024*) is supporting the same picture. The national export strategy (NEXT) 2019-2030 -that is currently undergoing a revision - is clearly defining water as one of the 5 focus areas and breakout points of the Hungarian industry that regularly returns on the conferences of the Joint Economic *Commissions (Horváth D. 2024)*. Within the sector, the engineering services, innovative construction solutions and digital technologies are listed as the most promising areas. Geographical potential of water industry according to the export strategy offers some interesting learnings too. It defines the South-East Asian markets as the most promising focus areas for Hungary and Africa, South America (together the Global South) as markets interesting in medium term, while eastern European and other Asian markets as existing active markets for the Hungarian Water Industry. Developed countries are not seen as prospective export markets. Projecting the potentials of the other four sectors, which are discussed (Food industry, Agricultural technologies, Pharmaceuticals, Medical Technologies, and Construction) the strategy assigns an icebreaker role to water industry. The existing markets of the water industry more or less overlap with the promising markets of the other sectors and the potential best markets of the water sector are medium-term opportunities for the others *(Ministry of Foreign Affairs and Foreign Trade 2017)*.

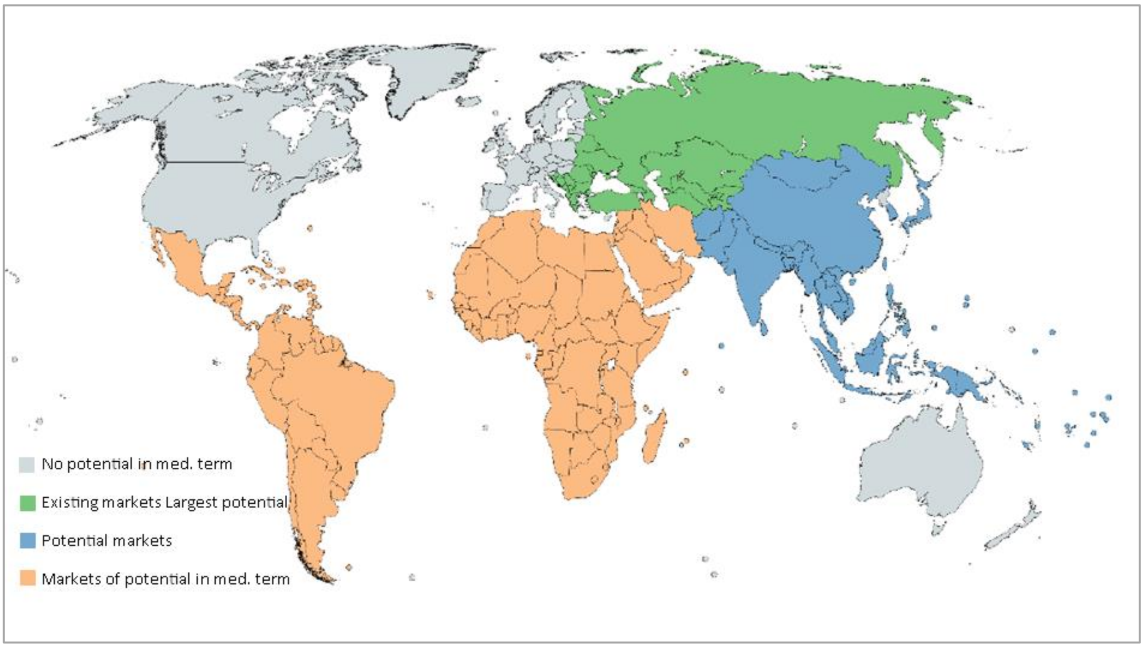

Figure 2. Market potential of the Hungarian Water Industry (National Export Strategy 2019)
2. ábra. A Magyar Vízipar piaci lehetőségei (National Export Strategy 2019)

Possible benefits and international perspectives of Hungary participating in professional water-based collaboration

Export promotion

If water industry is an icebreaker for other export sectors, then the MoU's are potential icebreakers for the water export. Bilateral Memoranda of Understanding (MoU's) on integrated water management, though signed at the ministerial level for establishing cooperation between professional organizations of both countries, can also boost export ambitions of the country that has more developed practices in the sector concerned. There are several ways this can happen.

For once in cultures with a more hierarchical structure, even a non-binding state-level paperwork can be a valuable reference point for foreign investors. Some MoU's are even initiated by export-oriented companies themselves, to pave the way for their intended export-endeavours in water management technology and services (*Kovács 2024*).

Not least ministers and ministerial officials often play a key role in decisions on water-related infrastructure projects, which require knowledge-exchange, technology-transfer, or even full-scale imports of solutions from a country with more developed practices (B2G).

Beyond this direct influence on project decisions, stronger political ties fostered through MoU's can lead to indirect economic benefits too. Countries may be more likely to secure development loans for infrastructural/water management projects, in a favourable political atmosphere (supported by the signature of an MoU) and for companies of a country with stronger political ties. Additionally, MoU's can create a more supportive environment for trade and investment in general by promoting regulatory harmonization.

Finally, the high-level political visits and ongoing collaborations established through MoU's can turn into momentum, fostering connections between companies and government officials. These connections can be crucial triggers for translating MoU intentions into actual export deals or investments (*Horváth D. 2024*). These MoU's can be instrumental in creating a framework for successful collaboration.

In conclusion, while Bilateral MoU's on integrated water management focus on professional cooperation, they offer significant indirect benefits for the country with more advanced water management practices. These benefits can range from increased foreign investment to securing contracts for technology and infrastructure projects.

GHG emission trade

In my research I only found one example for an investment where development in green infrastructure has led to a calculated carbon credit saving that became an element of finances and a factor of realization of the project. This case was in relationship with Serbia, which is a neighbouring country thus not subject of the MoU's in focus and is a country with a much more developed set of contracts and treaties with Hungary as most of the countries examined now. However, it is a fundamental theorem of the current work, that the MoU's are entrance tickets by their nature in international relations, not end stations. Successful cooperation fostered by MoU's can pave the way for more comprehensive agreements. These expanded agreements could explicitly address more complex matters (*Hesham 2017*).

Just with reference to the current subject (carbon credits) These can be frameworks for calculating, verifying, and trading carbon credits generated by green infrastructure projects (carbon credit accounting). Mechanisms to incentivize investments in green infrastructure by linking them to potential carbon credit revenue (investment incentives). Collaboration on developing and financing green infrastructure projects that maximize environmental benefits and generate tradable carbon credits (Joint Project Development). A successful cooperation along an MoU would probably lead to an expansion of the system of agreements that support trade, investment, various fields of cooperation and possibly allow an accounting of items of more complex nature.

Carbon credits represent a valuable, tradable resource for developing countries. MoU's can be instrumental in creating frameworks for exploiting this funding source. These frameworks can help developing countries in attracting investments making green infrastructure projects (more) lucrative for investors in the more developed country by exploiting the potential for carbon credit. Revenue from carbon credits can help developing countries finance the upfront costs of these projects. By enabling the development of green infrastructure, MoU's can contribute to a more sustainable future for both partner countries and promote sustainable development in general.

Carbon credit is by all means an additional resource that can be traded by a developing country, always in the search of funding for development for investments made in green infrastructure by a more developed industry.

Concluding: the fact that I have not found any other example does not mean that there aren't any for exploiting this additional funding source, but it needs a more developed paperwork (than an MoU) and real carbon-saving investments.

MOU'S OF THE HUNGARIAN WATER DIPLOMACY

Geographical focus

Even if the Global South is least a geographic category rather economic or socio-political, there is a clear picture that Hungary is signing these MoU's with countries "from the extended southern hemisphere". In Europe, with fellow nations Hungary is clearly cooperating through other channels. Once because the shared watercourses and the neighbouring status, we aim for a stronger and more detailed cooperation and because within the EU the collaboration of members is very much regulated and organised anyway. This way these European MoU's (going back to an earlier time and with a partly different content) count among the oldest, that the country has signed over the years.

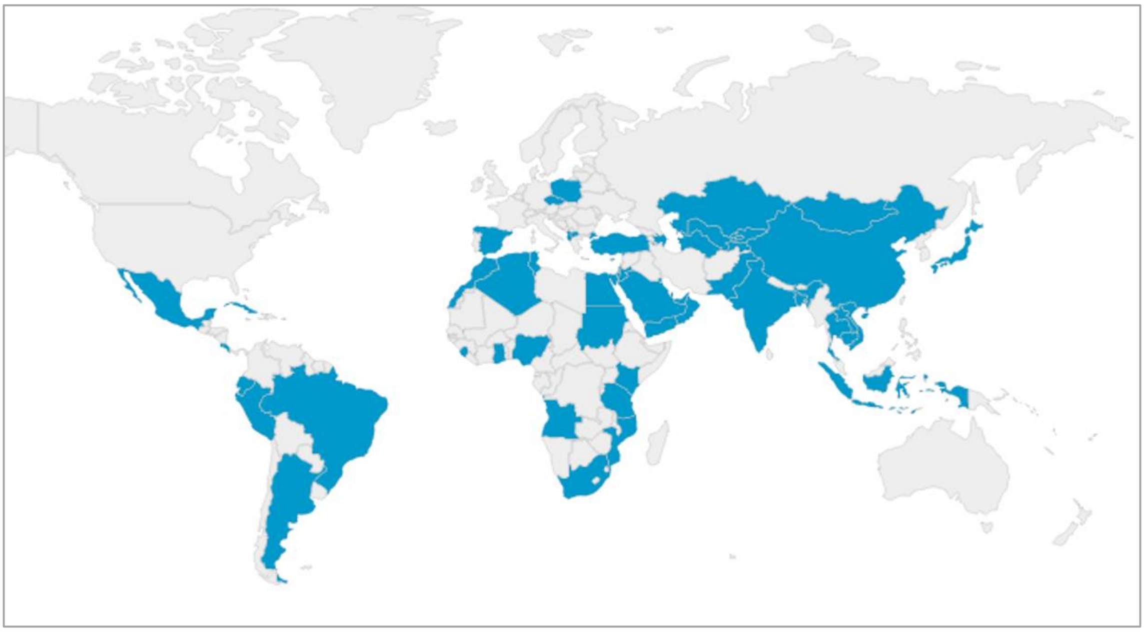

Figure 3. Water management MoU's of Hungary on a world map in 2025 (Rózsa 2024
3. ábra. Magyar vízügyi együttműködési megállapodások a világban 2025 (Rózsa 2024)

Beyond that, there is a special strong presence in Central Asia and South-East Asia, in the Middle East covering almost every country in these regions and a systematically growing presence in Africa and South America. In the article I handled those paperworks that were under preparation or standing before signature (at the moment including the Dominican Republic, Japan, Iran, Uruguay, Mozambique) as part of the set, but this mix is showing the multi-vectoral extension of cooperation.

Table 1. List of MoU's (Rózsa 2024)
1. táblázat. Együttműködési megállapodások listája (Rózsa 2024)

Partners		Signature			Memberships	
Country	**Location**	**Where**	**Date**	**Occasion**	**UNECE Water convention**	**UN Water convention**
Albania	Balkan	Tirana	2023-06-16		1994/01/05	
Algeria	North Africa	Budapest	2021-11-30	Planet Budapest		
Angola	West Africa	Budapest	2019-11-04			
Argentina	South America	Buenos Aires	2022-04-01			
Azerbaijan		Baku	2022-02-03	UN Climate Change Conference (COP7)	2000/08/03	
Bangladesh	South-East Asia	Budapest	2016-11-27	Budapest Water Summit		
Brazil	South America	Budapest	2022-02-17			
Cyprus	Middle East	Budapest	2019-10-16	Budapest Water Summit		
Costa Rica	Central America	Budapest - San Jose	2023-03-06			
Czech Republic	Central Europe	Prague	2001-09-18		2000/06/12	
South Africa	South Africa	Pretoria	2017-05-23	International Conference on Sustainable Development (ICSD)		1998/10/26
Ecuador	South America	Buenos Aires	2022-10-27			
United Arab Emirates	Middle East	Dubai	2022-02-16			
Egypt	North Africa	Budapest	2015-06-12			
Ghana	West Africa	Brussels	2019-01-22		2020/06/22	2020/06/22
India	South Asia	Budapest	2016-10-16			
Indonesia	South-East Asia	Budapest	2013-10-08	Budapest Water Summit		
Israel	Middle East	Ózd	2002-03-22			
Yemen	Middle East	Budapest	2023-07-19			2000/05/17
Jordan	Middle East	New York	2022-09-21	UN. General Assembly (UNGA) High-Level Meeting on Biodiversity		
Cambodia	South-East Asia	Phnom Penh	2019-11-03			
Kazakhstan	Central Asia	Nur-Sultan	2019-04-29	Astana Mining and Metallurgy Congress	2001/01/11	
Kenya	East Africa	Nairobi	2021-01-17	UN. Environment Assembly (UNEA)		
China	East Asia	Budapest	2003-04-17			
Kyrgyzstan	Central Asia	Budapest	2020-09-29			
Cuba	Central America	Budapest	2021-11-30	Planet Budapest		
Kuwait	Middle East	Budapest	2014-06-13	Danube River Basin Ministerial Meeting		
Laos	South-East Asia	Budapest	2016-11-29	Budapest Water Summit		
Poland	Central Europe	Warsaw	2017-03-22	Warsaw Climate Change Conference	2000/03/15	
Macedonia	Balkan	Skopje	2013-12-05	High-Level Meeting on the European Union's Eastern Neighbourhood and Western Balkans	2015/07/28	

Partners		Signature			Memberships	
Country	**Location**	**Where**	**Date**	**Occasion**	**UNECE Water convention**	**UN Water convention**
Kingdom of Morocco	North Africa	Budapest	2016-07-27			
Mexico	Central America	Budapest	2016-11-29	Budapest Water Summit		
Mongolia	East Asia	Budapest	1995-09-22			
Nigeria	West Africa	Budapest	2016-11-29	Budapest Water Summit	2023/03/22	2010/09/27
Oman	Middle East	Budapest	2022-12-15			
Pakistan	South Asia	Islamabad	2020-07-13	International Conference on Water, Environment, Energy, and Society		
Palestine	Middle East	Budapest	2018-09-03			2015/01/02
Peru	South America	Lima-Budapest	2022-05-20			
Sierra Leone	West Africa	Budapest	2021-11-30	Planet Budapest		
Spain	Southern Europe	Madrid	2001-11-21	UN Climate Change Conference (COP7)	2000/02/16	2009/09/24
Saudi Arabia	Middle East	Rijad	2020-10-21	Future Investment Initiative		
Sudan	North Africa	Budapest	2016-11-29	Budapest Water Summit		
Tanzania	East Africa	Dar es Salaam	2024-03-28	Africa Climate Week		
Tajikistan	Central Asia	Dushanbe	2018-05-04	High-Level International Conference on the International Decade for Action "Water for Sustainable Development", 2018-2028		
Thailand	South-East Asia	Budapest	2019-10-15	Budapest Water Summit		
Turkey	Middle East	Ankara	2013-12-18			
Tunisia	North Africa	New York	2019-09-27	UN Climate Action Summit		2009/04/22
Turkmenistan	Central Asia	Ashgabat	2023-06-29	Central Asia Energy Investment Forum	2012/08/29	
Republic of Uzbekistan	Central Asia	Astana	2018-10-10	Astana Economic Forum	2007/09/04	2007/09/04
Vietnam	South-East Asia	Budapest	2013-09-17	World Water Week		2014/05/19
Cape Verde Islands	West Africa	Budapest	2019-10-16	Budapest Water Summit		
Dominican Republic	Central America		Prepared for signature			
Iran	Middle East		In prep.*			
Japan	East Asia		In prep.*			
Mozambique	East Africa		In prep.*			
Uruguay	South America		In prep.*			

** In preparation*

Grouping of countries from political and cultural perspective

When attempting to categorize these countries in order to identify common trends, I encountered a lack of discernible patterns that could facilitate the extraction of meaningful insights. There is no significant bias towards a particular religion (islamic, judeo-christian, buddhis, other backgrounds are equally present), cultural sway, or relation towards authority. Analysis from political perspective of form of government, dominant ideologies, foreign policy determinants, or membership to international water conventions has not revealed any single defining factor that could establish a prevailing trend. Nevertheless, there exist certain attributes that may not directly influence the selection process but indirectly serve as common denominators among these countries. These include a notable prevalence of nations with colonial histories and varying degrees of democratic development, ranging from moderate to relatively lower levels. While apparently on political and cultural level these seem to be indirect connections, it all makes sense if we consider the economic perspective, that strongly resonates with the pragmatic solidarity detailed in the point where discussed opening to the south and east (improving international position). Otherwise, we should consider culture and politics (beyond their developmental status) as negligible factors in the selection of partners for MoU's.

Grouping of countries from economic perspective

Hungary has a Memorandum of Understanding on the field of integrated water management with a wide range of countries (*Table 1.*). The 51 countries (plus five in different stages of preparation) with whom Hungary signed a bilateral memorandum, have a mixed background as seen before, with very little recognizable pattern. However, if we try to characterise them along economic factors finally there are some patterns taking shape.

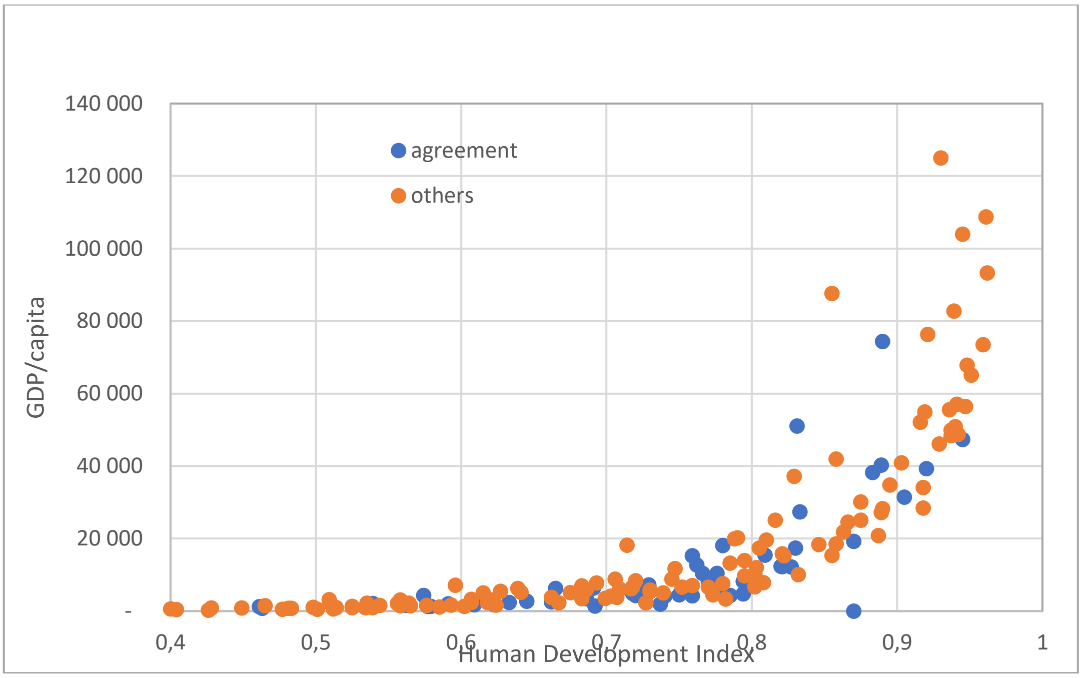

Figure 4. Countries along the level, of their Human Development Index and GDP value, coloured differently depending on whether they have or not an MoU with Hungary (Rózsa 2024)

4. ábra. A világ országainak diagrammja Human Fejlődési Index és GDP alapján (kék színnel akiknek van és narancssárgával akiknek nincs vízügyi kétoldalú együttműködési megállapodásuk Magyarországgal) (Rózsa 2024)

Among the countries with whom we have signed a Memorandum of Understanding, considering GDP/capita for assessment of the economic development and financial possibilities of a country we will see the following: A significant proportion comprises low and lower-middle income nations. It shows a trend towards collaboration with countries, which are facing economic challenges. The representation of the absolute poorest countries is lower and there are very limited instances of MoU's with high income countries, clearly indicating a selective approach in forging these cooperations *(UNDP Country Insights 2024) (World Bank Open Data 2024)*.

