

Research Article

Synergies in agriculture and nature conservation through hydrological restoration of ecologically valuable and cultivated wetlands in the drought-prone Hungarian Plain (Central and Eastern Europe)



Zsolt Pinke^{a,b,*}, Tamás Acs^c, Bence Decsi^c, Máté Krisztián Kardos^c, Matyas Arvai^b, Veronika Fabók^d, Jenő Zsolt Farkas^e, Zoltan Gribovszki^f, Dora Hidy^g, Peter Kalicz^f, Zoltán Kern^h, Andras Donat Kovacs^e, Eszter Tormáné Kovácsⁱ, Laszlo Pasztor^b, Zsolt Kozma^c

^a Department of Physical Geography, Eötvös Lorand University, Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary

^b Institute for Soil Sciences, HUN-REN Centre for Agricultural Research, Fehérvári út 132-144, H-1116 Budapest, Hungary

^c Department of Sanitary and Environmental Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, H-1111 Budapest, Hungary

^d Mungo-Consulting Ltd., Budapest, Hungary

^e HUN-REN Centre for Economic and Regional Studies, Institute for Regional Studies, H-1097 Budapest, Hungary

^f Institute of Geomatics and Civil Engineering, University of Sopron, Bajcsy-Zs. u. 4, H-9400, Hungary

^g HUN-REN-MATE Agroecology Research Group, H-2100 Gödöllő, Hungary

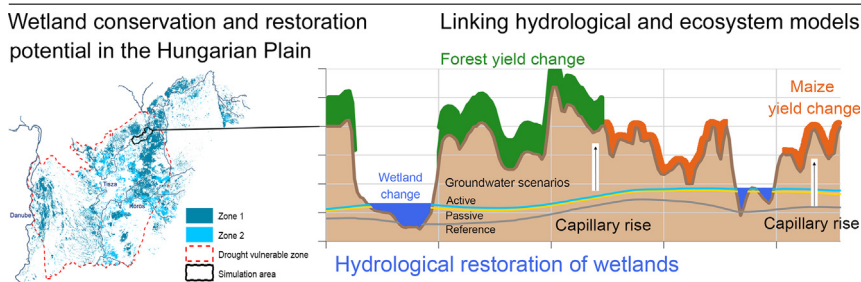
^h Institute for Geological and Geochemical Research, HUN-REN Research Centre for Astronomy and Earth Sciences, Budapest, Hungary

ⁱ Department of Nature Conservation and Landscape Management, Institute for Wildlife Management and Nature Conservation, Hungarian University of Agriculture and Life Sciences, Páter Károly u. 1, H-2100 Gödöllő, Hungary

HIGHLIGHTS

- Wetland restoration provides mutual benefits for nature conservation and agriculture.
- Rewetted wetlands improve soil hydrological conditions for the nearby ecosystems.
- Shallow water table could yield 44 %–67 % more maize than deep one.
- Hydrological restoration of wetlands increase cereal yields in their environment.

GRAPHICAL ABSTRACT



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ABSTRACT

The establishment of a sustainable land use system integrating the mitigation capacity of wetlands is crucial in the plains of the temperate zone. Following the approaches of green infrastructure development programs and the spatial planning framework, two zones with potential for wetland conservation and restoration were selected in the Hungarian Plain (Central and Eastern Europe) covering an estimated 21 % of the landscape. Then, linking hydrological and ecosystem modelling tools, we estimated the groundwater recharge that would result from a hydrological restoration and its impact on surrounding maize fields with different groundwater levels and soil conditions. The amount of groundwater recharge ranged between 367 m³ ha⁻¹ and 552 m³ ha⁻¹; thus, the horizontal impact of the hydrological restoration as indicated by the ratio of the extension of the groundwater impact area and surface water in the May–August period, would be almost 2:1. Croplands in transition zones between high terraces and wetlands may reap the greatest benefit from the hydrological restoration of wetlands

* Corresponding author.

E-mail addresses: pinkezsolt@gmail.com, pinke.zsolt@atk.hun-ren.hu (Z. Pinke), acs.tamas@emk.bme.hu (T. Acs), decsi.bence@emk.bme.hu (B. Decsi), kardos.mate@emk.bme.hu (M.K. Kardos), arvai.matyas@atk.hun-ren.hu (M. Arvai), fabok.vera@gmail.com (V. Fabók), farkas.jenozsolt@krtk.hun-ren.hu (J.Z. Farkas), gribovszki.zoltan@uni-sopron.hu (Z. Gribovszki), dori.hidy@gmail.com (D. Hidy), kalicz.peter@uni-sopron.hu (P. Kalicz), kern.zoltan@csfk.hun-ren.hu (Z. Kern), kovacs.andrasdonat@krtk.hun-ren.hu (A.D. Kovacs), kovacs.eszter@uni-mate.hu (E.T. Kovács), pasztor@rissac.hu (L. Pasztor), kozma.zsolt@emk.bme.hu (Z. Kozma).

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due to its edge effect, which results in more balanced year-to-year yields on fine-grained soils. This is what has led to an estimated 20–28 % increase in maize yields in such zones. The results of the investigation confirm the hypothesis that the hydrological restoration of wetlands may effectively mitigate increasing climate risk in drought vulnerable plains. These findings, complemented by the abundance of other services (e.g., flood regulation) provided by restored wetlands shed light on the intersectoral prospects of the hydrological restoration of wetlands in Europe.

1. Introduction

No other ecosystem has suffered more serious destruction by humans than wetlands in Europe (Davidson, 2014; IPBES, 2019). The ratio of lost European wetlands is an estimated 84 % (Schleupner and Schneider, 2012)—much higher than on other continents. Riparian floodplains are among the greatest victims of this human transformation of the land (Mills et al., 2023; Verhoeven, 2014), as they serve predominantly as places of agricultural production today (Davidson, 2014; Demeter et al., 2020). One of the largest wetland conversions in Europe took place in the Hungarian Plain (Central and Eastern Europe) (Timár et al., 2024). Here, as elsewhere, cutting floodplains from rivers and draining wetlands has been responsible for the emission of an incalculable amount of greenhouse gases (Mitsch et al., 2013; Dybala et al., 2019; Schuster et al., 2025), the increased vulnerability of landscapes to extreme hydrometeorological events (e.g., floods and droughts), and has also led to a serious loss of (ground)water dependent species (Kløve et al., 2011; Mills et al., 2023). Today, the intertwined anthropogenic pressures and the impacts of climate change exacerbate groundwater depletion and soil water loss (Wada et al., 2010; Pinke et al., 2022), hydrometeorological hazards (Alfieri et al., 2015) and biodiversity loss in Europe (EEA, 2020; Hochkirch et al., 2023).

In recognition of the role of wetlands in biodiversity, as well as their capacity to regulate climatic and hydrological processes (Hatvani et al., 2022; Neubauer and Verhoeven, 2019) wetland restoration is prioritised in the European Union (EU) environmental policy (EEA, 2017; European Commission, 2020), as well as in the global Sustainable Development Goals (Finlayson et al., 1999; Qu et al., 2024). To support the goals of EU ecosystem conservation and restoration and promote the improvement of ecosystem services through integrating biodiversity strategies into spatial planning and natural resource management, the concept of green infrastructure has been introduced (Hermoso et al., 2020). As a part of these efforts, the European Environmental Agency has developed a sophisticated method to identify the restoration potential of forests and grasslands with regard to abiotic conditions, ecological status and the potential social conflicts in relation to restoration: this, however, did not focus on wetlands. Following the recommendations of the European Environmental Agency planning methodology for green infrastructure (EEA, 2014), the Hungarian green infrastructure strategy identified potential areas of forest and grassland restoration, too; it did not, however, define wetland restoration potential (Banhidai et al., 2021). Meanwhile, the restoration potential of wetlands was identified in the water management plans (Grizzetti et al., 2019), although the procedures used in the identification of targeted wetlands vary widely; e.g., hydromorphological assessments are limited in the river basin management plans, and the relative weight assigned to wetland restoration is small in the targeted measurements (Mosselman et al., 2015). According to the European Environmental Agency synthesis based on data reported by Member States, the area of wetland habitats that require restoration amounts to at least 27,100 km² (EEA, 2022; Verhoeven, 2014). This represents 16 % of the total area of existing wetlands (EEA, 2022), and yet this figure even so almost falls beneath the threshold of detection in terms of the total loss of wetlands that once covered an estimated a quarter of the current land area of the EU (Schleupner and Schneider, 2012). In line with this, Hungarian river basin management plans defined wetland restoration potential within the narrow active flood-

plains of the rivers (30–1000 m), the flood conveying areas bordered by levees (OVF, 2009, 2022), which covers <5 % of the total wetlands lost over the last 150 years (Amisshah et al., 2018). Such a territorially restricted wetland restoration may well be incapable of having a significant impact on hydrologic fluxes, and thus it cannot support effective mitigation of the climate challenge at the landscape scale (Pinke et al., 2020). This underlines the necessity of mapping restoration potential with regard to temporary and permanent wetlands with a degree of sophistication similar to that employed with forests and grasslands in Europe (EEA, 2014). Europe is the most cultivated continent, and as a target of the EU common environmental and agricultural policy, a major part of the protected areas is maintained within agricultural landscapes (Polakova et al., 2011). Agricultural lands have, however, been subject to widespread abandonment in certain European regions, and the process is predicted to accelerate in the future mainly in remote, and less productive lands. Meanwhile, the majority of cultivated wetlands, and therefore the wetland restoration potential, is situated in these marginal lands (Lóczy et al., 2016).

Regarding these spatial aspects and the intrinsically strong relationship between surface and groundwater fluxes (Sophocleous, 2002), as well as the importance of shallow groundwater dynamics in water dependent semi-natural habitats (Decsi et al., 2020; Garamszegi et al., 2022; Kløve et al., 2011) or agro-ecosystems (Mercau et al., 2016; Kozma et al., 2022) groundwater conservation via wetland restoration is of common interest to both agriculture and nature conservation, and especially in the drought-prone plains. Therefore, the question of whether groundwater recharge through systematic and controlled flooding qualifies as managed aquifer recharge is the subject of intensive research (Levintal et al., 2023). Although previous analyses have dealt with the impact of groundwater-based artificial irrigation on cereal yields (Sun et al., 2015), the groundwater-rainfed crop yield relationships have been scarcely touched upon (Mercau et al., 2016; Pinke et al., 2020). Although forests can survive only by utilising any subsurface water surplus in drought-prone lowlands of Europe such as the Hungarian Plain (Herceg et al., 2019), the interdependence between shallow groundwater and forest growth is also an underresearched issue (Skiadareisis et al., 2019; Roebroek et al., 2020; Szabó et al., 2023). For instance, the climatic water demand of the Pedunculate oak (*Quercus robur* L.), a dominant species in lowland forests of the Hungarian Plain is ca. 650 mm to 700 mm of water per year (Gombasi et al., 2015). In many parts of the plain, however, precipitation is below the threshold, so available soil water plays an important role in meeting the water demand of the Pedunculate oak. Quantification of groundwater demand and the actual use of forests together are the key to getting a clear picture of drought thresholds (Groover et al., 2025; Li et al., 2023; Matyás et al., 2018). Accurate groundwater evapotranspiration estimates are, however, challenging because parameterisation is affected by uncertainties related to measured and modelled environmental variables (Gou and Miller, 2014). In the absence of the knowledge on the biophysical background of wetland edge effect on the yields of surrounding cultivated areas and forests, the provisioning and drought mitigation services of wetlands remain underestimated (Xu et al., 2020).

In light of the foregoing knowledge gaps, our aims are:

(i) To accurately define the physical framework of hydrological impacts on the surface and subsurface waters in a simulation area driven by hydrological restoration in cultivated wetlands;

(ii) To reveal the response of surrounding arable lands and forests to the restored hydrological (biophysical) fluxes in a simulation area by examining

(ii-a) yield changes in maize due to altered groundwater supply in arable lands, and

(ii-b) the interdependence between groundwater fluctuation and the ecophysiology and growth rate of a floodplain forest.

(iii) To provide a methodological approach by identifying the wetland restoration potential of the Hungarian Plain based on the results of the hydrological simulation and adopting the spatial planning framework of green infrastructure development programs in Europe.