Grouping of countries from the perspective of water resources and cooperations on water management

As mentioned before at the geographical focus, Hungary is cooperating on other platforms with neighbouring and EU countries. There is the legislation of the EU itself and various international public and civil organisations providing multilateral platforms for collaboration (Danube commission, ICPDR). With neighbouring nations having shared water resources, Hungary also signed a long row of bilateral treaties, that (contrary to MoU's) do represent legal obligations and have a much more extensive and detailed content, assigned institutions (bilateral commissions and subcomissions to the individual waterbodies).

Membership of the two multilateral water-conventions (UN Watercourses Convention and UNECE Watercon-vention) provides another forum and toolset for Hungary to handle water management issues on international level. Subject of the current article, the MoU's however create an excellent tool for Hungary to connect on a one-to-one basis with distant countries that have (or just lack) water-resources that need to be managed efficiently and sustainably. For this purpose, they might require both up to date knowledge and experience in the field of integrated water management, water governance policies and handling shared water resources, a highly valuable intellectual asset, that Hungary possess. Additionally, the sharing of developed practices and know-hows through visits, workshops trainings etc can open a further connection to the Hungarian higher education and the lack of industrial and engineering capacity in the host country can also provide an opportunity for the Hungarian water industry.

When looking for common patterns among the countries concerned, water scarcity issues clearly come up as common characteristics. Changeable precipitation patterns, due to climate change, challenge water economics of these countries more and more and almost without exception. In areas like the Middle East, Africa and Central Asia it "only" means a growing scarcity, but in South and South-East Asia or Latin America flood management is posing another difficult challenge. Population growth is exacerbating these problems and adds water pollution issues, with the degradation of natural habitats and biosphere. This latter characterises northern African and Sub-Saharan countries as South and South-East Asia as well. South America is slightly less concerned with these issues at the very moment but is excitedly preparing behind the curtain for the role of one of the worst hit parts of the world by climate change and global warming.

Shared water resources create a very serious issue in the Middle East, in Central- and in South and South-East Asia.

Different groups of countries have a varying set of problems, but most of them face with more than one of these issues and are keen for any assistance that can help in resolving them. The fact that unlike Hungary, majority of these MoU's are signed from the partner side by a ministry dedicated to water matters (whether its exclusively water or paired by agriculture, energy or something else like forestry, changes) show that it is a very much recognised challenge by the partners in these cooperations. According to research proportionally the larger the international basins of a country are (compared to their area), the more likely it is that they form bilateral water treaties *(Molly at al. 2004)*. While this concerns mainly international treaties, putting water resources in the center of thinking, it is also a factor of forming MoU's with distant countries like Hungary.

This latter fact has some far-reaching consequences in terms of most of these countries having similar MoU's with other countries of similar background to Hungary. Just for example Thailand has the same level MoU's on Water management not just with us, but with the Netherlands, with China, South-Korea, Vietnam. Four partners that of two are partners of Hungary too in a bilateral MoU in integrated water management.

Water management MoU paperwork in Hungary

History

Hungary as discussed at the history of foreign relations has a long and rich history in cross border water-based co-operations. However, these were either absolutely informal or based on paperwork between private or state-owned companies or not-distinguished parts of higher relations. We only signed our first watermatter MoU in 1995 (*Rózsa 2024* with our longterm water-partner: Mongolia and in the next almost 20 years only added 4 more with Israel, the Czech Republic, Spain and China. But even those in the first part of that period and absolute none in the decade between 2003 and 2013. However, in 2013 something happened and the initiative for signing water-based MoU's took off and since then we are signing more and more in a growing number. At the time of writing this article Hungary has 51 MoU's most of them signed on ministerial level (further 5 under preparation) with the exception of Vietnam, Kuwait and Brazil, having government level MoU's *(Nagyné Soós 2024)*.

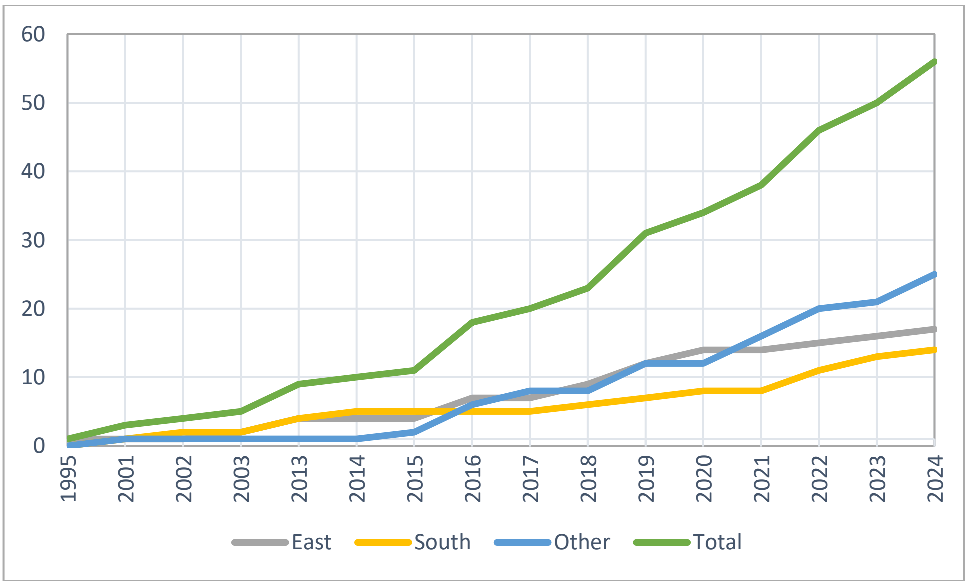

Figure 5. Signatures of Memoranda over time in main relations (Ministry of Interior 2024)
5. ábra. Vízügyi együttműködési megállapodások gyarapodása fő külgazdasági irányokban (Belügyminisztérium 2024)

In 2012 János Áder (*Wikimedia 2024*) has been elected as President of the Republic of Hungary and along with the conference of Rio de Janeiro, he announced a program with emphasis on environment and sustainability, putting the water issue in a central place on the Hungarian foreign agenda. In 2013 the Government of Hungary, the United Nations System and World Water Council organised the first Budapest Water Summit (*World Water Council 2013*), an event that beyond creating a forum for discussions around water in the realm of international relations, aimed promoting water as a single Sustainable Development Goal and played crucial role for water becoming the 6th SDG on the verge of creating the Program "Transforming our World".

The first BWS has brought the world political and water leaders to Budapest and presented an important success and excellent opportunity for Hungary to present its current position at the peak of water diplomacy. The world visiting Budapest created a momentum to meet and sign a row of MoU's. Since then, there is a periodicity to be observed. There are MoU's signed in the meantime's too, but there was always a jump during the repeatedly organised BWS's (in 2013, 2016 and 2019) and finally in the last year of János Áder's term. However, with President Áder's stepping down from office the process hasn't stopped. There are MoU's signed year after year with, at the time of finishing this article, 5 in preparation phase.

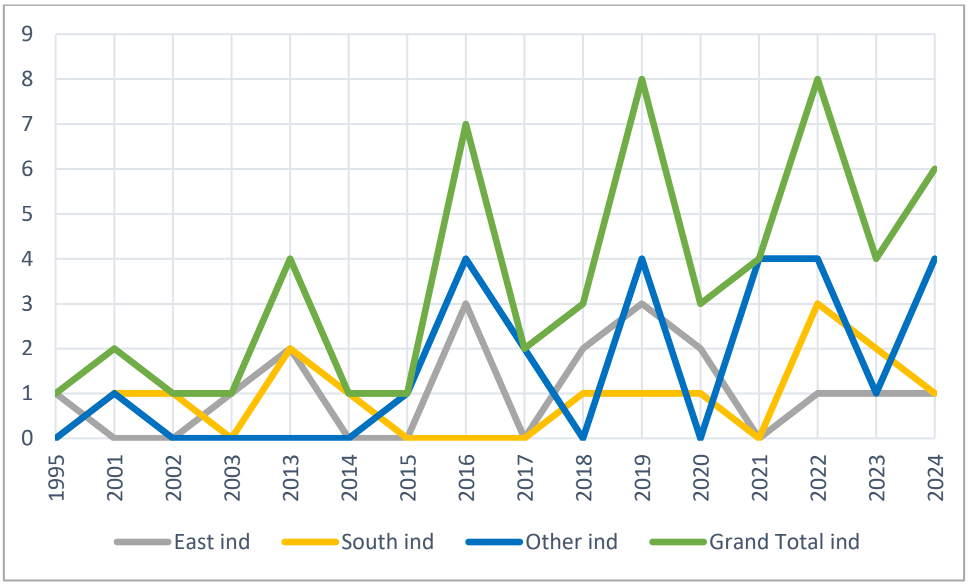

Figure 6. Periodicity of signature of Memoranda in different relations (Ministry of Interior 2024)
6. ábra. Aláírások időszakossága fő külgazdasági irányokban (Belügyminisztérium 2024)

Content, procedural, organisational framework

Over the years a mature structure has been developed for the upcoming MoU's as much that according to Peter Kovács (*Kovács 2024*): "Who has seen one of the MoU's has practically seen all of them." (It needs to be noted, that there are some exceptions like the three of them signed on government level and occasionally there are countries offering their own version for adaptation, which might slightly differ from the Hungarian draft.) The considerably greater part of the MoU's is based on the same three-pages-long template, which defines the objective, the areas and forms of cooperation, outlines an implementation, defines cost-bearers, mentions intellectual property rights and dispute settlement and some final provisions.

Without contemplating on the motives for signing the paperwork (that I already did in "Possible benefits and international perspectives") the objective of the MoU's is a policy cooperation on equal and reciprocal basis to which the parties enter for mutual benefit. The duration of the cooperation is variable, often (and more recently) signed for 5 years period, automatically prolonged after the deadline for a consecutive 5 years. A paragraph is dedicated in each case to the protection of intellectual property rights.

From procedural perspective it creates a collaborative framework grounded on the principles of parity, reciprocity, and shared advantages, while upholding compliance with domestic regulations. Possibly occurring disputes regarding the MoU's interpretation or execution are intended to be resolved amicably through bilateral discussions, excluding any external adjudication processes. Modifications to the MoU presumes the mutual consent and formal agreement of both of the involved parties. According to the general financial provisions both parties are responsible for their own costs incurring with the implementation.

From organisational perspective the participating organisations are to foster collaboration among other governmental bodies, educational and research institutions, commercial entities. A Joint Steering Committee, consisting of an equal number of representatives from each participating entity, is to supervise, monitor and evaluate the operational execution of the MoU, to ensure its effective implementation. It serves as coordination and communication channel. The MoU calls for collaboration in a wide range of the sector, encompassing initiatives related to water resource management strategies, efforts towards climate change mitigation, and the sustainable exploitation of water resources.

Recurring themes, avoided subjects

According to Peter Kovács Hungary's expertise is widely recognised in all the areas offered for cooperation, practically all areas of water management. Shall it be surface water extremely in focus in North Africa or groundwater especially concerned in Mongolia, Hungary has a wide range of experience recognised in the management of these resources from engineering, sustainability, education or policy side. Hungary has extensive experience in managing shared watersheds and also in international water diplomacy as founding member of both of the two multilateral waterconventions (*Kovács 2024*).

The main areas of cooperation are Integrated Water Management and related Legal Frameworks including elaboration and implementation of integrated water management strategies and legal regulations. The Sustainable Utilization and Protection of Water Resources to ensure their longevity and health. Climate Change Mitigation and Adaptation, calling for joint efforts to address the effects of climate change and adapting to its impacts. Risk Management for Natural Disasters including collaborative work on drought and flood management, including monitoring and risk mapping. Water Supply and Treatment with possible cooperation extending to drinking water supply and treatment, as well as sewage and wastewater treatment. Education and Research Collaboration, strengthening cooperation between educational and research institutions in the field of water management and Technology Innovation, encouraging innovation in technologies related to water management.

While this is the set Hungary offers for cooperation to the partners, it doesn't mean that in every memorandum all these areas are listed. Again, referring to the discussion with *Péter Kovács in 2024*, some countries might be uninterested, sensitive, even dismissive to areas of cooperation. As an example, he mentioned Turkey, who was refusing any kind of mention of shared water-resources even in an as basic instrument as an MoU.

Photo 4. János Áder's visit in Mongolia one of our oldest partners in Water management (Bruzák N. MTI)
4. kép. Áder János látogatása Mongóliában, egyik legrégebbi vízügyi együttműködő partnerünknél (N. Bruzák MTI)

Workplans

Workplans are essential for creating real value from the MoU. The cooperation initiated by the MoU can be addressed through specific work plans designed to the development of the chosen areas. Activities or projects started under the MoU's operation can continue even after its termination, suggesting that workplans for these initiatives are expected to be comprehensive and long-term.

For creating the workplans and for the practical implementation of the MoU, a Joint Steering Committee will be established of equal numbers of participants from the signatories as defined above.

Signatories, participating organisations

With three exceptions (Vietnam, Brazil and Kuwait) the signatories are Ministries responsible for water management in their countries, thereby representing their own country in this field on international level. For the other three the two governments are the participating organisations, which make the implementation (*Kovács 2024*) of the paperwork very difficult, as there is no party that would have a clear responsibility. However, there are two distinctive cases when a signature on government-level is required. One of them is if there is serious commitment involved with the implementation of the MoU or if that is the only possibility allowed by the other party's government structure.

In the further development of the relations, signatures of further agreements can become necessary like the involvement of the CO_2 quote (state property), the protection of investments or dual taxation, which lead to more serious cooperation, going beyond the MoU's of water management.

Presentation of 3 memoranda

There are common components and characteristics for the three cooperations pulled under examination in this article. From stakeholder perspective while being bilateral instruments all of them highlight the importance of multilateral engagements in addressing water management and sustainability issues, besides the bilateral relation.

From content perspective recurring theme is the integration of technology and innovation in water management practices, aiming to enhance efficiency and also sustainability since the cooperations align with global sustainability goals, particularly SDG 6, related to water and the climate action (SDG 13), and partnership (SDG 17) goals. Each cooperation initiative includes elements of capacity building, education, and knowledge exchange to foster long-term resilience and expertise in water management, manifesting a definitive focus.

As methodology of the research, I relied mainly on the following information sources: The Ministry of Interior (MI) keeps a record of the progress of each cooperation that served as a basis for this summary. It is strictly limited to the formation and work of workgroups and implementation of workplans, official visits. It doesn't hold any record of educational-, water industry cooperations, water export. To find out more of possible cooperations I contacted the attachés of foreign trade in the Hungarian foreign missions, which was provided for Egypt and China, but was not for available for Thailand.

Thailand

The MoU with Thailand was signed during the last BWS in 15. 10. 2019. As mentioned at the grouping of countries, Thailand has an extensive set of MoU's with other countries, and it also has a row of bilateral treaties of shared watercourses. Furthermore, Thailand is member of the Mekong River Commission for Sustainable Development, one of the most advanced river basins cooperations today.

Despite having abundant water resources overall, Thailand faces several challenges like water shortages for agriculture and even civil consumption due to the unevenly distributed rainfall and severe flooding during the monsoon season at other areas, both expected to strengthen as a result of climate change. Industrialization and agricultural fertilizer-use contribute to water pollution reducing usable freshwater resources. Urbanization, population growth and aging infrastructure add further strain that make the country highly interested in water-based cooperation.

The report shows a great interest in cooperation on both sides and contains a clear definition of the areas where the other party is especially interested (drought management and monitoring, drinking water treatment) and a wide set of presentations, visits, discussions, even donation of an appliance that successfully filled the MoU with content. Important to mention that the Covid epidemic has had a destructing effect on the implementation, similarly to many other cooperations, but the Thai relation gained a new impetuous after the normalization of the situation. The workgroup in this case is operational and the document defines financing needs as requirements for the further development of relations.

Egypt

Despite of being the "Gift of the Nile", Egypt is considered as a water-scarce country, because of its arid climate and high population density. Its special situation as a downstream hegemon, depending almost entirely on the Nile as a renewable water-resource, makes the state extremely interested in water-sharing and dispute resolution, sustainable agricultural practises.

The originally on 12. 06. 2015. signed MoU's implementation was initialized only after a few-years stillstand by the Joint Economic Committee under the Ministry of Foreign Affairs and Trade, however the Covid pandemic paused the further developments and the first session of the workgoup was held only 7 years after the signature of the MoU. Due to the current economic difficulties of Egypt, the initiatives of the Hungarian party are mainly failing because of financial obstacles *(Horváth P.2024)*.

China

China's interest in water-based cooperation comes from several challenges and opportunities related to water resources:

Uneven water distribution: (plenty of rainfall in the south, water scarcity in the north), severe water pollution (from rapid industrialization and fertilizer use), changes in weather patterns due to climate change (droughts and floods), aging infrastructure with high water loss pose serious challenges while it is not a one-sided (developed-developing) relationship as often in the case of the MoU's.

There are excellent opportunities present like sharing best practices on both sides and develop successful water management strategies and policies. There is a promising possibility to develop joint largescale water management projects.

The EU and EU members are strong partners for China in water-based cooperation because they can address water challenges more effectively, give access to advanced technologies, and share expertise.

One of the first MoU's Hungary signed (namely the 5th) has been concluded with China on the 17. 04. 2003. It was an actual codification of the previously existing cooperation over flood-protection, water quality and the adaptation of the EU Water Framework directive (Ministry of Enivronmental protection from the Hungarian side). The cooperation went through some renewal and modification and its history is fairly rich in visits, occasionally on high level of state administration until the hit of the Covid pandemic. Since then, the bilateral cooperation hasn't taken up a new start. However, the China-EU Water Platform is operational and has its meeting every year. Hungary is participating in this multilateral cooperation.

IMPLEMENTATION - BASIC QUESTIONS OF FULFILMENT / SEARCH FOR THE DRIVERS OF SUCCESS

Description of current practice

Initialization, stakeholders

Currently the initiative for creating an MoU can be either political (foreign relations) or economical (export). Concerning prospective implementation in the case of a Top-Down practice, it is a vital question whether the signature was initiated from high levels only wishing for an act of PR to present as just an instance to sew the ties tighter with another country, or based on real economic motivations (not contradicting to each other, but placing the emphasis to different places). If it is a Bottom-Up practice from an export-oriented company or maybe an educational institution (however I haven't found an example for the latter in the current set) looking for a reference when seeking/strengthening business or partnership overseas, then implementation is better founded (see the question of ownership in the conclusion), but still requires help from the state(s) for an ideal development. Until recently both were transmitted by the Ministry of Foreign Affairs and Trade (MFAT) towards the Department of Watershed-management, which in this regard was really impressively serving well-justified interests of other entities mainly based on foreign relations or trade. Currently with Peter

Kovacs as department leader having moved to the General Directorate for Water Management, the process became even more fragmented than before.

The correspondence was managed through the Missions by MFAT. The MoU would be signed after permission of the MI on level of a state-secretary, most often by the Minister of the MFAT.

From this point on the interests of the initiators were satisfied, whatever this was, and the MI had a new MoU to look after.

After the recent changes in the governance structure the role and future of the MoU's seem to be neglected and it remains a question for now, how long the inertia will take the currently operating cooperations.

Workgroups (number, participants, work)

Following the signature the work starts with the creation of workgroups or joint steering committees and their first session. Members of this team of experts are assigned by the parties, from Hungarian side usually professionals from the MI, the General Directorate of Water Management and occasionally the local Water Directorates, depending on the themes in focus. The workgroups have regular but not frequent meetings (ideally 1 per year) online or in person. The creation of a workplan can take up some time (occasionally several years according to the records) and contain a set of areas for collaboration and projected activities on those areas. Beyond capacity building (webinars, seminars, courses, exchange of young professionals), there are instances for project generation, definition of potential joint research, mutual participation on conferences and technical visits. The workplans are usually created for three years with a final completion report and definition of possible future collaboration.

There might be obvious opportunities where Hungary can assist with know-how, technology or capacity. For example, if the partner is unable to measure or monitor water yield. In this case we are able to provide with a measuring group and even train the partner. The work of the workgroup aims to define those areas where collaboration can be beneficial for both parties by defining problems and assessing the availability of knowledge, technology, institutional capacity.

Memoranda without workgroups, upcoming challenges

Currently only about 10 of the 51 memoranda are proving useful (for example Thailand, Bangladesh, China, Pakistan). The failure of a MoU can be traced back to various reasons. For once it might not even be a failure from the side of the initiator, because the original purpose was never the intensification of water-based cooperation, but "only" the development of the political relations. There also might occur political changes (like in the case of Sudan) that reduce the importance of this kind of relations, rendering the cooperation uninteresting. Sudden change in economics might pose challenges that affect the implementation of the collaboration (see the case of Egypt in at presenting the concerning memoranda). Once the MoU is there however, it does not take any resources to keep the paperwork. It is an ever-available basis for potentially emerging needs. If one of the parties feel it coming useful and can find common ground of interests, it is possible to reinitialize the cooperation with a short process.

Results – what's BEYOND the MoU's

Even as a hidden subpoint in this subject that is one of the critical factors and unfortunately even the most difficult one to acquire data for. Who are the stakeholders beyond the MI involved in the relations initiated or supported by the MoU's? Difficult to define what role of the MoU had in the development of the relations, but what happened in terms of export, investment or educational/research cooperation beyond the implementation of the MoU? This also raises the question who should keep records, follow-up these various aspects of relations? I thought of collecting this information from the foreign-economics attachés of the Hungarian missions. This however has proved problematic. Most of them referenced the MI as the sole responsible party for the implementation of the MoU's. While the MI has neither the capacity nor the interest in following development of foreign relations, very few of the attaché's could or wanted to provide information for the original thesis about water-based relations. There is information about few companies that found the existence of a MoU useful for investment in a developing country (for example Pureco – Ghana; Budapest Water Works - Pakistan). There are few students studying with Stipendium Hungaricum in Hungary (for example University of Public Service, Faculty of Water Sciences – Nigeria, Kazakhstan; Budapest University of Technology and Economics - Algeria), but much less than the program would allow in general, and in the area of water in particular *(Stipendium Hungaricum 2024)*. There is cooperation between the Hungarian Water Association and the Vietnam Water Supply and Sewerage Association, having organised a full-day seminar in water-management, but it's a side activity for an organisation like this.

The MFAT is supporting the export-oriented relations through the Joint Economic Committee's (JEC) repeatedly meeting with 40-50 countries. This has its declared purpose of exploring and defining business opportunities. Water is an often recurring, strongly emphasized subject on the JEC's program and in case it there is one, the MoU is referenced in the record of the JEC's meeting. The MFAT has also a flagship exporter program listing export-oriented companies from the water-industry and *HEPA (2024)* (Hungarian Export Promotion Agency) promotes also companies of a mature export-potential in foreign markets.

In the implementation of the MoU's the engagement of the ministerial background institutions (General Directorate of Water Management – Viziterv Export), chambers of commerce, remains random and unexplored.

Gap assessment

Intention

There was plenty of contemplation about the possible motives behind the MoU's of water management when discussing the geographical focus. However, it is quite clear that the Ministry of Interior, as (former?) owner of the set of these instruments has no direct interest in the implementation of these. While even if it seems strategically problematic, from a certain perspective it is possible to be justified subordinating the water-resources management to the Ministry of Interior. (That is changing as more and more areas of water-management become concentrated under the Ministry of Energy.) However, when we specifically touch upon the subject of the MoU's it is absolute logical to raise the question: why would be a department in the MI responsible for setting up this kind of relations shall it be export-focussed, foreign relationship centred or water management concentrated. The answer of the MoU's being cooperations in water-policy thus handled by the owner of the watershed-management come short when we ask about the initialization of the collaboration.

As discussed at the current practice the MI managing the MoU's was serving interests in foreign politics and trade. It's difficult to name any particular reason why the Department of Watershed Management (DWM) under the Ministry of Interior would engage for its own sake in a collaboration with Sub-Saharan or Latin-American countries based on water-policy and management. The cooperation eventually serves foreign policy and/or export purposes (responsibilities of the MFAT).

So, is there an intent to utilise these paperworks from every respect possible as discussed in among the possible benefits and international perspectives? I also turned the question a little more realistic, since the MoU's are not created for their own sake and are not goals themselves but serving other goals. So, is there an intent to utilise the MoU's up to their capacity?

From the side of the DWM or even the MI, there certainly isn't. Neither the political respect of the country, nor the export promotion, even additional possible benefits like carbon credit trade are relevant factors from the area of responsibility of the Ministry of Interior or any of its departments. Knowledge exchange is always useful and usually there is something to learn from everyone, however an institutionalised knowledge-exchange with the set of mainly developing countries we have MoU with, is somewhat overscaled, especially if we consider the mutually beneficial character of the cooperation and the more we narrow down the conceived knowledge exchange. With those having bilateral cross border water-treaties with Hungary, we don't even sign MoU's focusing on knowledge exchange. There is no valid reason for the MI to assign resources to the creation or successful implementation of the MoU's. This can be different in the case of the Ministry of Energy, assuming its growing involvement with water matters. Last year the government took big steps for eliminating the decade-long fragmentation of water governance and is concentrating more and more areas under a separate state-secretary for water management under the leadership of the Ministry of Energy. The case of the currently discussed paperwork clearly shows that there is still a long way to go in terms of reducing fragmentation, because currently the Ministry of Energy and the State Secretary of Water management still has absolutely no responsibility in the field of the water management MoU's.

We can ask the same question with respect of the Ministry of Foreign Affairs and Trade. There are present the responsibilities that we miss from the side of the MI. However, the question sounds different in this consideration. Is there an intent from the side of the MFAT to utilise the MoU's to their full capacity in favour of reaching its own purposes: export-development and international recognition, development of political relations, thus making them an integral part of its strategy? Probably there isn't, otherwise the MFAT would not just acknowledge the existence of these professional cooperation and occasionally use their signature as a PR act but would be active part of the workgroups and at least closely monitor but rather influence and stimulate the actual implementation. The MFAT seems to acquire information and incentive through the Joint Economic Committee's and rather uses the MoU's as occasional reference basis, but for that their pure existence is sufficient.

Eventually both the MI and the MFAT are serving higher political interests as ministries responsible for areas assigned to them. But is there a higher political will to utilize the MoU's to their full capacity? While there is no exact answer for that, the obvious lack of a coherent strategy in water and environmental management that is best expressed by the still the partial homelessness (Water in a statesecretariat in the Ministry of Energy) and fragmented institutional background and lack of coordination (see the section Institutionalisation of water in Hungary) even by limited flow of information, indicates that the creation of the MoU's is not fitting in an elaborate strategy promoting a sustainable integrated water management or a coordinated presence on foreign markets. However, there might be a conceptual direction in foreign politics (*Tarrósy and Solymári 2022*) which is well served by occasional signing of the MoU's but doesn't go beyond that in their utilization and ignores their actual implementation.

Resource

If there is no will, then usually availability of resources is at least questionable. When talking to ministry officials the most often raised complaint referred to the lack of funding. The current funding is sufficient for operation that is to be observed currently: gradual expansion of the set of MoU's and operation of the currently active relations, with occasional visits in every few years. It's a limited but existing financial background. The MI certainly has no other resources to be dedicated to this activity, being completely outside of its focus. Shall that be a completion of a feasibility study or any kind of support for export activities, foreign investments, the MI is not going to be able to finance that. The MI only can afford one person representative of the country to participate on some international water management conferences and represent the attractive knowledge present in Hungary. The MFAT had tenders in previous years for companies active in the water industry for stimulate export activities (before 2022). The *Exim bank (2024)* can contribute to successful investments with tied-aid loans and investment guarantees. The Hepa can facilitate the presence of the Hungarian industry abroad on trade fairs. Stipendium Hungaricum with an oversized (but decreasing) program can also support the expansion of water-based collaboration, however there are only a few applicants for the offered places. There are private initiatives like the Hungarian Water Partnership and

HWTC, financing their activities and operation from private sources.

So, considering the resources, while it is a returning deficiency and one difficult to overcome, I have to point out that there are resources available, but even those are being utilised fragmented, with limited efficiency, for the reason of lacking coordination and comprehensive strategy behind.

Photo 5. Delegation of Hungarian Water Experts in India led by Péter Kovács (www.ovf.hu)
5. kép. Kovács Péter vezette magyar vízipari szakemberek küldöttsége Indiában (www.ovf.hu)

Institution

When collecting the information for my original thesis, it became painfully obvious that while the MoU's create an easy but handy basis for cooperation, they have no real owner who would be – apart from the conscientious performance of duties - substantially interested in developing the foreign relations whether it is policy and knowledge or export based. There are capable institutions responsible for various tasks, but there is no real coordination utilising these into a coherent system and no real driver behind. There are also some cluster-like organisations in the private sector (Hungarian Water Technology Corporation - HWTC, Hungarian Water Partnership - HWP) who have partial knowledge of the current activities (*Hungarian Water Partnership 2024, Hungarian Water Technology Corporation 2024*), but are not involved in the collaboration in any way, however they could really act as driver of the cooperation as could also the MFAT if invited into the workgroups.

CONCLUSION - MAPPING OPPORTUNITIES, FORMING SUGGESTIONS

Potential of the Memoranda of Understanding of water management

The MoU-like non-binding instruments are a useful tool that the Hungarian Diplomacy has discovered and started to use in fairly large scale. It is easy to create them. It has a positive image. It can improve personal, political and economic ties through professional collaborations that encourage and facilitate knowledge transfer. The better relations can lead to actual and well-funded (based on real knowledge) businesses that improve not just the human well-being but also the state of the environment and provide developing countries with the most up to date (most effective and cost-efficient) solutions. An MoU without workplan and workgroup can improve political relations, and the pure act of signature can be conceived as "a form of communication" (*Kardos 2024*). It can also facilitate the relations between a Hungarian exporter and a recipient country, creating a reference and providing a contact (since the MoU has been signed by someone). All this for a minimal cost. However, the MoU really rises to a useful level when a workgroup is formed and a workplan is created. The realisation of successful common projects – shall that be policy and management based or an actual export – due to successful implementation of an MoU, that opened the door for further, more serious treaties can/could bring in convertible strengthening of political relations, in addition to tax-income from foreign work and order.

Financial resources, motivators

Beyond the formation of workgroups financial resources are the next decisive factor of contributing to the potential benefits of an MoU. During my research and the formation of this work, I repeatedly met the issue of limited financial resources. Finances can play an important role in implementation of the MoU at several stages. Without facilitating actual visits and common participation on conferences even the political effect can stay very limited, reduced only to the act of signature. Even more true for the actual exchange of knowledge and experience that is vital for discovering the real potential for export or Hungarian presence on trade-fairs and exchange programs or scholarships that are to build a network of experts, related to Hungary. In case of available resources, the Hungarian party could be in the position of financing a feasibility study based on the discoveries made by the workgroup of an MoU. Depending on the financial position of the partner, in case of existence of those the Hungarian companies might be preferred applicants on an international tender (due to the complementary creation of the study) or in case the partner lacks financial resources a tied aid loan can bring Hungarian companies' ready businesses.

Despite the complaint from various sources, there are certain resources available. The MI has/had a department focusing on the development of the MoU's and occasionally can organise visits to and from Hungary for the workgroups. Hepa is supporting Hungarian companies, including those from the water industry presence in trade fairs. MFAT is including water in the joint economic committee's program and has a department exclusive for water diplomacy (but not exclusive for the overseas relations). Private sector companies and a cluster or consortium like the HWP or HWTC can gather their strength and finance activities, presences that they hope to bring some breaking point in their export endeavours. With a still noteworthy but recently lowered budget the Stipendium Hungaricum is bringing in year after year students to Hungary, however neither their choice of major nor their relationship to actual companies is coordinated or advertised in the above channels and I'm not aware of an alumni program.

All in all, there are resources available, however these are scattered and fragmented, their efficient use is not ensured.

Supporting legislation and organisational structure

Unfortunately, the still fragmented institutional background of the Hungarian water governance leaves its mark on the question of the MoU's too. There are several players involved, each responsible for a separate field, lacking a coordination process between them, while the limitless flowing and connecting characteristics of water itself is similarly true for its management process too. Boundaries in water matters are rarely exact and eventually everything is connected. The same water that comes into the country through a shared watercourse (don't forget to consider quantity and quality) will be used for the energy-industry as power-generator or coolant, agriculture as irrigation, will cause flood or drought, will eventually penetrate underground and serve as drinking water for the populations and after being returned to the environment contribute to the health and well-being of the biosphere. All this is interconnected and requires a holistic approach, which would be called integrated water management.

However, it is difficult to talk about integrated water management when the institutional background, handling water is greatly disintegrated and difficult to provide know-how for developing countries when even communication is limited within our own system and suggest best practices, when we don't even consider reasoning for our own as a best practice.

Additionally, without clear separation of the responsibilities and the proper connection of stakeholders the successful operation of management processes is not coded in the system but often left to personal commitment and willingness of undertaking.

Specific suggestions

From the focus of this article the fragmentation of the Hungarian water management system has only tangential significance. The MoU's to my view (as discussed before) have their main role in promoting export and political relations. Creating a supportive environment for their implementation (so that they can perform their role at an optimal level) would be easier with an integrated legislational background, but the connecting of various players within the frame of the MoU would be necessary anyway and that is possible even among the current circumstances. However there seems to be missing a coherent strategy behind the MoU's that would clear up their purpose and define the goal of Hungary with these MoU's as a whole and also one by one. Another approach would be to define how these MoU's can fit in a more-comprehensive strategy of foreign politics or foreign trade, but an important finding of the current work is that apart from the above, the MoU's can prove useful and beneficial in many respects. So, I really suggest a strategy behind the MoU's as a whole and also for each. With an individual MoU, Hungary might have a definite export purpose, might have a simple openness, or might not aim to complete anything beyond the signature. So, I suggest a definition of Hungary's goal with each MoU. According to the strategy this status can be revised from time to time and be changed, automatically initializing necessary actions (in case of raising importance calling for a workgroup or adding dedicated resources etc or in case of being reduced in importance postpone activities etc).

To complete any kind of achievements though there is an essential factor missing: A proper owner of the process with strong motivation. This is a two-component factor, very difficult to be replaced by personal commitment and dedication. There are partial solutions that can produce better results than today, meaning here for example invitation of export-oriented organisations into the workgroups and providing them with initiator role. For a real useful, efficient system of MoU's however there would be a motivated process-owner necessary who is required to involve a wide range of stakeholders both in the formation and update of the system of the MoU's and in the implementation and further development of the individual collaborations. This player should play a forward-moving coordinator role in connecting the stakeholders and operating those MoU's in a professional way that points in a determined direction. About what that direction is, a decision must be made by the involved stakeholders which suppose that the meeting of workgroups does not exclusively mean the conferences held with the party, but also the thorough coordinated preparation of those. So, for using the MoU's up to their full potential I find absolutely necessary a strong coordination between the stakeholders and that of the process.

Also, necessary but only after what was mentioned above, I take the question of the availability of resources. What these resources are and how to define them is a far-reaching question to answer. It certainly is the strategy where this has to be handled. From a goal-oriented, progressive approach strategy must touch upon the matter of the aim of these paperworks and depending on their validity dedicate sufficient resources to their implementation. However, it is rarely the case that strict financial limits are not to be considered. As the MoU's are expected to bring actual income (direct and/or indirect tax benefits and profit for Hungarian companies) for the country, the definition of these prospective resources could/should be a source of the finances and a reason for dedicating them. Beyond the above there are two more components to consider. One is that behind the MoU's the economic reasons are not exclusive and there are political goals involved too without direct economic benefit. The other is that even so far, there were resources used for this purpose (as listed at section Financial resources, Motivators).

Finally, not to be excluded that the efficient and coordinated use of the resources is a requirement that I would hope to fulfil by a motivated owner and a coherent strategy but absolutely include in the latter by a detailed budget.

Limitations of the current work and possible prospective research

The chosen subject is touching upon an unexplored area with scientific resources only peripherally relevant. Most of the information had to be collected from individuals working in the area. For some of this, in future research I would probably use or suggest a conform questionnaire and seek support from MFAT to acquire comprehensive data, that would allow to properly assess the actual situation of the relations in the partner countries.

I have conducted several interviews and run a general inquiry, but the subject is quite extensive. Future research should include detailed analysis of economic relations, assessment of export (the share of water sector), educational-, scientific relations on various fields, human and financial capacity of potential Hungarian exporters, possibly a more detailed mapping of the place of water in the Hungarian administration, comparison/analysis of similar programs in Europe or the developed world.

Even going further, prospectively I would concentrate on the relation between bilateral and multilateral collaborations and trying to optimise mechanisms that could pair the capacity and funding present in the individual countries and international organisations with the needs and opportunities across the world.

This is subject of extensive research, which is going beyond the capacity of the current work but is well based on this research.

In fact, it was a conscious choice of mine not to cut too short the limits of this original research to a certain area, but rather creating a full picture, which creates a detailed outline for future work. Like a sketch that can be filled by fine brushstrokes and detailed fine work but has all the main elements and gives a general understanding.

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Author

BALINT RÓZSA economist, specialized originally in logistics. Later in the position of the Secretary General of the Hungarian Water Association (MaSzeSz) he had the opportunity to face several aspects of the current state of the Hungarian water management and observe on a daily basis the challenges our institutions and water industry experience. He completed a master's degree in water diplomacy and international water governance at the Department of Water and Environmental Policy of the Faculty of Water Sciences at the National University of Public Services (2024). The current article is mainly based on his original research of the bilateral Memoranda of Understanding that he concluded in a thesis at the University.

Historical snapshot

Columnist: László FEJÉR, honorary associate professor, chairman of the Water History Committee and honorary member of the Hungarian Hydrological Society.

The "heroic age" of Dégen

Gábor ALBERT[1, 2]

[1] Senior Research Fellow, University of Szeged Faculty of Agriculture, (email: albert.gabor@szte.hu)
[2] University of Public Service Faculty of Water Sciences (email: albert.gabor@uni-nke.hu)

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Abstract
The older generation of water management engineers looks back with nostalgia on the period between 1955 and 1975, associated with Imre Dégen's water management policy, referring to it as the "heroic age" of Hungarian water management. Following the dismissal of his predecessor, Dégen became the head of the General Directorate of Water Management in 1955, and later, as State Secretary, served as the President of the National Water Office. He retired in 1975. The beginning of his water management policy thus dates back to 70 years and its conclusion to 50 years ago. These two anniversaries provide an appropriate opportunity to review the results of Imre Dégen's water management policy and assess the impact of his professional work. This overview of his official career is based on bibliographical sources, archival documents, and personal recollections of his contemporaries.