2. Materials and methods

2.1. Study areas

2.1.1. The hungarian plain

The plain studied (45°93'N–48°33'N, 18°69'E–22°83'E) is located in the temperate-continental climate zone (Fig. S1a–e and Fig. S2 in the Supplementary materials), and covers a considerable part of the Pannonian Biogeographic Region. The most characteristic landscape types are fluvial floodplains covered by mainly hydromorphic soils with a high clay fraction, loess ridges with fertile loam-dominated soils, and aeolian sandy plateaus and ridges (Mezosi, 2017) (Fig. S1b). Hungary is reckoned to be among the driest countries on the continent (Pinke et al., 2022), and the landscape in question is the most drought-prone part of the country. As a result of the 19th–20th century modernisation of agriculture, wetlands were drained almost totally (>95 %) by an extensive channel system. Today, cultivated wetlands cover an estimated 30 % of the landscape regularly inundated by inland excess water (Pasztor et al., 2013). Nonetheless, two-thirds of drained wetlands have preserved considerable remnants of natural ecosystems, and thus, have become protected areas over recent decades (Table S1a in the Supplementary materials). In numbers, 39 % of the Hungarian Plain now belongs to the Pan-European Ecological Network including the Natura 2000 network (22 %) and the High Nature Value Farming System (22 %) (Table S1a). Despite the protection, the increasing drought vulnerability of the plain has pushed these habitats to the brink of extinction. To preserve such habitats, e.g., the last remnants of Pannonic steppe-forests, the hydrological restoration of wetlands has become unavoidable (Erdős et al., 2018; Molnár et al., 2012).

2.1.2. Ohat simulation area and the ohat forest

The scene of the hydrological simulation is a flood-protected lowland catchment (243 km²) situated along the River Tisza, near to Lake Tisza, an artificial reservoir created in the 1970s (Fig. 1). The landscape is characterised by primarily alluvial loam-silt-clay soils in floodplains and aeolian sand-loam compositions in ridges that developed in different periods of the Late Pleistocene and Holocene (Timár and Gábris, 2008). The relief of the site is low, differing by approximately only seven metres between the top of the eroded terraces and the bottom of silted meanders. Land cover ratios are basically similar to those of the Hungarian Plain (Fig. S1c; Table S1a).

The study area of the forest hydrological monitoring was the Ohat Forest (19.7 km²) lying in the centre of the simulation area (Fig. 1; Fig. 2a, 2b). The forest is a Natura 2000 site under ecological restoration by the Hortobágy National Park Directorate. Steppe oak forests formerly occupied extensive areas of the Hungarian Plain (Erdős et al., 2018). One of their largest remnants is the Ohat Forest (Fig. 1; Fig. 2), growing on the saline clay soil of the bank of a drained floodplain, the eroded ridge of an early Holocene meander of the River Tisza (Fig. 1). Today, the river flows at a distance of 6–7 km from this forest. The mean height of the middle-aged oak forest stand is about 26 m with a mean trunk diameter (at a height of 1.3 m) of 0.35 m (Fig. 2a, 2b).

2.2. Analyses

2.2.1. Hydrologic modelling: wetland edge effect on the groundwater regime

Using the MIKE Zero integrated hydrological model we assessed the territorial impact of three water management scenarios on the surface and the groundwater levels (depth measured from the surface) within the Ohat simulation area (Fig. 1) for the period of May–August between 2000 and 2010: (i) a reference scenario mirroring current water management practices, where the channel system redirects inland excess water away from the protected floodplain, (ii) a 'passive' scenario that consists of the retention of inland excess water via the omission of the drainage channel to evaluate the effects of the drainage activities and the hydrological consequences of undisturbed lowland catchment processes, and (iii) an 'active' water management scenario which goes further than the previous scenario by actually channelling floodwater of the River Tisza towards floodplains, to examine a combined approach of nature-based flood risk mitigation and managed aquifer recharge (for technical details of the modelling see Table S2, Table S3, Fig. S3a–c, and Fig. S4 in the Supplementary materials). By modelling the hydrological dynamics of the study area, the effects of water management measures were identified for the 2000–2010 period. As part of this, using a daily time step and 50 m spatial resolution we simulated all key processes of the near-surface terrestrial water cycle, including snow hydrology, interception, vegetation root water uptake, evapotranspiration, surface flow, unsaturated zone seepage, and groundwater flow. The inundated terrain surfaces and the subsurface areas of impact of rising groundwater levels in the active hydrological scenario were regarded as the precisely delineated actual framework of potential hydrological restoration for the Ohat simulation area.

Finally, we considered the groundwater impact area as the region where the average May–August period (critical for corn yields) experienced at least a 10⁻¹ m increase in groundwater level in the active management scenario compared to the reference one. When the 10⁻¹ m threshold of groundwater level increase was defined to delineate the groundwater impact area, data and model uncertainties as well as the range of model outputs were considered (Table S4 and Fig. S5a–b in the Supplementary materials). Next, we defined the space requirement of water retention as the average April water coverage exceeding a 10⁻² m deep threshold in the active management scenario. Surface conditions in April are critical for crop cultivation work, and areas affected by inundation or full saturation are not suitable for tillage or sowing. The typical range of micro-topography in flat croplands is 10⁻³ m to 10⁻² m (Liu et al., 2024a; Verhoest et al., 2008). This micro-scale topography occurs mostly as a result of tillage and other agricultural activities. The applied 50 m × 50 m cell size smoothes out the fine topography; simulated water coverage therefore generates a bias of the order of 10⁻². We investigated the effect of this threshold on impact area (Fig. S6a–l and Fig. S7 in the Supplementary materials) and selected 10⁻² m water depth as a reasonable threshold value was considered.

2.2.2. Cereal crop modelling: wetland edge effect on maize yields

To reveal the expected impacts of the 'passive' and 'active' water management scenarios (see Section 2.2.1) on maize yields, the dominant crop in the Ohat simulation area, we used the BiomeBGC-MuSo v7.0 terrestrial ecosystem model (Hidy et al., 2012). This biogeochemical model is capable of simulating the upward capillary flow from groundwater (Hidy et al., 2022), making it suitable for assessing the influence of shallow groundwater and soil moisture interactions on nutrient and carbon balance, crop physiological processes and yield responses. Three monitoring wells (well IDs: 2680, 2683 and 2684 on Fig. 1) with different topographic elevations and groundwater depths were selected to reflect the topographic heterogeneity and groundwater availability of the Ohat simulation area (Fig. 1; Fig. 5). The reference scenario for the maize yield modelling, in line with the hydrological modelling baseline, corresponds to the past/current conditions without water management