Keywords
'Heroic age' of the Dégen era, water management policy, flood control and excess water in the inland, technical and mid-level water management training.

A dégeni hőskor

Kivonat
Dégen Imre vízgazdálkodási politikájára, a nevével fémjelzett 1955 és 1975 közötti időszakra az idősebb mérnökgeneráció nosztalgiával tekint vissza, azt a hazai vízgazdálkodás hőskoraként emlegeti. Elődjének menesztése után, 1955-ben lett az Országos Vízügyi Főigazgatóság vezetője, később pedig államtitkárként az Országos Vízügyi Hivatal elnöke. 1975-ben vonult nyugállományba. Vízgazdálkodási politikájának kezdete tehát 70, befejezése 50 évvel ezelőtt történt. E két jubileumi év feljogosíthat minket arra, hogy Dégen Imre vízgazdálkodási politikájának eredményeit áttekintsük, munkásságának hatását mérlegeljük. Hivatali útjának bemutatását könyvészeti szakmunkák, levéltári források és kortársak személyes visszaemlékezéseire támaszkodva összegezzük.

Kulcsszavak
A dégeni hőskor, vízgazdálkodási politika, árvíz-és belvízvédelem, műszaki-vízügyi középkáderképzés.

THE LIFE PATH, LEADERSHIP QUALITIES, AND CADRE POLICY OF IMRE DÉGEN

Due to the numerus clausus restrictions in Hungary, Imre Dégen began his university studies at the German University in Prague, and in 1934 he earned an engineering degree in Vienna. In 1945, the Minister of Agriculture appointed him as an engineering member of the National Land Consolidation Council. From 1948 onwards, he worked as the director of the Cooperative Credit Institute and later that of the Hungarian National Cooperative Centre. He eventually became Secretary General and, in 1954, President of the National Federation of Cooperatives (SZÖVOSZ) (*Fejér 2020, Albert 2024*).

It was during these years that he established a working relationship with Rezső Nyers, who later became one of Dégen's main political supporters during the era of the New Economic Mechanism. He also developed an excellent professional rapport with Lajos Fehér, one of the most influential party functionaries, who served as Deputy Prime Minister between 1962 and 1974, covering most of Dégen's tenure in office. During his time in the cooperative sector, he also became acquainted with his future economic advisor, Lajos Danicska, who had learnt cooperative work in the Hangya Cooperative Alliance (*Reich Gyula 2023*).

After the dismissal of the former director general Kálmán Rajczi, Dégen was appointed head of the General Directorate of Water Management in 1955. The unified water management service, established in 1953 by merging former flood prevention associations and hydraulic engineering offices, was made operational under his leadership after 1955 (*Mt 1.060/1953. 1953, Dr. Béla Hajós 2023*). The unified system consisted of the General Directorate of Water Management and, by 1955, eleven, later twelve, regional water directorates. In 1968, following the modernisation of the water sector, the General Directorate of Water Management became the National Water Office.

Imre Dégen's leadership qualities were respected even by the older generation of engineers. He had excellent situational awareness and a strong ability to capitalise on opportunities. He consistently identified ways in which the water sector could benefit from the historical context. Recognising the potential of the 1961 education reform and its legislative framework, he succeeded in establishing a Higher-level Water Management Technical School in Baja. In 1974, during his honorary university professorship, he managed - together with the Minister of Transport and Post - to secure funding for constructing the renowned UV (Road-Lab) building at the Budapest University of Technology and Economics (*Dr. Mészáros Csaba 2023*).

The older generation of engineers affirms that Dégen represented professional interests within the party. His technically-orientated secretariat was organised on a rotational basis. His emphasis on professional qualifications and personal conduct in cadre selection, as well as his conscious delegation of responsibilities, demonstrate his strong leadership skills.

Imre Dégen often relied on professionals who, although not deemed the most politically reliable cadres, were outstanding in their fields. These included the renowned hydrologist and former civil engineer Woldemár Lászlóffy and his close colleague László Dávid. Zoltán Bényei, the head of the Codification Department within the Administrative Directorate, also belonged to this group (*Dr. Szanati Henrik 2023*).

At the same time, Dégen also recognised leaders who, despite lacking higher education, significantly supported the water management sector through strong organisational skills and professional experience. Sándor Vezse, who had a basic education as a *watermaster*, owed his decades-long career in water management leadership to such qualities. Thus, Dégen valued experts who had been socialised in the previous regime (e.g., civil engineers, *watermasters*) while also ensuring professional succession and training (*Dr. Hajós Béla 2023*). However, he was less tolerant of servile leaders in his immediate environment (*Dr. Gerencsér Árpád 2023*).

1. image. Imre DÉGEN, State Secretary, in his office
(DM Water Management Photo Archive_4760. Photographer: László Körtvélyesi 1975.)
1. kép. Dégen Imre, államtitkár az irodájában in his office.
(DM Vízgazdálkodási Fotóarchívum_4760. Fotós: Körtvélyesi László 1975.

He consistently sought out and always found the people who were the most outstanding experts in their respective fields. He could always rely on his general deputy, Miklós Breinich, and on Iván Wisnovszky in matters of technical education. In organisational issues and reorganization, his legal advisors, Zoltán Bényei and Henrik Szanati, provided assistance, while in economic matters he was supported by the previously mentioned Lajos Danicska. Regarding irrigation issues, Kurt Budavári offered his expertise, and in scientific matters, Ödön Starosolszky served as his advisor. In the area of large-scale infrastructure and macro-regional water management systems, he was assisted by Ede Kertai (*Reich Gyula 2023*). Woldemár Lászlóffy, among others, drew Dégen's attention to the importance of hydrodiplomacy (*Lászlóffy 1959*). He managed to recruit Sándor Katona - former world champion in powered aerobatic aircraft - as the chief pilot of the Water Management Air Service (*Reich Gyula 2023*). During times of flooding, the regional water directorates supported his work. His closest advisors included György Kiss the water directors of Baja (later of Pécs), Kálmán Karászi of Székesfehérvár, and Lajos Takács of Gyula (*Dr. Rudolf Halász 2023*).

IMRE DÉGEN'S WATER MANAGEMENT POLICY

In 2010, the historian and the president of the Academy, Ferenc Glatz emphasised Imre Dégen's role in the advancement of European water management culture: "*The European tradition of water management, represented in Hungary's water affairs by figures such as Vásárhelyi, Kvassay and Sajó, was continued in the work of Dégen.'* (*Glatz 2010*). László Fejér summarised Dégen's water management policy as follows: *"His name is associated with the establishment of effective flood and inland water protection, the water construction industry, modern water management, the launch of a new association movement, and the development of professional training for water management specialists."* (*Fejér 2019*). In his 2019 volume, István Ijjas identified Dégen's most significant contribution as his role in developing water management as a professional and scientific field (*Ijjas 2019, Dr. Ijjas István 2023)*.

During major floods – most notably in 1965 and 1970 – Dégen served as Government Commissioner for Flood Protection. Given the gravity of this responsibility, he approached the task with due diligence and was able to make prompt, responsible decisions after on-site assessments. This was the case during the 1970 Tisza River flood, when he made the decision to evacuate the town of Makó. On 17 May 1970, after learning of the unexpected flooding of the Mureş River near Alba Iulia (Gyulafehérvár), he ordered the highest level of flood alert by telephone. On 19 May, he conducted a site inspection of the dike of the Mureş River and met with local leaders in Makó. He then held discussions with László Forgó, Director of the Szeged Regional Water Directorate, along with the flood defence leadership team. Following this meeting, he ordered the evacuation of the town (*Vágás 2010*).

As state secretary and flood defence commissioner during these major events, Dégen not only coordinated damage mitigation and defence operations, but also drew conclusions and initiated necessary organisational reforms and equipment acquisitions. One such example was the procurement of the Swiss-made Pilatus Porter rescue aircraft, which was later first deployed during the 1973 flood events along the Zagyva and Tarna rivers (*Reich Gyula 2023*).

In the latter half of the 1960s, Dégen was a supporter of the *'New Economic Mechanism'*, an economic reform initiative. Within the socialist framework, he endorsed the adoption of entrepreneurial thinking. He played a key role in the creation of Hungary’s domestic water construction industry, overseeing the development of a full state and corporate system that included planning, investment coordination, construction and operation (*Albert 2024*).

He was also instrumental in the implementation of the large-scale water management system of the Great Hungarian Plain, most notably the construction of the Kisköre Dam and Reservoir (now known as Lake Tisza). The project enabled the resolution of long-standing water supply and irrigation issues in the middle Tisza and Körös regions (*Albert 2024*).

Dégen also played a leading role in the security of residential and industrial drinking water supplies. To this end, he revitalised the pre-1948 waterworks associations during the 1960s. Recognising the growing demand for potable water and sewage infrastructure, he understood that the state alone could not finance all regional water projects. Therefore, he supported the formation of self-organising local waterworks associations and the inclusion of residents' financial contributions. The state, in turn, supported legally operating associations through favourable loans provided by the National Savings Bank (*Albert 2024*).

IMRE DÉGEN AS A UNIVERSITY LECTURER

Imre Dégen joined the Budapest University of Technology and Economics in the late 1960s and was granted the title of honorary university professor in 1970. He taught in the Department of Institute of Water Management and Hydraulic Engineering, headed by Imre V. Nagy. Although he had excellent memory, recollections from students and colleagues suggest that he was not particularly gifted as a lecturer. Unlike Emil Mosonyi, who, according to former students, 'captivated his audience with his brilliant lectures and presented otherwise dry and 'watery' topics in an exciting way' (*Fejér 2020, Fejér László 2023*) -Dégen’s style was more reserved.

However, it should be noted – as Professor István Ijjas emphasised it – that Dégen’s greatest contribution to the development of water management was the acknowledgement of this issue as a professional and scientific discipline. Dégen’s vision for the BME Civil Engineering faculty was to replace traditional hydraulic engineering with an Integrated Water Engineering Course. He believed that water-related professions must encompass not only engineering tasks, but also economic and ecological aspects. To advance this multidisciplinary approach, he founded the Departmental Group of Hydro-Economics and Water Resource Management (*Dr. Madarassy László 2023*). His university lecture notes, created with the help of colleagues, especially László Dávid and József Csuka, also reflected this integrative perspective. His university textbook on water resources management and the specialised engineering textbook Hydro-Economics were received with high respect by the scientific community. The Environmental and Water Archives preserve valuable materials from Dégen’s legacy, including correspondence and recommendations related to his teaching materials. Among them are the appreciative words of Woldemár Lászlóffy regarding the *Hydro-Economics* textbook for technical engineers: *“Due to the infrastructural nature of water-related tasks, economic considerations were pushed into the background for a long time. When cost-effectiveness analyses were conducted in relation to certain facilities, they were limited to the specific project itself and did not account for broader community interests. At that time, water was still regarded as a commodity (goods) free of charge. In planned economies - an approach that is gaining ground even in the capitalist world - a new mindset is required, one that all your writings advocate.“* (*Lászlóffy undated*) Imre Dégen did not become a scientist. Although he aspired to earn a doctoral degree in engineering, he was ultimately unsuccessful in doing so (*Fejér 2020*).

HISTORICAL CONTINUITY AND EVIDENCE-BASED DECISION MAKING

For Imre Dégen, the preservation of the past and the honour of the legacy of the water management profession were of great importance. His commitment to historical remembrance is demonstrated by the founding of the Water Management Museum (today Danube Museum) and the Water Archives (today Environmental and Water Archives), as well as his support for historical research in the field. He deeply respected the profession's great predecessors. The erection of the statue of József Beszédes in Siófok, the memorial of Pál Vásárhelyi in Tiszadob, and the honorary grave of the reform-era engineer in the Kerepesi Cemetery all attest to his appreciation of historical figures. Even before the establishment of the Historical Committee of the Hungarian Hydrological Society in 1973 (*Lászlóffy 1973*), Hungarian hydrologists had shown an interest in the study of water management history. Zsigmond P. Károlyi, one of Dégen’s favourite water history writers, regularly contributed articles to Journal of Water Management (*Vízgazdálkodás)*, the publication of the National Water Office, commemorating key figures and events in the field (*Albert 2023*). He also edited the *Water Management Historical Booklet* series. László Bendefi was another regular contributor to the historiography of water management. The growing interest in the history related to water was undoubtedly influenced by the supportive institutional environment, which in turn shaped the professional attitudes of the water engineers of the era. Few know that Woldemár Lászlóffy also conducted research in this field. His studies on József Péch, founder of the Hungarian Hydrological Service, and his manuscript on Roman navigation on the Tisza River are noteworthy contributions (*Albert and Farkas 2022*). The mining engineer Eligius Róbert Schmidt also published a history of thermal water research in Hungary (*Lászlóffy 1973*). There is little doubt that under Imre Dégen's leadership, the historiography of the water sector gained a central role, one that continued to thrive for decades after his tenure. Dégen frequently referenced historical examples in his speeches, writings, and ceremonial addresses. In his speech at the First Watermaster Meeting held in Debrecen on June 11, 1960, he emphasised the symbolic significance of the venue, noting: *'This is the place from which many pioneering decisions in Hungary's water management originated. Here, the first general assembly of a Hungarian flood prevention association was held, which led, in 1846, to the initiation of Tisza River regulation by István Széchenyi, based on plans by the great Hungarian water engineer Pál Vásárhelyi, thereby launching flood control efforts. '* (*Dégen 1960*).

In the same address, Dégen also highlighted the work of Jenő Kvassay, who founded the first civil engineering institution with only four engineers, as well as the historical roots of Hungarian Royal Watermaster School in Košice**,** initiated by Kvassay. This historical knowledge informed Dégen's concept of training middle-level technical staff, which he saw as a modern continuation of the old expertise of the profession that used to be called watermaster. For him, the newly established technical secondary schools of water management were the institutional means to preserve and transmit that legacy of practical skills (*Dégen 1960*).

In 1973, Dégen honoured Hugó Lampl on his 90th birthday, as recorded in the Journal of Water Management (*Vízgazdálkodás 1973)*, issue 4 of that year. In his speech, he praised Lampl's remarkable contributions to water management and hydraulic engineering all over from his career beginning in 1903, covering several historical eras. He mentioned, among other things, Lampl's joint work with Elemér Sajó on the Tass Barrage, the initiation of irrigation in the Tisza Valley, and his role in leading the National Royal Irrigation Office (*Vízgazdálkodás 1973*). Upon Lampl's death at the age of 93 in June 1976, Dégen authored an obituary in October that year. He sent the manuscript to Zsigmond P. Károlyi for review and even incorporated parts of Károlyi's previous writings into the final version (*Dégen 1976*).

It is evident that Imre Dégen had a deep knowledge of the determinant eras of Hungarian water management history and held the legacy of pioneers like Vásárhelyi, Kvassay and Sajó in the highest regard.

ASSESSMENT

The older generation of engineers looks back on Imre Dégen's water management policy with a sense of justified nostalgia. Dégen oversaw the various fields of water management like a careful steward. He was an excellent organiser, possessed a keen sense of timing, and strategic insight. In today's terminology, one could say he had outstanding managerial skills, even if these were sometimes paired with Machiavellian methods.

Within the rigid structures of state socialism, he managed to establish a full-spectrum domestic water construction industry and consistently sought to apply economic and efficiency-orientated principles in the water sector. He demanded effectiveness and entrepreneurial thinking from his colleagues, even under central planning constraints.

In his everyday decision-making, the preservation of historical legacy was also a guiding principle. He attributed special importance to sectoral memory and historical awareness, and his commitment to institutional remembrance was manifested in both symbolic and practical ways. Historian Ferenc Glatz's claim is hardly an exaggeration. Dégen was indeed a successor to Vásárhelyi, Kvassay, and Sajó, continuing the tradition of European water management culture**.**

At the same time, idealising his role may hinder a clear and objective historical positioning of his period in office. He had an excellent eye for choosing collaborators, who in turn provided consistent and loyal support. However, his inner circle did more than just assist the head of the water administration: They played a role in shaping Dégen's leadership character and personal style. He was the kind of leader who could be persuaded by professional arguments (*Pesthy Imre 2023*).

As an honorary professor at the Budapest University of Technology and Economics, Dégen was actively involved in education, although recollections suggest that he was not a particularly engaging lecturer. However, this does not diminish his achievements. Even though he never became a scientist, it was largely due to him that the water management sector evolved, using the terminology of the time, into a full-fledged national economic sector.

This article is based in part on the 2023 Dégen Research Project supported by the General Directorate of Water Management as well as additional archival investigations conducted at the Environmental and Water Archives. The author also integrates the findings of this research into higher education, regularly delivering elective lectures titled 'Water Management in the Era of Imre Dégen' at the Faculty of Agriculture of the University of Szeged.

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THE AUTHOR

GÁBOR ALBERT is a historian who completed his Ph.D. in 2003 at the Doctoral School of Hungarian History of the 19th-20th century, Faculty of Humanities, Eötvös Loránd University (ELTE), Budapest. In 2016, he earned his habilitation in educational sciences in Eger, Hungary. He is a senior research fellow at the Faculty of Agriculture, University of Szeged, and the head of the Gyula Fekete Institutional History Research Programme and Research Group. At the Faculty of Water Sciences, Ludovika University of Public Service he is responsible for the comprehensive historical research of the Faculty's predecessor legal institutions. His main research areas include the history of agricultural vocational education, water management history, and institutional history.

Youth Corner

The Hungarian Journal of Hydrology is committed to fostering the next generation of professionals. As part of this mission, the Youth Corner's pages provide high school students with the opportunity to present their research. We encourage our readers to welcome and support their study with respect. This study was prepared for the Hungarian competition of the Stockholm Junior Water Prize in 2024.

Improving the water retention properties of our soils

Benedek SANTA[1], Márton FREI[1], Zoltán BAROCSAI[1,2]

[1] Béla I. Gimnázium in Szekszárd, Hungary

[2] Corresponding author (email:barocsai.zoltan@belamail.hu)

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Abstract

Changes in weather patterns over recent decades have had a significant impact on agricultural production. Due to changes in the distribution of precipitation extremes and an increase in the frequency and length of drought periods the loss of soil moisture is increasing. By studying soil samples collected in Szekszárd (Hungary), the area around our residence, by designing soil mixtures and analysing them, we would like to draw conclusions and make suggestions for improving soil water management. Our hypothesis is that the water management of soils can be improved by the application of soil improvers, which could have a significant positive impact on the water balance of Hungary. Changes in climatic elements started with an analysis of 40 years of meteorological data from the area where we live. Soil samples, soil mixtures and soil amendments (perlite, alginate, zeolite, compost, peat, cattle manure) were analysed for texture, water retention capacity, humus content and pH, and finally, our soil samples, our nine soil mixtures and the two soil samples treated with soil cover were tested for water retention capacity by growing wheat in 120 pots under the same conditions for 13 weeks. The soils tested are silt, silty loam soils, with soil amendments mainly enhancing the sand fraction. The water retention capacity improved with the amendments; the humus content increased more significantly with organic amendments. The pH of the soil mixtures shifted the soil samples towards the alkaline direction. Soil mixtures and soils treated with soil cover were able to retain water to a greater extent than the soil sample.

Keywords

Soil, water retention, soil test, soil moisture retention.