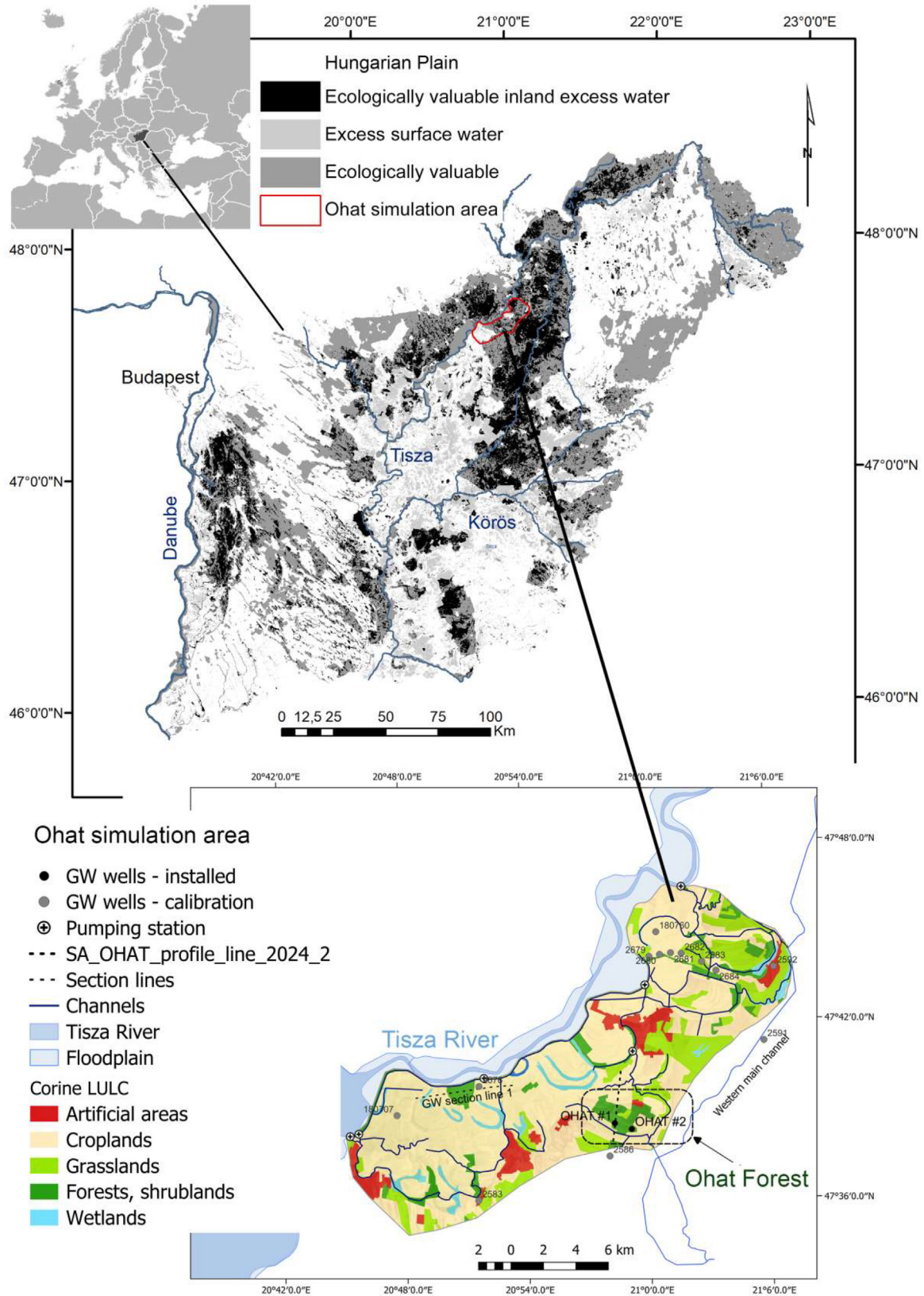


Fig. 1. Study areas. Ecologically valuable areas with inland excess water: the intersection of ecologically valuable areas (the sites of Pan-European Ecological Network) and areas with a > 20 % probability of inland excess water inundation (Pásztor et al., 2015); Inland excess water: inland excess water occurrence with a > 20 % probability, but without ecologically valuable status; Ecologically valuable areas: the sites of the Pan-European Ecological Network without or with a < 20 % probability of inland excess water inundation. Additional data sources: Land cover (Ministry of Agriculture, 2022); GW wells: groundwater wells.

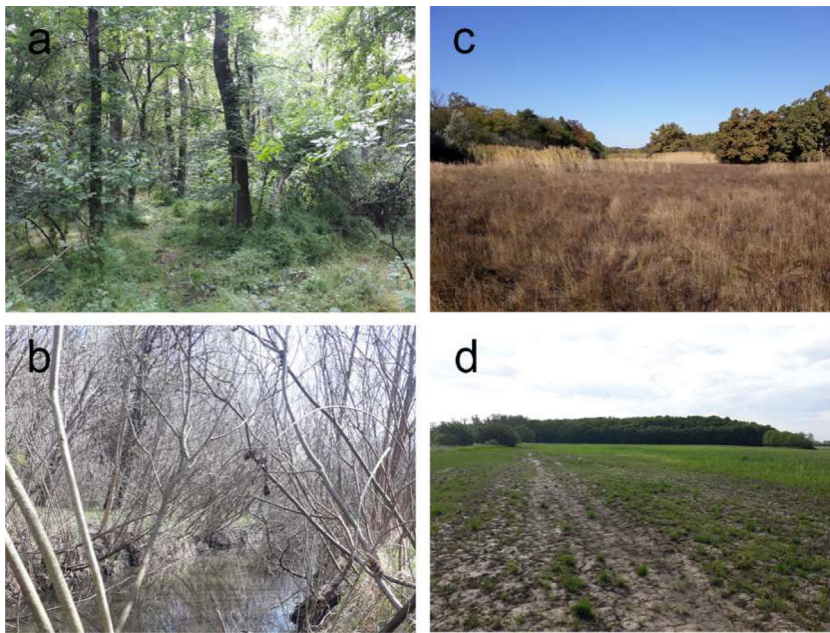


Fig. 2. (a) Characteristic picture of the Ohat Forest in May 2021; (b) Temporary wetland in a steppic open field of the Ohat Forest in October 2021; (c) Drainage channel on the border of the forest; (d) Fully saturated soil shortly after a seasonal inland excess water inundation in a cropland next to the forest in May 2021.

measures. For this, daily groundwater levels in the three monitoring wells covering the 1971–2010 period were employed as bottom boundary conditions in the BiomeBGC-MuSo model. Inconsistencies and data gaps in the raw measured groundwater level time series were handled using a simple water balance model based on daily precipitation and potential evapotranspiration (Fig. S8 in the Supplementary materials). Next, altered groundwater levels as the results of the ‘passive’ and ‘active’ water management scenarios simulated by the hydrological model for the locations of the monitoring wells were used as alternative crop yield scenarios. Meteorological data as atmospheric drivers of the model were derived from the open-access 0.1° gridded Carpatclim database (Szalai et al., 2013).