Talajaink vízmegtartó tulajdonságainak javítása

Kivonat

Az éghajlat változásai az elmúlt évtizedekben jelentős hatást gyakoroltak a mezőgazdasági termelésre. A csapadék eloszlásának szélsőségessé válása, az aszályos időszakok gyakoriságának és hosszának növekedése csökkentik talajaink nedvességtartalmát. A lakóhelyünk környékén (Szekszárd, Magyarország) gyűjtött talajminták tanulmányozásával, talajkeverékek létrehozásával, elemzésével szeretnénk következtetéseket levonni, javaslatokat tenni a talajvízháztartás javítására. Hipotézisünk az, hogy a talajok vízgazdálkodása javítható talajjavító anyagok alkalmazásával, ami jelentős mértékben javíthatná a magyarországi talajok vízháztartását. Az éghajlati elemek változását a lakóhelyünkről származó, 40 évet felölelő meteorológiai adatok elemzésével kezdtük. A talajminták, talajkeverékek és talajjavító anyagok (perlit, alginit, zeolit, komposzt, tőzeg, szarvasmarha trágya) textúráját, víztartó kapacitását, humusztartalmát és pH-értékét vizsgáltuk, majd a talajmintánk, talajkeverékeink és fedéssel javított talajunk víztartó képességét vizsgáltuk úgy, hogy búzát ültettünk 120 cserépben és azonos körülmények között 13 hétig neveltük. A vizsgált talajok iszapos, iszapos vályogtalajok, melyekben a talajmódosítások főként a homokfrakciót növelik. A vízvisszatartó képesség a módosításokkal javult, a humusztartalom jelentősebben nőtt a szerves talajjavító anyagokkal. A talajkeverékek pH-ja a lúgos irány felé terelte a talajmintákat. A talajkeverékek és a talajtakaróval kezelt talajok a talajmintánál nagyobb mértékben voltak képesek visszatartani a vizet.

Kulcsszavak

Talaj, vízvisszatartás, talajvizsgálat, talajnedvesség-megtartás.

Introduction

Soil moisture retention is on a negative trend across Europe and the world. Eastern Europe has experienced the most severe decline, while Northern European countries have suffered the least soil water loss over the last nearly forty years. Soil moisture levels are decreasing also in Hungary, especially in the spring and summer, posing difficulties to agricultural production. In a study by ELTE researchers, several options are proposed to tackle the problem, one of which is to shift arable cultivation from drought-prone regions to less drought-prone ones. To solve the problem locally, they suggest leaving more ponds, mulching or replacing the missing water with surface water (*Pinke et al. 2022*).

In Hungary, the number of extreme precipitation events and the length of consecutive dry periods have increased over the last 30 years. Based on the past decades, it is not impossible for a summer to be without precipitation for up to half a month, but the number of extreme precipitation events in the summer is also increasing. In Budapest, too, the distribution of precipitation is becoming more extreme, leading to more frequent flash floods, basement collapses and can also hamper transport due to overloading of the sewer network. In rural areas, the extreme distribution of precipitation in agricultural areas poses difficulties to crop production, as our soils dry out quickly and cannot store rainfall for long periods. Most of our soils cannot suddenly absorb the large amounts of rain that do fall, and the rivers drain the water out of the country. 95% of Hungary's surface water comes from abroad, imported by rivers, when the volume of incoming water is compared to the total river runoff. According to data from 1961-1990, an average of 112 km^3 of water arrives from abroad, 6 km3 is domestic runoff and 117 km^3 leaves the country, i.e. our water retention is low (*Somlyódy 2011*). Long periods of drought occurred in the last century, too, i.e. drought can be considered as a characteristic of Hungary's climate, but the summers are getting hotter and intense heat waves are increasing the drought risk (*Szentes 2022*). The damage could be reduced by retaining inland water and abandoning farming in the most vulnerable areas, but this would also reduce our productivity. In the case of drought, the solution is a combination of water recharge, increasing the amount of water infiltrating into the soil and adaptation. The problems of territorial water management can be solved by considering flooding, inland water, and drought together (*Somlyódy 2011*). Soil water absorption and drainage is a complex process in which processes of different directions and magnitudes take place. The soil itself is a passive water source, only able to provide the plant with what it can store from precipitation or absorb from groundwater. Because the distribution of precipitation is uneven, the soil must have the ability to retain water against gravity, but not to such an extent that the plant cannot take it up. The ideal soil composition for most plants is 50% sand, loam and clay, 25% water, 25% air (*Kocsis 2012*). To help solve these problems, we came up with the theme of our project at the end of September 2022, with the aim to propose ways to increase the water retention capacity of our soils. Our aim is to help agricultural crop production and thus a more economical food supply for the country. We have also sought the views of farmers' experts on the extreme weather, who have confirmed the above facts, and local news portals increasingly publish reports on the subject. Our aim is to detect the problem locally by analysing meteorological data and to suggest ways of increasing water retention capacity by examining the properties of the soils in our environment. Our hypothesis is that the soil improvers that can be formed in the country can increase the water retention capacity of our soils to such an extent that our water balance would move towards equilibrium or even shift to be positive and our agricultural production would become more reliable by maintaining soil moisture.

MATERIAL AND METHOD

The meteorological statements were prepared from the data of the Tolna County Government Office *(Tolna County Government Office 2024),* and that of the agro-meteorologist László Kővári from the last forty years (1977-2021). Our aim is to verify the national trends locally (*Kővári 2024*).

Analysis of meteorological data

- For the calculation of the standardized precipitation anomaly index, we determined the mean and standard deviation of precipitation for the period 1977-2021 for each month separately. We then subtracted the mean from the rainfall totals for each month of each year and divided by the standard deviation.
- We examined the number of different precipitation events (0-0.99 mm, 1-4.99 mm, 5-9.99 mm, 10-19.99 mm and 20 mm<) in Szekszárd between 1977 and 2021, broken down by year. We grouped the different rainfall events in each year and then examined the extent to which their number changed over time.
- We determined the amount of precipitation in mm that fell during the extreme rainfall events (20 mm<) in each year and then used the trend line to determine the direction of change.

Soil sampling

The soil samples were collected according to the *MSZ 21470 regulation* from seven different locations: from Decs, Koty, Solt, Hidas, Sióagárd, Fadd, Szekszárd. Samples were taken from the top 30 cm of the soil from several locations within the designated area and then mixed to create the soil sample. The samples were placed in tightly sealable containers and labelled according to their place of origin. Our aim was to learn about the soils in the surrounding areas.

Soil tests

Soil texture analysis

Soil texture analysis was carried out in the laboratory of the Institute of Geography of the University of Pécs, where the samples were dried for 24 hours at 105 ºC using a drying oven. Afterwards, 50 grams of soil samples were weighed and treated with 10% hydrochloric acid and 35% hydrogen peroxide to decompose the aggregates. Finally, the soil samples were placed in distilled water and textured using a Malvern hydro2000M machine. The water is passed through the machine's channel, where it illuminates the soil particles, and the laser can create an accurate image of the size of the soil particles. The values obtained were categorised into clay, silt, sand and then plotted using a soil texture triangle diagram to show the results. The same analysis was carried out with soil mixtures and soil amendments where necessary.

Analysis of humus content

The soil samples were left to dry for 2 weeks, then their humus content was tested in the laboratory of the Institute of Geography of the University of Pécs. The test was performed using the chromic acid method: 1 g of soil sample was weighed into a test tube and then 10 ml of 5% $K_2Cr_2O_7$ solution was added. After 10 minutes of shaking and resting, 20 ml H_2SO_4 was added to the samples. After cooling, the samples were made up to 100 ml with distilled water and left to stand for 16 hours. Subsequently, the determination of the humic matter was performed by spectrophotometry using a Bichrom Libra S-12 spectrophotometer. To use this instrument, a standard must first be set up, for which a glucose solution was used. All soil samples and soil mixtures were placed in the machine, which provided as a result the organic matter content of the soils based on colour.

Permeability test

Soil samples (7), soil mixtures (9) and soil amendments (7) were weighed out as samples of 20-25 grams into special plastic cylinders with a thin dense woven gauze at the bottom, which was fixed with a rubber band (*Figure 1*). The gauze ensured the free flow of water and the retention of the soil samples in the tube. The cylinders were then placed in a water bath at room temperature and allowed to stand in the water for one hour. After this, the water was left in the cylinders for 3 hours and we put the samples in a sand bath. The sand bed ensured the loss of excess water from the samples. After three hours, 25-gram samples by weight were taken from each tube and dried in a drying oven at 105 ºC for 24 hours to constant weight in specially designed annealing crucibles. After drying, the annealing crucibles were placed in a desiccator containing anhydrous calcium chloride until they cooled. After cooling, the crucibles containing the dried soil samples were weighed on an analytical balance. The weighing procedure is shown in the *Figure 1*:

$$WHC = \frac{Mn - Msz}{Msz} * 100 \quad (1)$$

where: WHC: water holding capacity of the soil sample (%), Mn: the exact mass of the wet soil sample taken from the cylinder (g), Msz: the mass of the sample dried to constant mass at 105 ºC for 24 hours (g) (*Kirchkeszner 2017*).

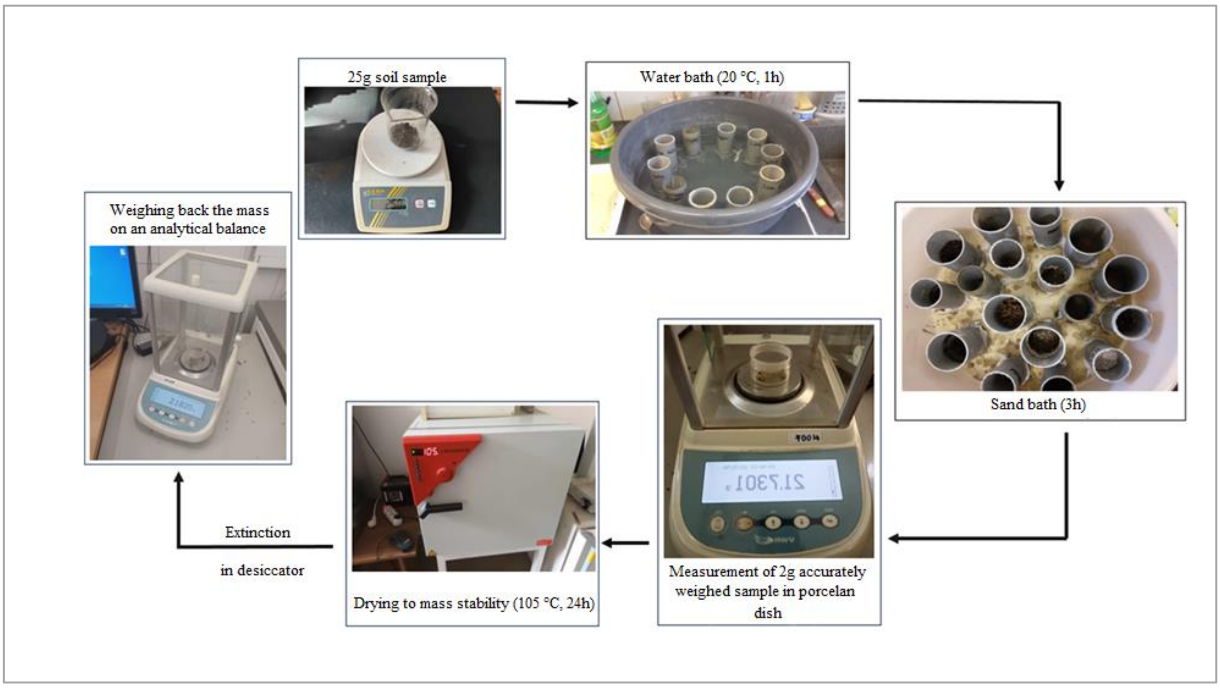

Figure 1. Determining the water-holding capacity of soils
1. ábra. Talajok víztartó kapacitásának meghatározása

PH measurement

Soil pH was measured using a 100-ml sample of the soil texture analysis water. A vwr MU 6100H digital machine was used for the tests, which gives a measurement accurate to two decimal places. In its operation it uses an electrode which is placed in the sample to be measured. Our aim is to get an idea of the pH influence of soil improvers.

Laboratory testing of the water retention capacity of soil mixtures

After testing the soils, the Szekszárd soil sample was selected because it was the easiest to bring large quantities of it to the high school laboratory. We wanted to increase the water retention capacity of the soil by using different materials: compost, perlite, cattle pellets, mulch, peat, alginate, clay pellets and zeolite (*Table 1*).

Table 1. Mixing ratio of soil mixtures
1. táblázat. Talajkeverékek keverési aránya

	Soil collected from the Szekszárd area		Alginitic soil mixture		Zeolitic soil mixture		Perlite soil mixture		Matured cattle manure soil compost		Beef pellet soil mix		Composted soil mix		Peaty soil mix		Base mix containing zeolite, alginate, perlite		Large mix containing peat, cattle manure, perlite, compost, zeolite, alginate	
	%	**g**	**%**	**g**	**%**	**g**	**%**	**g**	**%**	**g**	**%**	**g**	**%**	**g**	**%**	**g**	**%**	**g**	**%**	**g**
Soil	100	1 400	80	1 120	80	1 120	75	1 050	80	1 120	80	1 120	70	980	70	980	55	770	35	490
Alginate	-	-	20	280	-	-	-	-	-	-	-	-	-	-	-	-	15	210	5	70
Zeolite	-	-	-	-	20	230	-	-	-	-	-	-	-	-	-	-	15	173	5	58
Perlite	-	-	-	-	-	-	25	40	-	-	-	-	-	-	-	-	15	24	10	16
Matured beef manure	-	-	-	-	-	-	-	-	20	180	-	-	-	-	-	-	-	-	15	135
Beef pellets	-	-	-	-	-	-	-	-	-	-	20	180	-	-	-	-	-	-	-	-
Compost	-	-	-	-	-	-	-	-	-	-	-	-	30	220	-	-	-	-	10	73
Peat	-	-	-	-	-	-	-	-	-	-	-	-	-	-	30	90	-	-	15	45
Total	100	1 400	100	1 400	100	1 350	100	10 90	100	1 300	100	1 300	100	1 200	100	1 070	100	1 177	100	887

The soil amendments were weighed on a laboratory balance and 10 pots of each sample were mixed. A total of 12 samples were created and tested. One sample remained 100% Szekszárd soil sample, seven samples were mixed with one type of material in the range of 20-30%. In two samples (mulch, clay ball), we placed the water retention material on the soil surface, and in two cases (base and large mix) we used several soil amendments to make up the mix. In the case of the large mixture, only 35% of the original Szekszárd soil sample remained. The pots filled with the different soil mixtures had different weights, as the percentage by volume of each material was considered when the mixtures were made up, so that the pots were filled with the mixtures in all cases. We used the same 2 litre plastic pots and placed the same underlay under them. In the room where they were placed, they received diffused light, they were not exposed to direct sunlight, they were uniformly affected by air movement, i.e. the 120 pots were equally affected by the weather elements (*Figure 1*). In each planting medium, 25 seeds of Triticum aestivum wheat were planted (*Photo 1.*). The seeds were scattered in the centre of the pot and planted 1 cm deep, and then the soil mixes were watered uniformly with 2 decilitres of water. The mulch and clay balls were placed on top of the soil after germination and sprouting at a rate of 20%. The aim was to test water retention by growing the plants under uniform watering and environmental conditions until their root systems were developed and then to stop watering uniformly to simulate long periods of drought in summer. This allowed us to test the ability of a given soil mix to retain water and keep the plant alive. After the last watering, we sampled each soil mixture once a week to measure the amount of water retained. About 15 grams of soil was weighed out of the sample when wet and placed on a watch glass. The weight of the watch glass was recorded beforehand. The sample was dried for two weeks and weighed again on an analytical balance. The measurements were carried out for 13 weeks. The moisture content was calculated using the following *(2)* formula:

$$\mathrm{Tn\%} = \frac{(\mathrm{Tn}-\mathrm{O})-(\mathrm{Tsz}-\mathrm{O})}{\mathrm{Tn}} * 100 \quad (2)$$

where: Tn%: soil moisture percentage, Tn: mass of wet soil, O: mass of watch glass and Tsz: mass of dried soil (*Stefanovits et al. 1999*).

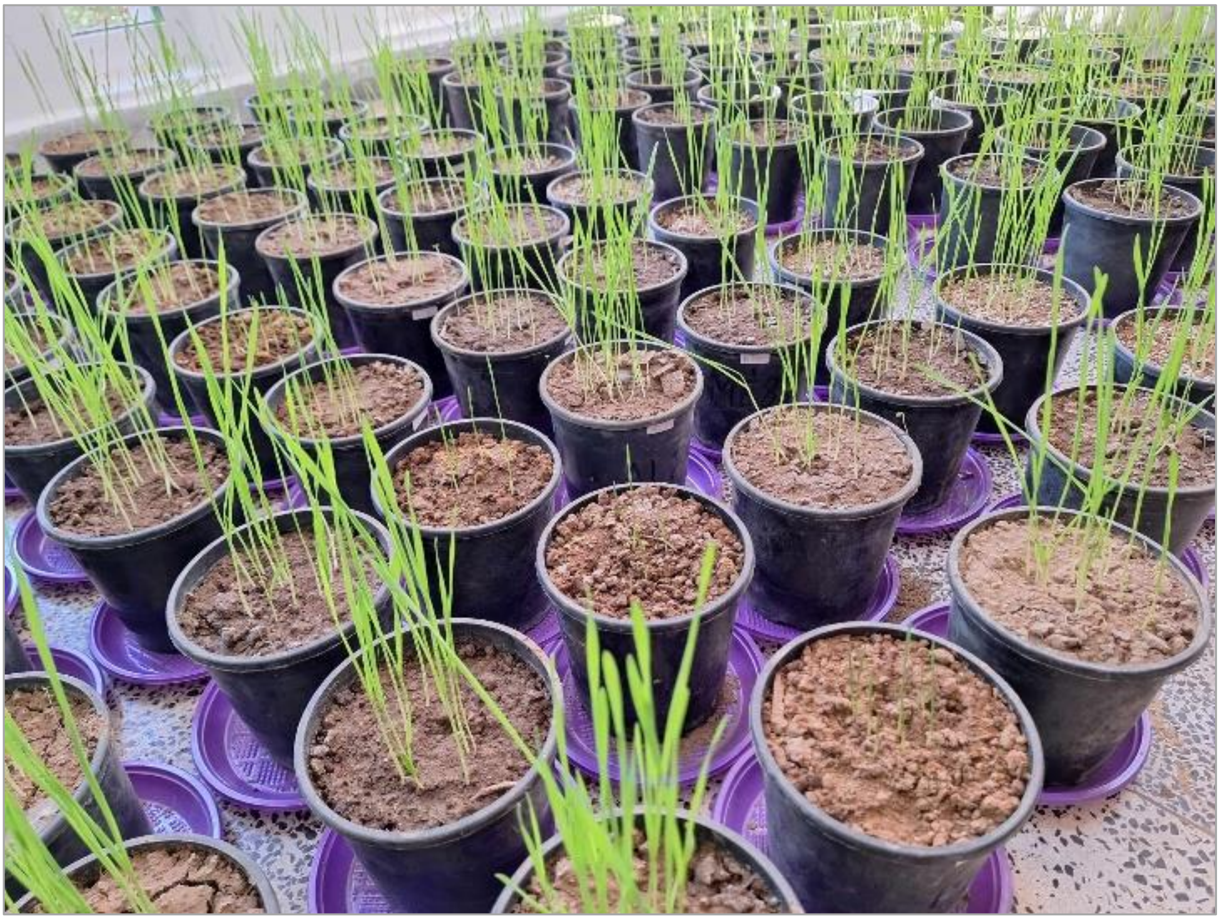

Photo 1. The 120 pots of wheat growing in 12 soil mixes (Photo by Z. Barocsai)
1 kép. A 120 cserép búza növekedése a 12 talajkeverékben (Fotó: Barocsai Z.)

PRESENTATION OF SOIL IMPROVERS

All our soil improvers are available in Hungary. They can be divided into two groups, organic and inorganic. Our organic materials are peat, cattle manure, cattle manure granules and compost. Inorganic materials: alginates, perlite, zeolite. Soil cover materials: mulch, clay pebbles. The map on *Figure 2* shows the soil improvers sites in Hungary.

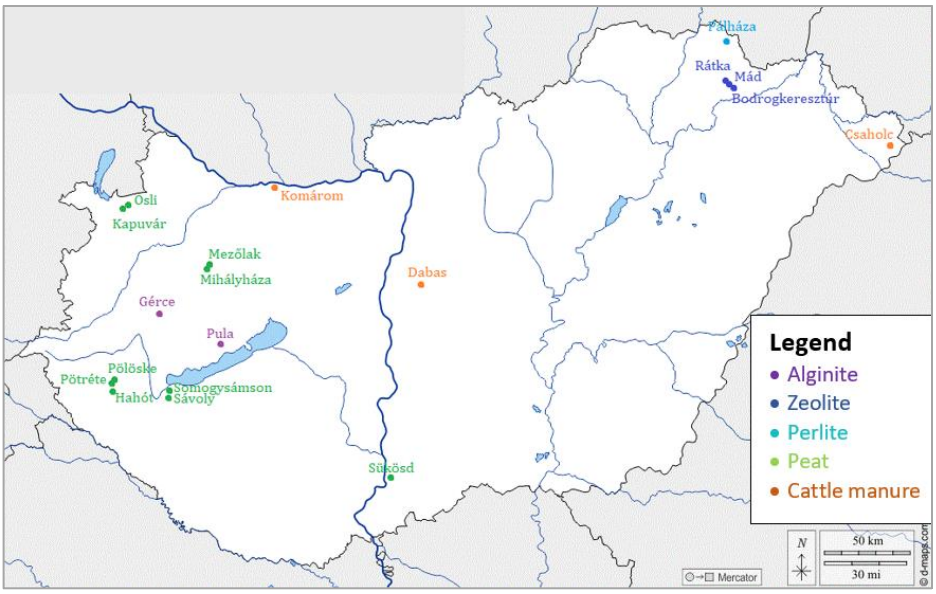

Figure 2. Soil improvers sites in Hungary [edited by B. Sánta and M. Frei based on Barkóczi and Szakál (2007), Dömsödi (2023), Kádár (2002), Hannus (2012)]
2. ábra. Talaj javító anyagok lelőhelyei Magyarországon [(szerkesztette: Sánta B. és Frei M., Barkóczi and Szakál (2007), Dömsödi (2023), Kádár (2002), Hannus (2012) alapján]

RESULTS

The analysis of the meteorological data

The evolution of the standardised precipitation index (*Figure 3*) shows that the distribution of precipitation between years has become increasingly extreme in recent decades.

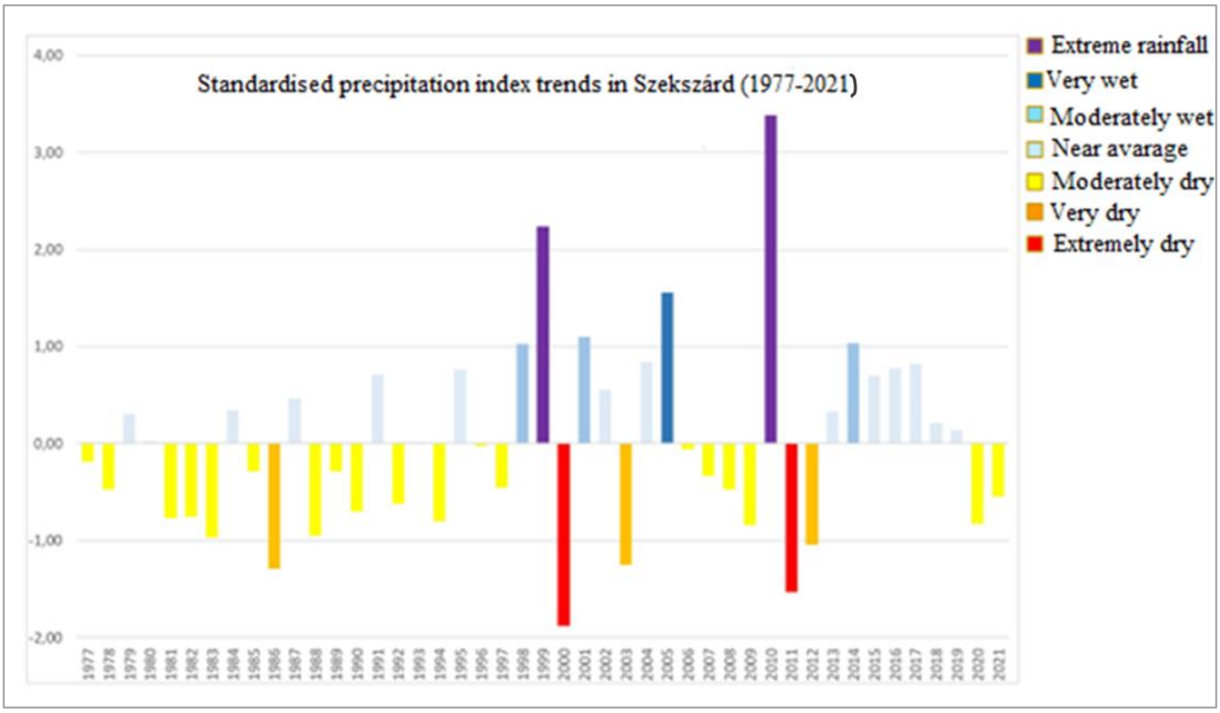

Figure 3. Evolution of the standardised precipitation index in Szekszárd (Hungary) (1977-2021)
3. ábra. A standardizált csapadékindex alakulása Szekszárdon (1977-2021)

As we move towards the present day, we are more and more likely to see years with extreme rainfall and years with extreme drought, even in succession. However, the area around Szekszárd would basically fall into the category between 1 and -1 (moderately dry-average-moderately wet) according to the national records.

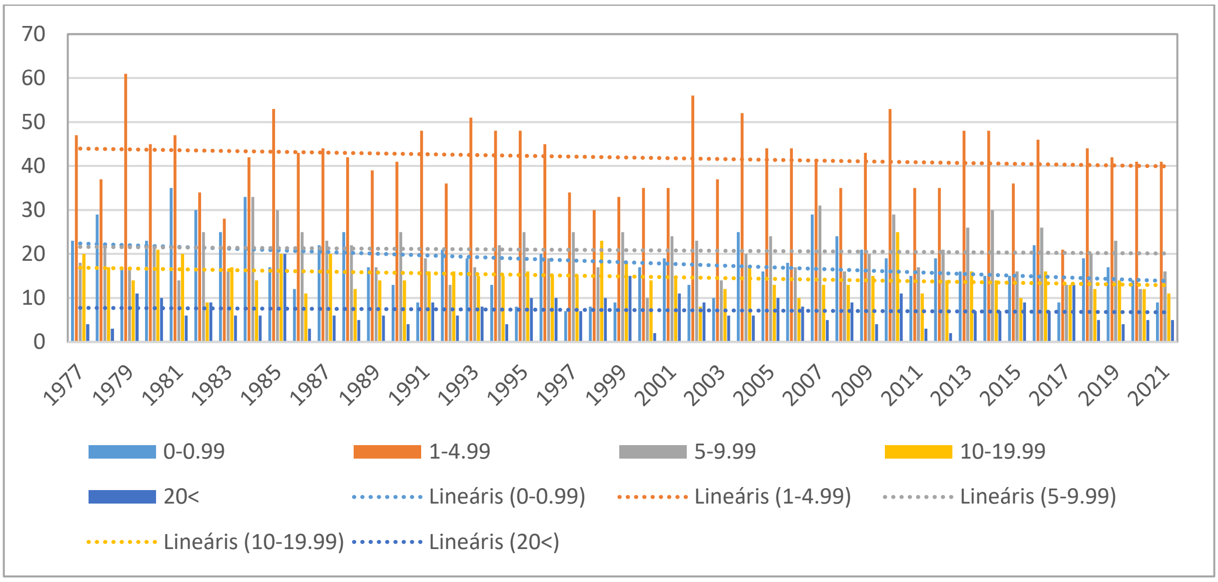

Figure 4. Number of different rainfall events in Szekszárd (1977-2021)
4. ábra. Különböző csapadékesemények száma Szekszárdon (1977-2021)

Looking at the different precipitation events (*Figure 4.*), we can see that the occurrence of precipitation types of below extreme precipitation has decreased in recent decades, while that of extreme precipitation has stagnated. Overall, this means that the same amount of precipitation falls but in fewer days whereas less rainfall, i.e. longer droughts and more frequent heavy rainfall events occur. Soils dry out for longer periods and the rainfall that does fall suddenly runs off, meaning that the soil may not be able to absorb the same amount of water as 40 years ago.

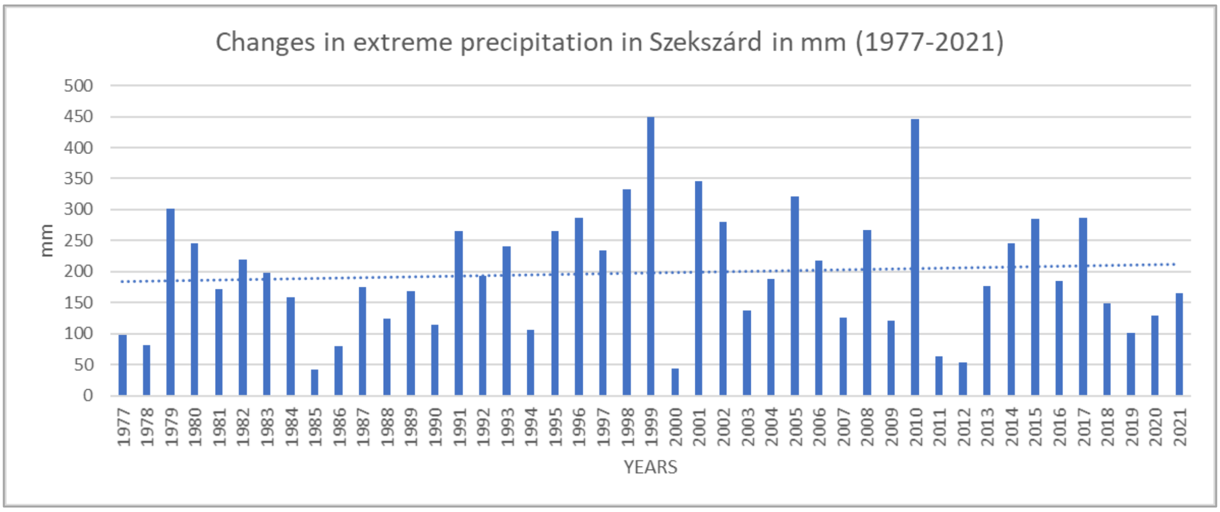

Figure 5. Variation of extreme precipitation in Szekszárd in mm
5. ábra. Az extrém csapadék változása Szekszárdon mm-ben

The amount of water falling as a result of extreme rainfall events is shown in *Figure 5*, which clearly shows an increase. These processes also result in flash floods, which further erode and erode the soil and cause a significant amount of water to run off the area. In sloping areas, it becomes even more difficult to retain rainwater in the soil.

Soil texture analysis

The soil samples clearly fall into the silt, silty loam category (*Figure 6*), which is typical of the loamy soils found in our area. Their water retention capacity is not bad, higher than that of sandy soils, but due to the relatively small space between the soil grains, their permeability is lower than in the case of sandy soils. As a result, these soils are less able to infiltrate sudden heavy rainfall and can store less water in the long term. After creating the soil mixtures, we also examined their grain composition and basically found that the texture of the soil was shifted towards the sand fraction, i.e. the silt and sand fraction started to balance out, but the silt fraction still remained the more. We believe that this has increased the permeability of the soil, meaning that vertical downward seepage may be greater in the event of an extreme rainfall event, but it has not lost any of its water retention capacity due to the water retention properties of the added materials.

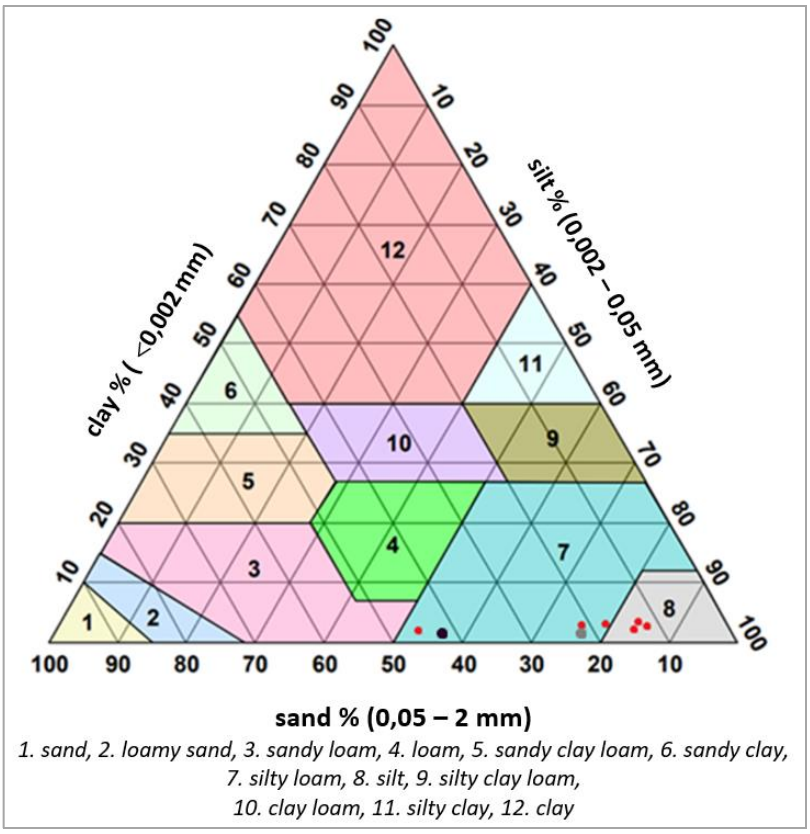

Figure 6. Determination of physical soil types of the tested soils (red: tested soils; grey: average of tested soils; black: average of tested soils with amendment) [Edited by B. Sánta and M. Frei, based on Füleky (2011)]
6. ábra. A vizsgált talajok fizikai talajtípusainak meghatározása (piros: vizsgált talajok; szürke: a vizsgált talajok átlaga; fekete: a vizsgált talajok átlaga módosítással) [Szerkesztő: Sánta B. és Frei M., Füleky (2011) alapján]

Analysis of humus content

The humus content of the tested soil samples (*Figure 7*) ranges widely, as low, medium and high humus content values were found. The highest humus content was found in the Szekszárd sample, the lowest in the Hidas sample. The average of the 7 samples was 3.07%. The large variation may be due to different farming practices, the use or absence of manure or fertiliser and different levels of soil erosion.

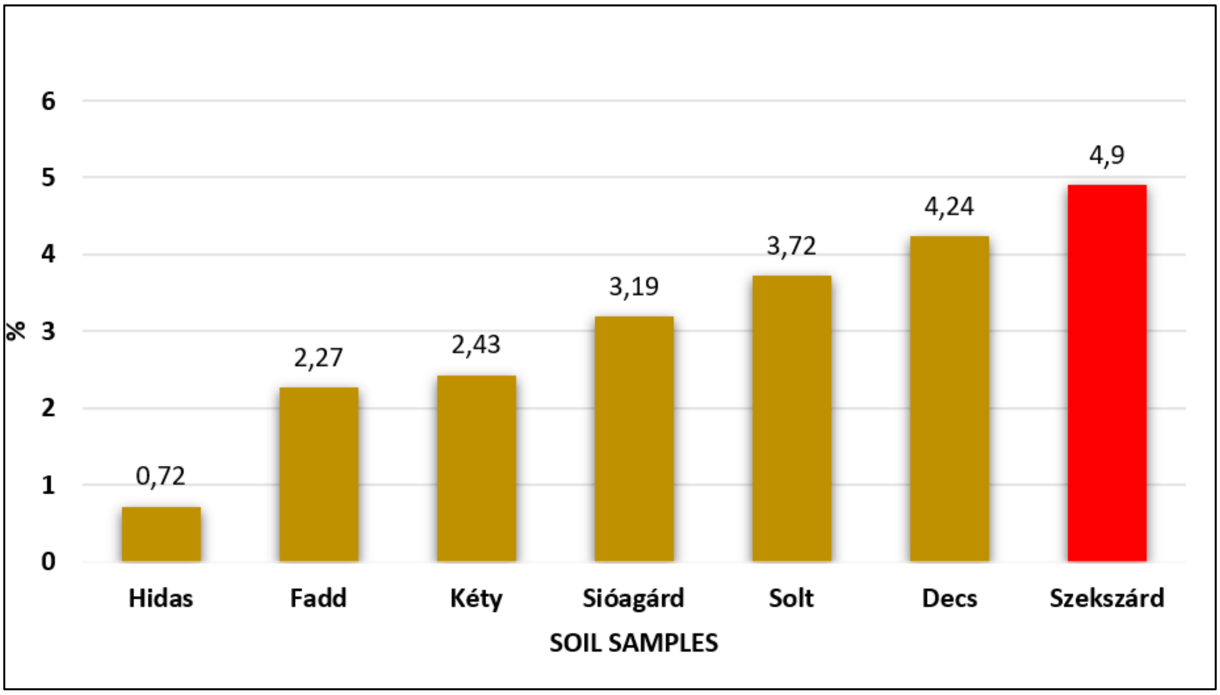

Figure 7. Humic matter content in soil samples in %
7. ábra. A talajminták humusztartalma %-ban

For the humus content of the soil mixtures, all but the base mixture (alginitic-zeolitic-pearlitic) showed an improvement (*Figure 8.*). No significant differences were expected for these soil amendments compared to the selected Szekszárd soil sample, as their organic matter content is either not significant or there is not any. The difference is not significant for the perlite and alginate soil mixes, but significant for the zeolitic mix. In the latter case the high value is due to the high phosphorus and potassium content of zeolite. The mixture with cattle pellets also does not show a significant increase, as confirmed by testing the mixture with wheat, where germination and growth were slower than in the other mixtures. At the end of the range are the peat, matured cattle manure and compost mixtures, which are not surprisingly placed as they have a significant organic matter content. The sample with the name "large mix" contains only 35% of the original soil, so the significant increase in humus content is not a coincidence.