While the variations in the seasonal and interannual groundwater level fluctuation reconstructed for the three wells showed high degree of similarity ($r \geq 0.93$) (Fig. S8) in the 1971–2010 period, the average groundwater depths differed significantly (Table S5 in the Supplementary materials), allowing for the evaluation of the role of groundwater availability in maize production at different topographical zones within the study area. The degree and dynamics of groundwater level changes simulated using the hydrological model for the passive and active water management scenarios varied greatly between the three monitoring wells (Fig. 1; Fig. S5). Retention of inland excess water resulted in only a minor increase in the water table (depth measured from the surface) between 2000 and 2005 due to the below-average precipitation sum in the period. Groundwater levels actually decreased in this scenario in 2003–2004, as omitting the channels built primarily to drain inland excess water eliminated the occasional ‘loosing-stream’ effect, and hence, the groundwater stabilising function of the channels in the dry periods. The years in each of the groundwater scenarios in which sowing could not be carried out due to the groundwater table being higher than -0.5 m in the sowing period of maize (mid-April to late May) (Pinke et al., 2022), were excluded from the analysis. Interestingly, the positive effect of a one-time inundation of the low-lying areas with riverine floodwaters in 2003 lasted right through the period to 2010.

For the model setups three soil profiles characteristic of the area were selected: clayey loam, silty clay and loamy sand soil profiles in the upper 2 m, while homogeneous sand was assumed to be present below 2 m in all profiles, reflecting the general stratigraphy of the study area. Input soil hydraulic parameters were the same as those used in the hydrological model, while management and plant phenology parameters were taken from a former countrywide crop assessment (Fodor et al., 2021). The modelling time-frame was divided into three temporal phases:

- 1) A multi-decade spin-up period in which grassland was assumed as land-use (currently the model does not support crop production spin-up), imitating pre-cultivation conditions. The aim of the spin-up was to supply the default ‘empty’ soil with water, nitrogen and organic matter.
- 2) The period between 1971 and 1999 with maize production to allow the dynamic equilibrium of soil water, nitrogen and organic matter to develop under cultivation and under different groundwater-influenced conditions.
- 3) A simulation period of maize yields between 2000 and 2010 (the same period chosen for the hydrological modelling) starting with the initial conditions of soil water, nitrogen and organic matter provided by the 2nd phase.

No measured maize yield records allowing for formal model calibration were available for the simulation area. Therefore, maize yields were simulated for the profile with clayey loam in the upper 2 m (characterising more than half of the croplands in the county) with a free drainage bottom boundary condition (no groundwater impact, often referred to as a rainfed condition) were compared with county-level statistical yield records between 2000 and 2010 (KSH, 2025) (Fig. S9 in the Supplementary materials). Then, yields calculated in the 3rd modelling phase for the different groundwater scenarios were evaluated.

2.2.3. Groundwater level in the Ohat forest

Forest groundwater uptake generally shows a strong correlation to forest growth (Ciruzzi and Loheide II, 2021; Pilas et al., 2007; Roebroek et al., 2020). Furthermore, the groundwater replenishment rate of dry periods has a strong correlation to groundwater transpiration and thus to the biomass production of groundwater dependent forests. The methods for estimating evapotranspiration and replenishment of groundwater are based on the observed diurnal variation of groundwater table dynamics, which has two main phases: daytime, when plant transpiration decreases the groundwater levels, and at night, when the decreased plant transpiration gives an opportunity for the replenishment of the groundwater table (Loheide et al., 2005). Data on groundwater level have been collected at two sampling points since 2021 in the Ohat Forest (Fig. 1; Fig. S10 in the Supplementary materials). Following White (1932), the diurnal fluctuation of groundwater table was used to calculate the groundwater replenishment rate during dry periods as follows

$$\text{Recharge} = S_y \times 24 \times R \quad (1)$$

where 'Recharge' is daily groundwater replenishment from below (mm/day); 'Sy' is the specific yield of the aquifer: 0.134, as determined by soil texture type following [Loheide et al. \(2005\)](#); and 'R' is the hourly recharge in the late-night period (mm/hour). To exclude the effect of precipitation on forest evapotranspiration and groundwater replenishment only those days when the rainfall total was ≤ 5 mm in the previous 5 days were considered for the analysis. Diurnal fluctuation and the analysed replenishment rate of the dry periods are induced by the water uptake of the vegetation. Therefore, diurnal signals in the groundwater time series refer to groundwater uptake by the vegetation. If the diurnal signal weakens, the water uptake is less as well. Beside these monitoring data regional composite monthly groundwater depth was calculated measurements available from three groundwater monitoring wells surrounding the Ohat Forest (Fig. 1; Fig. S11a in the Supplementary materials). The composite mean groundwater level fluctuation record (Fig. S11b) was scaled to the monthly mean water table record of Ohat well 1 (Fig. 1, Fig. S10) using the mean and the standard deviation of their overlapping period (06.2021–08.2023) to represent the long-term fluctuation of groundwater levels beneath the Ohat Forest.

2.2.4. Identifying wetland conservation and restoration potential in the Hungarian plain

Due to the limited resources of the analysis there is no possibility of simulating hydrological processes over the entire Hungarian Plain (41,478 km²). The selection of wetland restoration potential, however, claims to be based on the delineated pattern of potential water accumulation. There have been a number of attempts to map the actual and potential location of wetlands, all differing in their spatial coverage, degree of resolution, the question of which environmental data are considered, plus, which observations and methodology. For Europe, the Copernicus Corine Land Cover and the Water and Wetness products provide observation-based wetland datasets for water accumulation maps (Copernicus, 2019, 2025). [Schleupner and Schneider \(2012\)](#) attempted to delineate Europe's 'wetland conservation potential' combining soil, climate, slope, and elevation factors in a GIS environment. However, due to the spatial resolution of the global digital elevation model (GTOPO30) they used (30' \sim 1 km²), it was not possible to determine most of the geomorphological features of plain landscapes ([Schleupner and Schneider, 2012](#)), which are one of the main locations of wetland formation. Moreover, [Schleupner and Schneider's \(2012\)](#) analysis considered neither inhabitancy, nor ecosystem or hydrological conditions, and therefore possesses only a limited potential for the delineation of areas suitable for and capable of restoration. To summarise: although, there are a number of conceptual frameworks, including some of those under development, such as [Murányi and Kocsos \(2022\)](#), which aim to estimate the flood reservoir potential of deep surfaces in the Hungarian Plain, currently there is no large-scale map of wetland restoration potential for the region.

To fill this gap, we followed the approaches taken by green infrastructure development programs that have emerged in the EU and Hungary ([Banhidai et al., 2021](#); [EEA, 2014](#)), as well as the main documents of the spatial planning framework in Hungary, and selected two zones in the Hungarian Plain with wetland conservation and restoration potential. First, the following were excluded from the analysis: areas where socioeconomic pressure may be presumed to be high (artificial areas of the land use land cover base map of the National Ecosystem Map of Hungary ([Ministry of Agriculture, 2022](#)) (Table S1a); areas with good-excellent agro-ecological potential ([Pásztor et al., 2013](#)); and the waters of the National Ecosystem Map of Hungary. Second, the areas of the Pan-European Ecological Network including the Natura 2000 sites and recorded in the High Nature Value Farming Systems were defined as ecologically valuable areas (Department of Energy, 2022). In this study we especially focus on wetlands identified by the accumulation probability (0 % to 100 %) of inland excess water that was estimated at a resolution of 1 ha for the studied part of the Hungarian Plain considering soil, climate, slope, groundwater levels, land use-land cover and the

remotely sensed inland excess water ([Pásztor et al., 2015](#)). The areas of inland excess water potential were correlated with the areas covered by water, as simulated in the active hydrological scenario at the Ohat site (Fig. 1; Fig. 3), where the inundated surfaces were regarded as precisely identified areas of potential wetland restoration. Based on this local scale comparison, the surfaces where the probability of inundation was 10 %–20 % provided the best match, therefore, the surfaces where the probability of inundation is >20 % were selected as input data in the analysis of wetland restoration potential. Then, the intersection of ecologically valuable (ecological indicator), nitrate vulnerable areas ([Németh et al., 1998](#)), and as the areas regularly inundated by inland excess water with at least 20% probability (abiotic indicator) were selected to represent Zone 1. Next, the areas with low and moderate agro-suitability (a socio-economic indicator), and without ecologically valuable status were selected to represent Zone 2. In Zone 1, the conservation and restoration potential of wetlands was obvious ([EEA, 2014](#)), and economic pressure against restoration was presumably relatively low due to medium or weak soil productivity. In confirmation of this point, in the northern part of the Hungarian Plain, socio-economic investigations have pointed out that the narrowing perspectives of agricultural production have already contributed to a reduced aversion towards the hydrological restoration of wetlands ([Fabok et al., 2023](#)). Next, the areas with wetland restoration potential but without conservation potential (Zone 2) were selected through the intersection of the areas regularly inundated by surface water with at least 20 % probability, and the areas with low and moderate agro-suitability without ecologically valuable criteria. Finally, a sub-zone of Zone 2 was selected in which, due to high drought vulnerability, not only the restoration potential, but the economic potential of restored hydrologic fluxes provided by balanced and growing yields is also explicit. We also emphasise that wetland restoration potential in any urban environment was not examined here due to its different list of considerations; the present analysis was restricted to rural areas (which in any case constitute 94 % of the simulation area) (Fig. 1).

3. Results

3.1. Hydrologic modelling: wetland edge effect on groundwater fluctuation

Evaluating the three simulated water management scenarios enabled site-specific conclusions about lowland hydrological regimes to be drawn. The reference scenario showed that groundwater levels are dominated by meteorological conditions, terrain morphology, the drainage network, and land cover conditions (Fig. 4; Fig. S4, Fig. S7). The periodic impact of groundwater driven by rainfall or snowmelt driven recharge in the winter season and the depletion induced by evapotranspiration during the vegetation period are well represented by the fluctuation of the simulated groundwater storage, as are the multiannual drought in 2001–2004, the drought years of 2007 and 2009, and the wet years accompanied by inundations of inland excess water in 2006 and 2010 (Fig. S4). Beside the temporal variations, the spatial pattern of the groundwater table, governed by surface elevation, is also a factor of lowland hydrology: deep floodplains and meander scars (abandoned riverbeds) are characterised by a shallow groundwater table, and eroded terraces by a deeper one. In fact, the elevation of the groundwater phreatic surface follows a much smoother pattern (Fig. 4) and the rapid changes identified on the groundwater depth map can be attributed to the more distinct terrain morphology. The drawdown effect of channels is indicated by groundwater depressions in the vicinity of the drainage network (Fig. 3). A strong depression in the average groundwater levels under forests is obvious in all scenarios (Fig. 4). Depending on the scenario, the maximal drawdown underneath the wooded areas is ~ 0.5 –1.2 m, while the horizontal impact area is 400–500 m.

Calculations for the passive scenario revealed that the area inundated by inland excess water would double by elimination of the drainage network. Additionally, the analysis highlighted the area of influence and