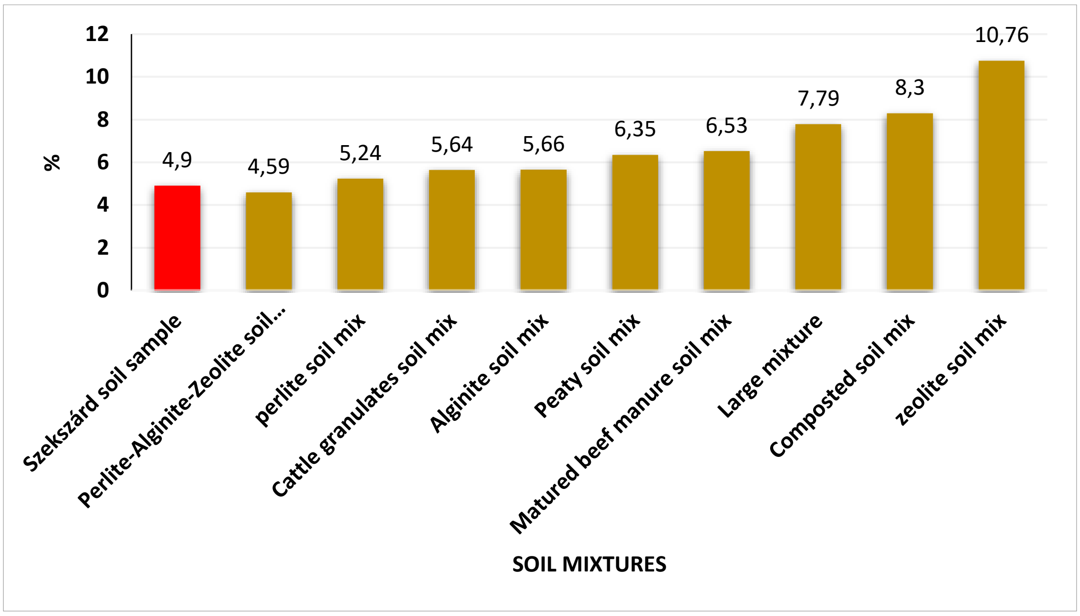

Figure 8. Humus content of soil mixtures in %
8. ábra. Talajkeverékek humusztartalma %-ban

Water retention capacity test

The water retention capacity of the soils tested (*Figure 9*) shows an average value of 28%. Of these, the sample taken in Szekszárd was the highest with a value of 43%. Together with the samples, potting soil was also tested, with a water retention capacity of 101%. Overall, the water retention capacity of the surrounding soils, which are mainly loess and floodplain soils, is not high. Most of our lowlands are also covered by loess soils and floodplain soils, which means that their water retention capacity may be similar. In our sandy areas (e.g. Nyírség, Kiskunság) the value may be even lower, as the coarser grain fraction has better permeability but lower water retention capacity. In the case of clay soils, the water retention capacity may be higher, but the permeability is lower, which makes it less effective in retaining the less frequent rainfall.

For the soil mixtures (*Figure 10*), the water retention increased except for zeolite. Nevertheless, zeolite may be suitable for soil improvement, but it had a negative effect mainly on sandy soils and on silty loam soils. The most significant increase in water retention was for the large mix, which contained 65% water retention enhancers. The peat and compost mixtures with high organic matter content also showed an outlier. Again, there was little variation in the cattle manure sample, so it not only does not add enough to the soil to increase humus content but also does not improve water retention. In general, it can be concluded that organic soil amendments contributed more to water retention and inorganic amendments contributed less.

The soil conditioners (*Figure 11*) alone confirmed the values in the previous diagram. Zeolite is weak while peat has a high water retention capacity.

PH measurement results

It is important to note that our crop and most of the crops we grow are most profitable in slightly acidic, neutral (pH 6-7) soils. When pH is shifted to extremes, either directly or indirectly, but always adversely, it will affect plant growth. Of the soil samples tested (*Figure 12*), one was in the slightly acidic range, one in the neutral range, and the others in the slightly alkaline range. The Szekszárd soil was a fortunate choice as its pH is in the ideal range for crop production. A pH value between 6 and 7 is where the uptake of most nutrients is close to the maximum. Changes in chemistry directly affect the solubility of nutrients.

Soil pH is basically in the neutral to slightly alkaline category and would shift even more towards alkaline with the use of soil amendments (*Figure 13*). The shift is not significant, the soil mixtures are still in the neutral to slightly alkaline category, which does not significantly affect the uptake of nutrients by the plant, but it is worth measuring when they are applied to get an indication of the extent of the shift.

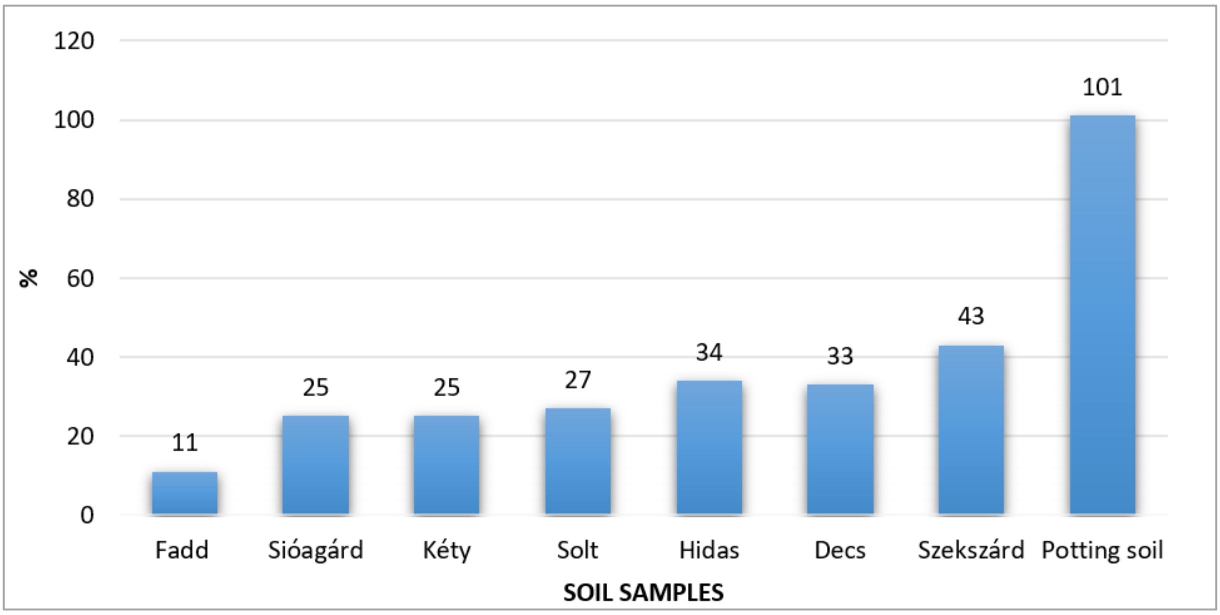

Figure 9. Soil water-retention capacity in %
9. ábra. Talaj vízmegtartó kapacitása %-ban

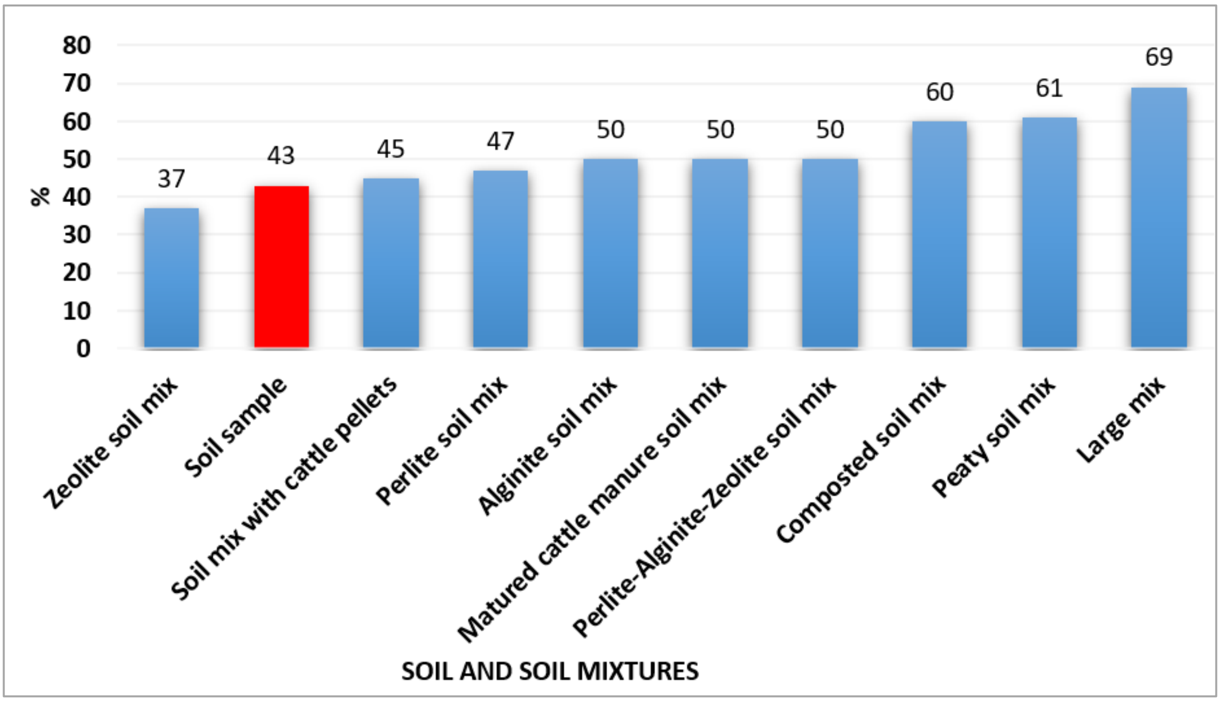

Figure 10. Water retention capacity of soil and soil mixtures in %
10. ábra. Talaj és talajkeverékek vízmegtartó kapacitása %-ban

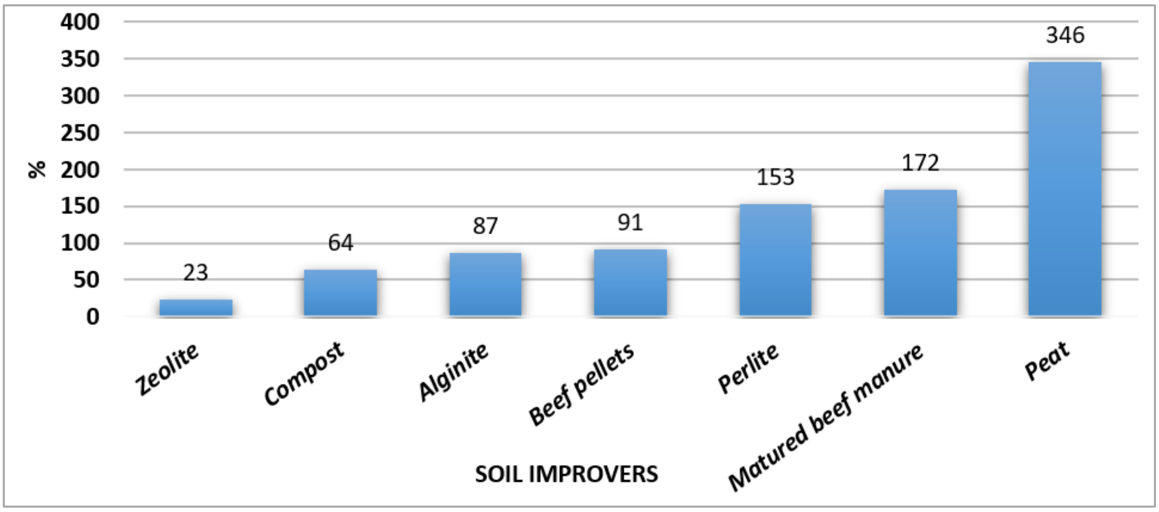

Figure 11. Water retention capacity of soil improvers in %
11. ábra. Talajjavító anyagok vízmegtartó kapacitása %-ban

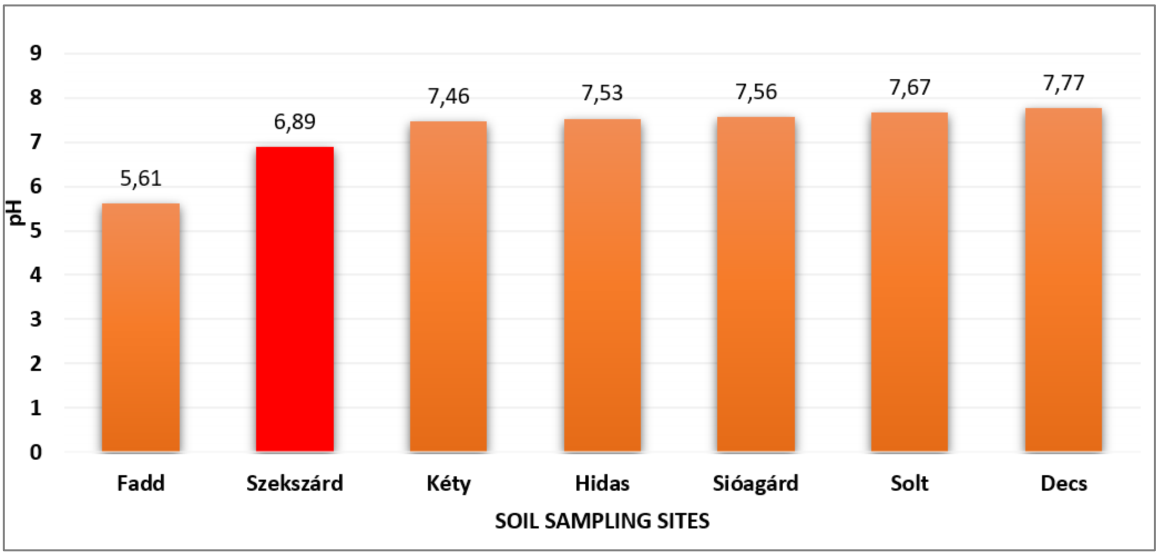

Figure 12. pH of soils around Szekszárd (0-30 cm)
12. ábra. Szekszárd környéki talajok pH-ja (0-30 cm)

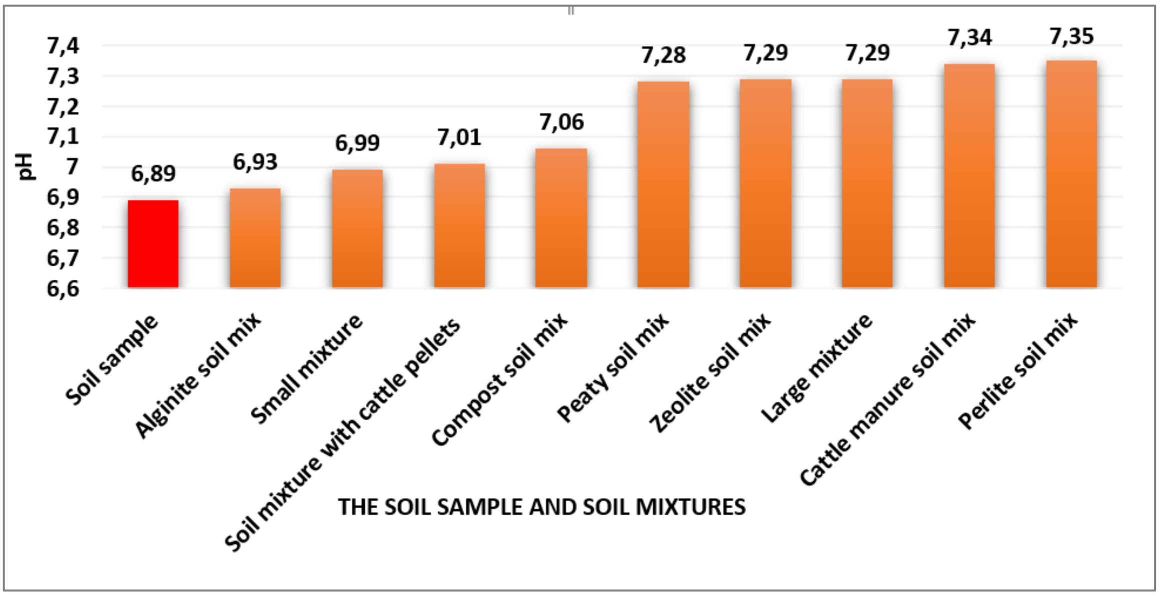

Figure 13. pH value of soil samples and soil mixtures
13. ábra. Talajminták és talajkeverékek pH értéke

LABORATORY TEST RESULTS FOR WATER RETENTION IN SOIL MIXTURES

The results of the test (*Figure 4*) showed (*Figure 14*) that soil collected from the Szekszárd area had the poorest water retention. It was characterised by a water retention of less than 10% throughout the period under study, decreasing to less than 5% from the 3rd to 4th week. At this value, all soil mixtures had a higher water retention. During the first 4 weeks they ranged between 10-30%, except for the large mixture (containing peat, cattle manure, perlite, compost, zeolite, alginate) as it only dropped from an initial value above 50% to below 30% after week 6 (*Photo 2*).

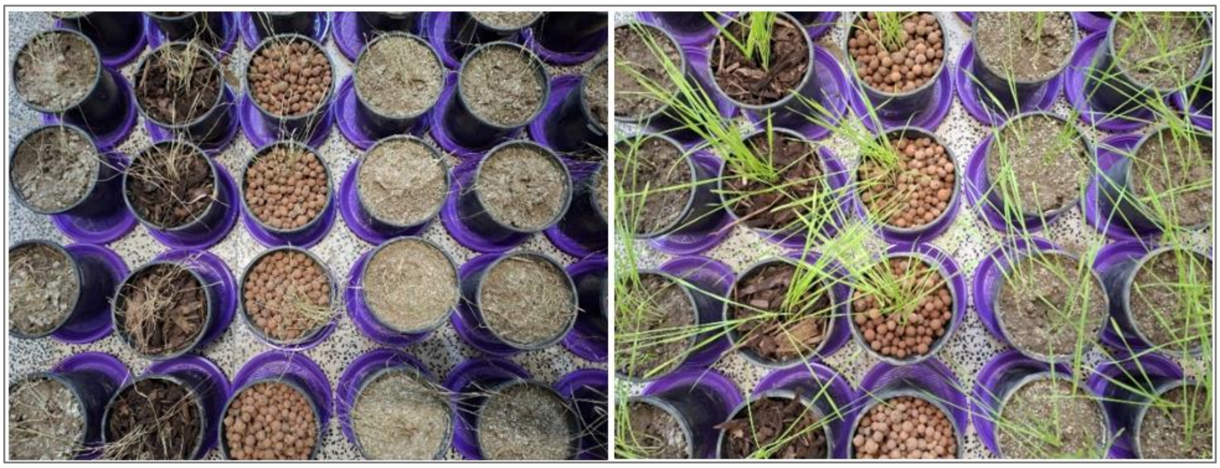

Photo 2. Soil mixtures at the beginning of the study (right) and after 6 weeks (left)
2. kép. Talajkeverékek a vizsgálat kezdetekor (jobbra) és 6 hét után (balra)

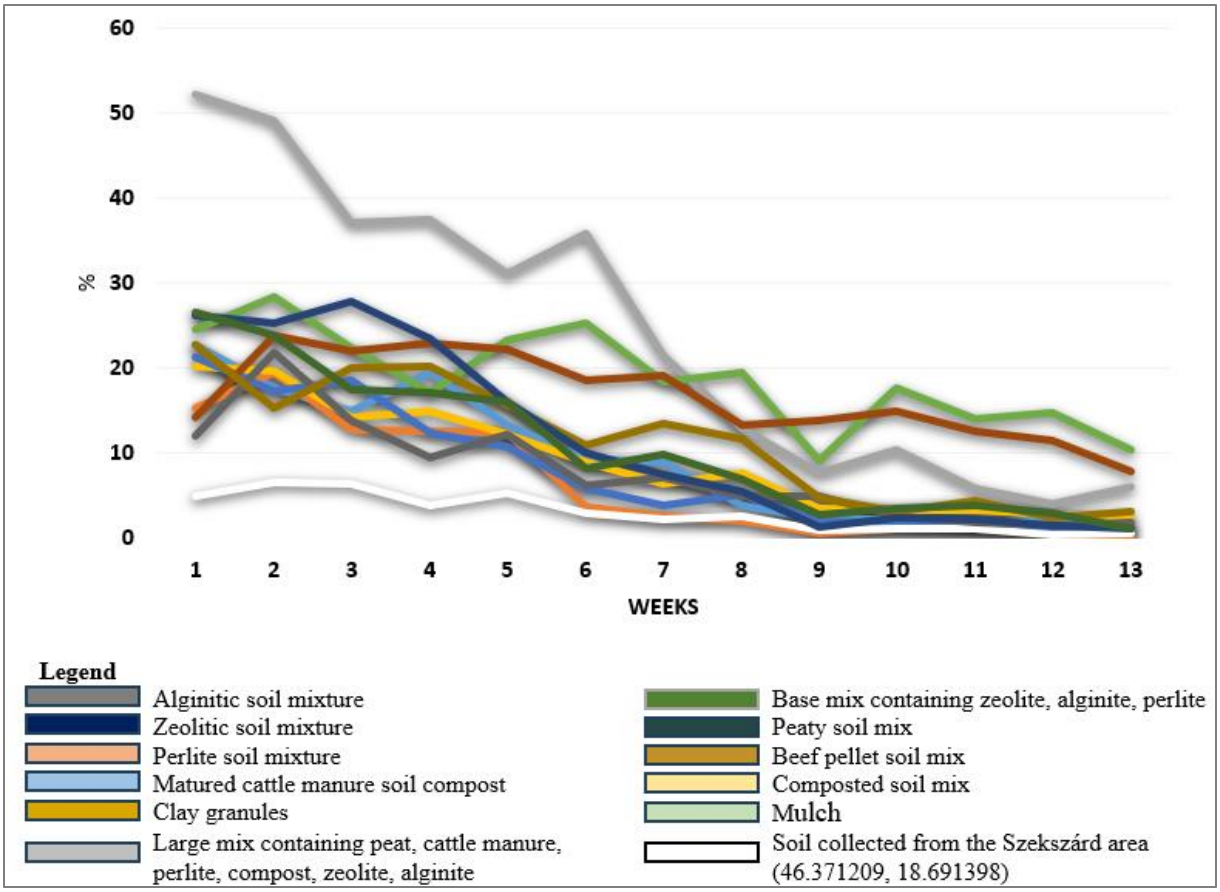

Figure 14. Laboratory testing of water retention capacity of soil mixtures
14. ábra. A talajkeverékek vízvisszatartásának laboratóriumi vizsgálata

Samples improved with soil cover (mulch, clay granules) also gave highly good results. Even after the 5th week, the soil water content was still above 20%, while the other samples apparently started to decline. Soils treated with soil cover were still retaining water significantly better at week 13. At week 6, the water retention of one of the soil mixtures (perlite) dropped down to the level of our soil sample for the first time, but from week 10 onwards none of the soil mixtures showed a significantly large difference from the soil sample. The wheat plants were gradually dying with water deprivation. Slightly earlier in the soils of poorer water retention capacity. In conclusion, our soil mixtures show on average higher results than our soil sample even after 7 weeks of drying, which means that we could retain significant amounts of water in the soil for several weeks or months during long summer droughts. If soil cover were applied in combination with mixtures, even better results could be achieved.