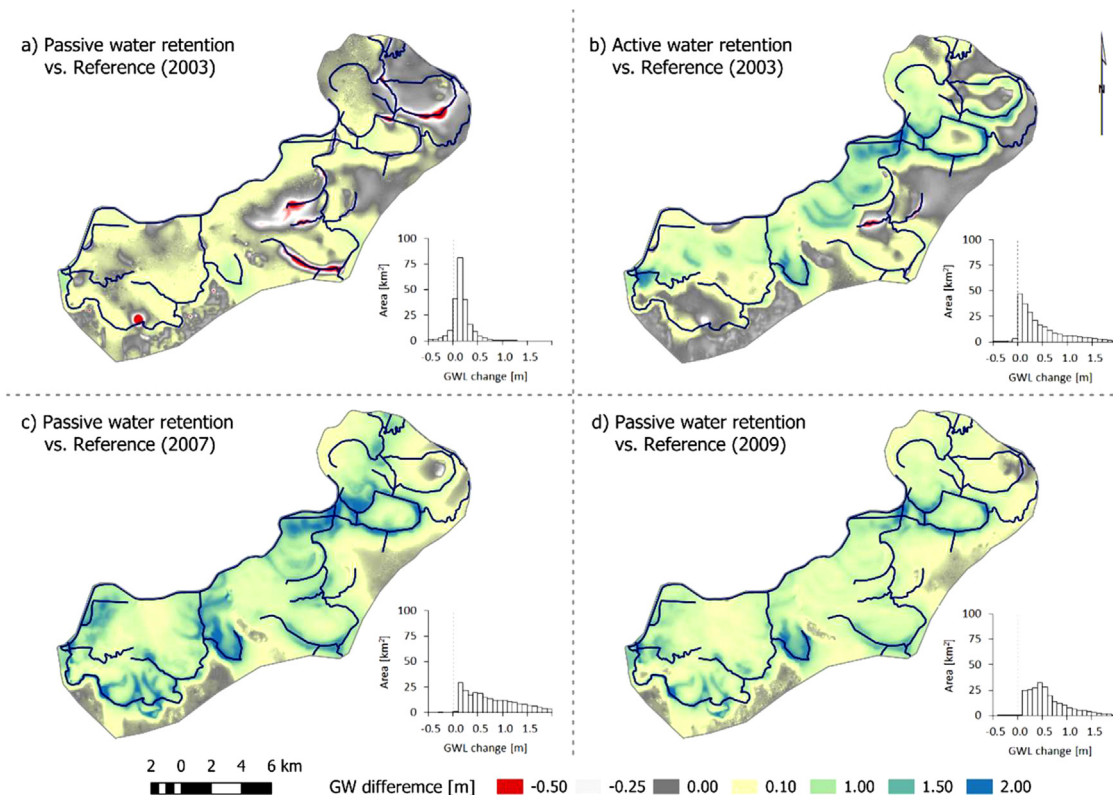


Fig. 3. Comparison of the simulated May–August average depths of groundwater table for selected years and scenarios at the Ohat simulation area; passive water management versus reference scenario in drought affected years (a, c, d); active water management (flooding) versus reference scenario for 2003 (b) Positive values (blue shades) indicate increasing groundwater levels compared to reference scenario, negative values (red shades) indicate decreasing ones. Histograms indicating the areal distribution [km²] of groundwater level differences [m] between the compared scenarios.

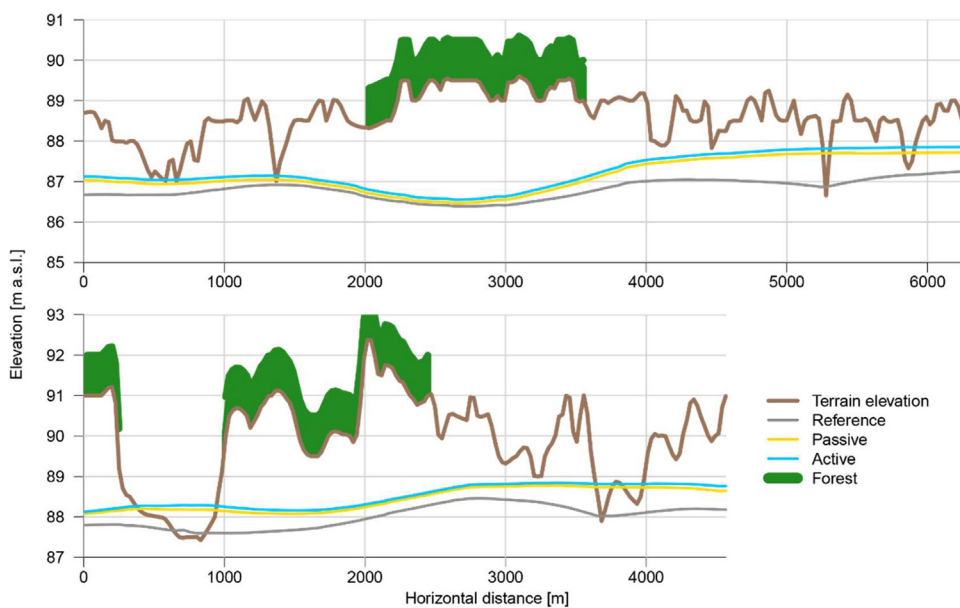


Fig. 4. Terrain surface (black curve) and average level of May–August groundwater at the Ohat simulation area along two groundwater section lines (1, 2) indicated in Fig. 1 for (i) the reference (yellow curve), (ii) the ‘passive’ (green curve) and (iii) the ‘active’ (blue curve) water management scenarios. Forested areas are highlighted with green stripes. m.a.s.l.: metres above sea level.

drawdown effect of the drainage network, which was notably extensive in the deep floodplain but surprisingly limited in meander-terrace regions. Comparison of the reference and passive water management scenarios resulted in substantial changes not only in water coverage duration but also in time-averaged groundwater levels (Fig. 3; Fig. 4). Moreover, a close linear relationship was found between the horizontal and vertical impacts of surface water on groundwater. Halting drainage operations via channels led to an average 0.34 m rise in groundwater levels

for the May–August periods of each year, albeit with noticeable spatial variations. Conversely, the contrast between passive and active water management scenarios was less distinct, contributing an additional 0.08 m increase on average in groundwater levels for the May–August periods within 2000–2010. The estimated differences in groundwater storage corresponded to 367 m³ ha⁻¹ and 552 m³ ha⁻¹ of precipitation respectively across the simulation area, equating to 6 % and 10 % of the annual precipitation sum in the region, respectively (Table S4).

Additional groundwater storage displayed considerable variation in the passive and active scenarios, not only annually but also over the 2000–2010 period, when changes in groundwater storage caused by either droughts or retention measures turn up with a lag of 1–2 years. This is even more emphasised in case of groundwater impact areas, for which, in contrast to the situation with groundwater storage, the effects of the 2007 and 2009 droughts are not visible. Besides the spatial aspect of the wetland edge-effect, this temporal balancing/buffering capacity is also important as the relatively balanced/buffered groundwater table offers a more reliable water resource for managed and natural ecosystems (Fig. 5a–b).

3.2. Cereal crop modelling: wetland edge effect on maize yields

Shallow groundwater conditions contributed to the highest average of maize yields under the reference ($-1.3 \text{ m} \pm 0.4 \text{ m}$) and the passive water management scenarios ($-1.1 \text{ m} \pm 0.2 \text{ m}$) in 2000–2010 (Table S5 in the Supplementary materials). Only a clayey loam soil profile showed similar averages of maize yields in the reference and the passive water management scenarios (Fig. S5; Fig. 6). Shallow groundwater conditions gave almost one and a half times higher yields of maize on average than deep ones under the reference ($-4.0 \text{ m} \pm 0.3 \text{ m}$) and the passive water management scenarios ($-3.7 \text{ m} \pm 0.3 \text{ m}$) (144 % to 169 % for the studied soil profiles). Nevertheless, average yields did not change significantly due to passive or active water management scenarios, under all but one of the shallow groundwater conditions. Only the active management scenario brought about a significant decrease of yields on the loamy sand soil profile in the wet years. Due to the cumulative impact of the high precipitation sums and the prolonged inland excess water cover of the active scenario soil saturation caused an estimated 80 % lower yield than in the reference scenario for these years.