SUMMARY, CONCLUSIONS

We have succeeded in carrying out our planned studies. The analysis of meteorological data has confirmed the global and national trends of increasing extremes in the distribution of precipitation, i.e. less frequent but with an increase in extreme precipitation. The study revealed that the soils collected and tested in the wider area of our residence are classified as silty loam soils, silt loam soils, by texture. They are quite diverse in terms of humus content, due to different farming practices, the use or absence of manure or fertilisers and different levels of soil erosion. Soil pH is generally in the neutral to slightly alkaline category and would shift further towards alkaline with the use of soil amendments. They have a medium water retention capacity, and a lower permeability compared to a sandy soil, but they can retain more water. The use of soil amendments increases the sand fraction in their texture, which increases water permeability, but does not reduce water retention due to the water retention capacity of the materials. Laboratory testing of the soil amendments has confirmed our previous measurements, and we have been able to demonstrate that their application could retain significant amounts of water in our soils over the long term. Our country receives 112 km^3 of water per year from rivers coming from across the border, plus 6 km^3 of runoff from within the country. A bigger problem is that we have 117 km^3 of runoff, meaning we can retain relatively little and use only 1 km^3. In Hungary, a large part of the agricultural areas is characterised by loess soils like those around where we live or by sandy soils with poorer water management (Nyírség, Kiskunság). If we look at our samples, we find an average water retention of 43%. If 20% of the soil is supplemented with better water retaining materials, the water retention improves significantly. We have calculated 20% because that is what is usually recommended when soil amendments are applied. These soil amendments alone, on average, have a water retention capacity of 150%. Overall, we calculated that the water retention capacity of the soil would increase from 43% to 64.4% in this case. We have calculated that an area of 1 km^2 would retain 0.000172 km^3 of water, which means that for every 10 000 km^2 of area, this would be 1.72 km^3 of water. If the top 40 cm is upgraded with one of these materials and the upgraded value is used, this is 2.56 km^3 of water. This means that we can retain 0.86 km^3 of water per 10 000 km^2. Hungary's arable land use is about 55% of the country (agroinform.hu), or 51166.5 km^2. In total, we could retain 4.2 km^3 more water in this area than without the soil amendment. This would still not put us on a positive water balance, but it would move the country's water balance in a positive direction compared to the current one. If a smaller area or a less efficient increase in water retention capacity is expected, this value would decrease, but it would improve the water balance. So, this alone is not enough to solve the agricultural problems caused by climate change, but it could make a significant contribution. The construction of reservoirs and the use of additional irrigation could significantly improve or even turn positive the water balance of our country.

In the case of soil samples collected around Szekszárd, Hungary, soil samples, soil mixtures and soil amendments (perlite, alginate, zeolite, compost, peat, cattle manure) were analysed for texture, water retention capacity, humus content and pH, and finally, our soil samples, our nine soil mixtures and the two soil samples treated with soil cover were tested for water retention capacity by growing wheat in 120 pots under the same conditions for 13 weeks. The soils tested are silt, silty loam soils, with soil amendments mainly enhancing the sand fraction. The water retention capacity improved with the amendments; the humus content increased more significantly with organic amendments. The pH of the soil mixtures shifted the soil samples towards the alkaline direction. Soil mixtures and soils treated with soil cover were able to retain water to a greater extent than the soil sample.

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AUTHORS

BENEDEK SÁNTA I am a tenth-grade student of the Béla I. High School in Szekszárd, and I am a student of geo-digital culture. My interests are wide, but I am most interested in geography. I started researching our topic when I was in ninth grade, when we were learning about the relationship between soils and water in an advanced geography class. The topic appealed to me, and I became more and more motivated, luckily my geography teacher was supportive. I plan to continue my studies in this direction.

MÁRTON FREI I am currently a ninth-grade student at the Béla I. High School in Szekszárd, studying English and Computer Science. I have a wide range of interests, I like music very much, both listening and playing. My father is an agricultural engineer, so I have been exposed to and involved with materials used in research since childhood. I started working as a researcher in the autumn of 2023 and my interest in natural sciences, especially in water and soil geography, has grown in parallel. I have no plans for further studies yet and would like to try myself in as many fields as possible.

ZOLTÁN BAROCSAI I graduated from the Eszterházy Károly University (Eger, 2004) and the University of Pécs (Pécs, 2007) with a degree in geography and history. Currently I teach at the Béla I. High School in Szekszárd. I attach great importance to helping my students who want to do research in natural sciences. I have been conducting investigations with my students in the field of hydrology for more than ten years. Our research has been successful in national and international competitions and conferences.

Participants of the 2024 Hungarian final
A 2024. évi magyarországi döntő résztvevői

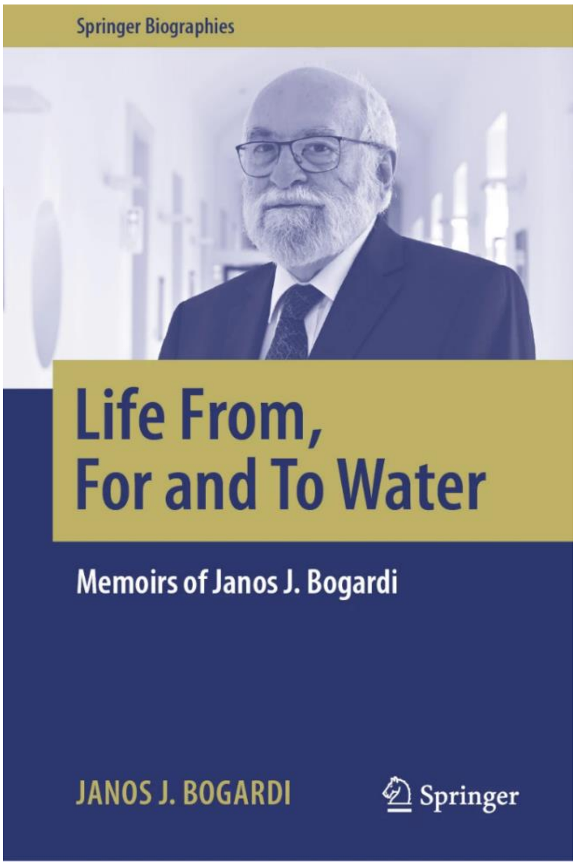
Book Review

In December 2022, **Professor János Bogárdi published his book titled "*I Am Made of Water, I Will Become Water – Why Does the World Revolve Around the Water Cycle?*"**, a summary of his more than 50-year professional career.

The volume was released under the initiative and coordination of the Scientific Water Council of the General Directorate of Water Management (OVF).

In 2025, **Springer Publishing published the English version of the book under the title "*Life From, For and To Water*"**, describing the book as: Motivation for those who search for a future profession and/or start their own "water career".

In the Introduction, we read about six extreme events that the professor refers to as pivotal moments in his professional life, which also provide the structural framework of the book: the Tisza flood (1970), the Zambezi drought (1981–1984), the Indian Ocean tsunami (2004), Hurricane Katrina (2005), the Cape Town water crisis (2017–2018), and the Ahr River flash flood (2021).



The next three chapters present János Bogárdi's active career in 15–17-year periods, while the fourth chapter summarizes the past decade, which he refers to as his "restless retirement years." The volume concludes with an Epilogue and seven appendices.

In the first chapter, *The Years of Becoming an Engineer and Researcher (1964–1979)*, the author discusses his choice of career, reflects on his university years, and recounts the fight against the 1970 Tisza flood. He attended a six-month postgraduate hydrology course in Padua in 1971, after which he sought and found work in West Germany. He earned his doctorate in Karlsruhe in 1979 with a dissertation on the role of flood retention basins in water management.

He also had the opportunity to gain experience outside the academic world. The second chapter, *The Years of Research, Consulting, and Teaching (1979–1995)*, recounts the drought in the Zambezi Basin and the challenges related to the Kariba Dam. Based on these experiences, he drew fundamental conclusions about water management.

From 1985, he taught at the Asian Institute of Technology in Bangkok. Reservoirs remained a central topic of his teaching and research. He and his students applied dynamic programming to revisit the earlier Kariba Dam question—how the disaster-level low water levels might have been avoided. His work also involved the operation of Taiwan's Feitsui Reservoir, where his first PhD student conducted research. In this section, Bogárdi's engineering philosophy is also presented.

From 1989, he served as head of department at Wageningen Agricultural University. His inaugural lecture was about the road toward integrated water management. The text is enhanced with commentary added from today's perspective. The chapter also recalls the "golden age" of scientific and educational collaboration in the 1990s, particularly the successes of the Erasmus and TEMPUS PHARE programs.

In 1995, he joined UNESCO's Water Sciences Division. The third chapter, *Science Management on and Beyond Water (1995–2012)*, describes this period. At UNESCO, Professor Bogárdi participated in many high-impact projects as a scientific diplomat, including water transfer from Lesotho to South Africa, and strategic planning for the Aral Sea and Volga Basin. Even 20 years later, his co-edited volume with Z. Kundzewicz, *Risk, Reliability, Uncertainty and Robustness of Water Resource Systems*, is still widely cited. He initiated the long-running project "From Potential Conflict to Cooperation Potential."

As the coordinator for education in UNESCO's International Hydrological Programme, Professor Bogárdi was involved in dozens of training courses worldwide, including the former VITUKI's International Post-graduate course. He also fought for four years to grant international institutional status to IHE Delft, a prestigious institute for water education, under UNESCO.

Between 2003 and 2009, he was founding director of the Institute for Environment and Human Security of the United Nations University. Following the Indian Ocean tsunami and Hurricane Katrina, the issue of environmental migration came to the forefront. Under his leadership, the institute quickly became a key player in scientific discourse on this topic.

Between 2009 and 2012, he led the revival of the international project office of the Global Water System Project, which focused on examining global water management interrelations and disseminating the findings.

The fourth chapter deals with his ongoing *restless retirement years (2012–)*. During this time, he chaired a UNEP committee tasked with drafting a guideline for a future international directive on the sustainability of aquatic ecosystems. He also organized a conference in support of incorporating a dedicated water goal into the Sustainable Development Goals adopted at the 2015 UN General Assembly.

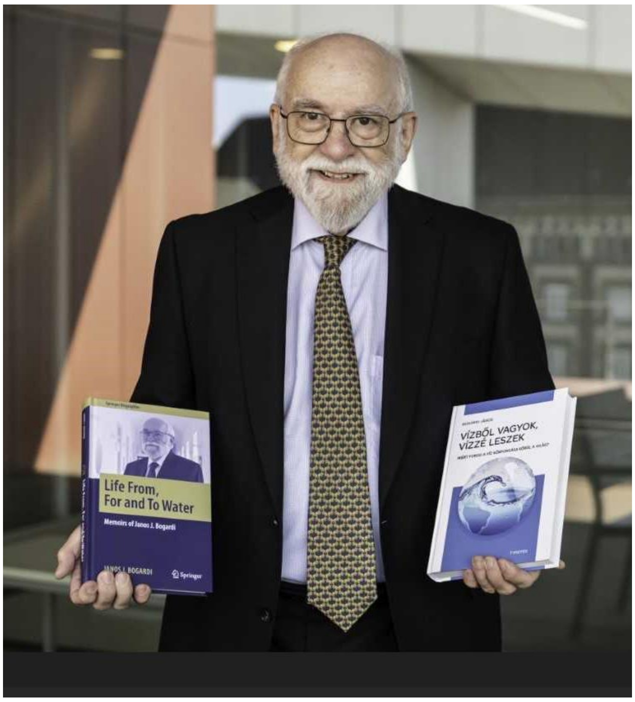
In 2021, he served as editor-in-chief of the *Handbook of Water Resources Management: Discourses, Concepts and Examples*, a volume with over 100 contributors, providing a comprehensive overview of ongoing professional debates, facts, theories, and methods to support decision-making processes.

Based on personal experience, he reflects on the failure of flood protection in the Ahr River valley in the summer of 2021, which resulted in over 100 deaths in one of the world's most developed regions.

In the Epilogue, titled *Four People, Four Dimensions*, he reflects on the four individuals who most shaped his career. Among all his achievements, Professor Bogárdi is most proud of his students, in whom he places his hope for the continuation of scientific progress.

Today, Professor János Bogárdi contributes his knowledge and experience to the Institute of Advanced Studies in Kőszeg (Hungary). Since 2023, Professor János Bogárdi has been a research professor at the Faculty of Water Sciences at the Ludovika University of Public Service. His autobiographical volume is not only insightful but also highly engaging.

Dr. József Gayer
Member of the Editorial Board of *Hungarian Journal of Hydrology*

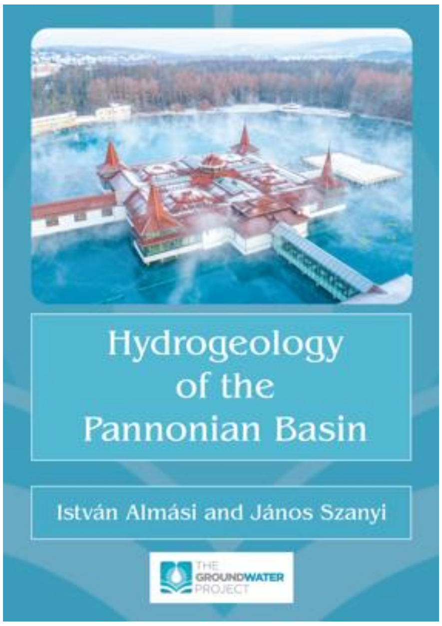


At the presentation of Professor Bogárdi's oeuvre volume on June 24, 2025, at the Ludovika University of Public Service

Book review

István ALMÁSI and János SZANYI (2021): Hydrogeology of the Pannonian Basin,
Publisher: The Groundwater Project, Guelph, Ontario, Canada, 2024,
Printed version: 73 pages https://doi.org/10.21083/978-1-77470-044-0

The book *Hydrogeology of the Pannonian Basin* is part of the "Important Aquifer Systems of the World" series created by *The Groundwater Project*, as the Pannonian Basin is one of the world's most complex sedimentary aquifer systems, shared by nine countries.



The Groundwater Project is a non-profit organization established in 2017 under the leadership of Dr. John Cherry, with the mission of solving problems related to groundwater and improving the accessibility of groundwater knowledge. To achieve this goal, it produces and provides high-quality educational materials on groundwater free of charge in several languages, all available for download on its website (www.gw-project.org), including this book.

Authors István ALMÁSI and János SZANYI aim to present the development of groundwater knowledge in the Pannonian Basin from a historical perspective and to convey the concept that moving groundwater should be considered a geological factor, as it can mobilize, transport, and deposit both heat and materials. The book primarily focuses on Hungary, which covers nearly three-quarters of the Pannonian Basin, while also offering insight into the hydrogeology of neighbouring countries, since the basin contains many of Europe's transboundary aquifers.

The book is divided in eight substantive chapters, complemented by exercises and their solutions to deepen understanding of the content.

The first four chapters introduce the hydrogeological environment — geology, topography, and climate — which shaped the complex hydrogeological features, including geothermal conditions, and how these have developed, persisted, and been utilized over the past two millennia. A clear and illustrative figure presents the chronology of key events. It is emphasized that, in addition to its abundant drinking water resources, the Pannonian Basin is particularly renowned for its geothermal wells, thermal spas, and the modern use of geothermal energy. The book describes two superimposed flow systems in the central part of the basin: a gravity-driven shallow system and an over pressured deep system. The existence of these systems is supported by results of isotopic and water chemistry studies from previous publications, presented in an accessible manner. The figures are well-developed and aesthetically pleasing, significantly facilitating understanding. Furthermore, the authors conducted an extensive literature review.

At the end of Chapter 4, the authors thoroughly present Dr. József Tóth's theory of gravity-driven flow systems. Tóth emigrated from Hungary to Canada in 1960, where he pioneered the development of modern thinking about gravity-driven groundwater flow. His influence on the authors is significant, as they both attended his hydrogeology course 30 years ago, which marked the beginning of a close friendship and professional collaboration.

In the second half of the book, the authors discuss the types and temporal changes of water usage, the various forms of geothermal energy utilization, and its impacts on groundwater. In the chapter on oil hydrogeology, they thoroughly explain the similarities and differences between hydrocarbon and groundwater flow, highlighting that they often occur in the same reservoir — information that is especially important for medium- and high-enthalpy geothermal energy use. The overpressure systems were also discovered during petroleum exploration in the last century.

Overall, this book is a highly valuable resource for university education and even for curious high school students. It provides a clear and comprehensive summary of nearly two centuries of hydrogeological knowledge of the Pannonian Basin. A Hungarian translation is also expected to be published, which will undoubtedly attract an even wider audience.

Together with the authors, I encourage readers to make beneficial use of this book and discover further fascinating details about the basin and the geothermal processes occurring at the boundary zones of its surrounding limestone mountains. The book is available for download at the following link: https://gw-project.org/books/hydrogeology-of-the-pannonian-basin/

Happy reading!
László LÉNÁRD