Compared to the reference scenario, the highest average yield growths were calculated for a medium groundwater depth ($-2.4 \text{ m} \pm 0.3 \text{ m}$) under the passive water management scenario: 0.8 t ha^{-1} (11 %) for the clayey loam, 1.1 t ha^{-1} (19 %) for the silty clay and 1.1 t ha^{-1} (20 %) for the loamy sand soil profiles, respectively (Fig. 6). The order of soil profiles is reversed when comparing relative yield differences between the medium and shallow groundwater zones: the difference (45 %) is most pronounced in the case of the loamy sand profile, followed by the silty clay (24 %) and the finally the clayey loam (8 %) soil profiles. It is also worth noting that a higher groundwater table resulted a higher standard deviation. In the case of the loamy sand profile standard deviations of 1.4 t ha^{-1} , 1.4 t ha^{-1} , 1.8 t ha^{-1} were calculated for deep, medium and shallow groundwater, respectively. In the case of fine textured soils, however, the picture was a little different: standard deviation increased from 1.6 t ha^{-1} to 2.5 t ha^{-1} and from 1.4 t ha^{-1} to 1.9 t ha^{-1} for clayey loam and silty clay, respectively, when comparing deep groundwater with medium groundwater conditions, but yields were significantly more balanced in the case of shallow groundwater conditions with standard deviation = 0.8 t ha^{-1} for clayey loam and 0.7 t ha^{-1} for the silty clay soil profile, that is, about half of the standard deviation calculated for the deep groundwater condition.

In accordance with the dynamics of groundwater level changes driven by the passive water management scenario, yield growth hardly exceeded 1 t ha^{-1} between 2000 and 2005 and remained well below 0.5 t ha^{-1} in 2003 and 2004, regardless of the soil type in the upper 2 m. Then, yield growth rates 5–6 times higher than in the preceding 6 years were achieved, reaching 3 t ha^{-1} in the 2006–2009 period. In contrast, the active water management scenario increased yields the most in 2004 and 2005, peaking at 4.5 t ha^{-1} , 5.4 t ha^{-1} and 1.7 t ha^{-1} in the case of the clayey loam, silty clay and loamy sand soil profiles, respectively, which corresponds to 80 %, 129 % and 34 % higher yields than those calculated for the passive scenario. Yield changes simulated for the extremely wet year of 2010 varied greatly depending on the soil profile. While the surplus water in the passive scenario reduced maize yields under medium groundwater conditions in the case of the clayey loam pro-

file by 23 % and the negative effect was further amplified in the active scenario, yield increase for the year reached almost 40 % in the loamy sand profile under both the passive and the active scenarios. The effect was practically neutral for the soil silty clay in the passive scenario (-1%) and turned decidedly negative (-9%) in the active scenario. Considerable yield growth (29 %–36 %) was simulated in the active scenario for the three years of drought: (i) in 2003, when the lowest groundwater levels were recorded, (ii) in 2007, when the groundwater level increase in the passive scenario (on average 0.37 m) was significant in the previous winter half-year (October to March) and (iii) in 2009, when an optimal level of soil moisture was ‘inherited’ from 2008 (Fig. 6).

3.3. Oak growth and the hydrological factors

Based on the composite records, the groundwater table fluctuated around a depth of 3 m until the early-1980s, when a long-term deepening trend started beneath the Ohat Forest (Fig. 1; Fig. 7a). From the late 1990s, what had previously appeared as an oscillating trend-like decrease in groundwater began to witness sudden jumps, rather than oscillations, and this seems to have been due to extreme hydrological events. The seasonal *high* groundwater levels in the five years 2019–2023 (Fig. 7a) could not reach even the seasonal *low* groundwater levels recorded in the early 1980s. The lowest-ever March–Sept groundwater level was observed in 2022 (Fig. 7a; Fig. S11) when extreme drought affected the landscape (Gharun et al., 2024) (Fig. 7a; Fig. S4). The drought significantly reduced nightly replenishment at depths of 4.8–5 m (Fig. 7b; Fig. S10) indicating that the root system lost the contact with the water table. The following hydrological year (2022/2023) brought a limited replenishment, which lasted until August 2023 (Fig. 7c).

3.4. Wetland restoration potential in the hungarian plain

The mapping framework (Section 2.2.4) generated a $6,567 \text{ km}^2$ (16 % of the plain) wetland conservation and restoration potential in Zone 1 where agro-ecological potential is low or moderate, the ecological value or nitrate vulnerability is high, and flood occurrence is regular. In this zone the abiotic conditions and the ecological status relevant to wetland conservation or restoration, together with the low profitability of cropland farming due to weak or moderate agro-ecological suitability predicts a relatively low and manageable level of social conflicts negatively impacting the conservation or restoration of hydrological conditions of drained wetlands. In terms of potential social conflicts an important point is that an estimated 80 % of the plain is highly drought-prone where extreme damage to agriculture is regular. As for the land use regime, the recent land pattern in Zone 1 reflects the cropland-dominated (41 %) conditions of the landscape (Table S1a) but in the grassland-forest ratios, a significant difference appears; while grassland and forest cover is basically balanced in the Hungarian Plain (13 % and 16 %, respectively), more than one-third of Zone 1 is covered by grasslands (37 %), and a mere 2 % by forests (Table S1b). Besides, the analysis identified another $2,105 \text{ km}^2$ (5 % of the plain) area with wetland restoration potential without ecologically valuable criteria in Zone 2 where flood occurrence is regular and agro-ecological potential is low or moderate. The correlation between actual and potential vegetation is basically negligible, since an estimated 88 % of the zone’s poor soil is covered by arable lands (Table S1a). In this zone of cultivated wetlands, wetland restoration may be considered economically reasonable. Comparing water coverage induced by the water management scenarios (163 km^2) (Fig. 5a) and the wetland restoration potential (81 km^2) in the Ohat simulation area (Fig. 8), the morphological similarities and the patterns of the surfaces concerned are identifiable. An important difference emerged in the south-western part of the area, where due to geomorphological conditions hydrological simulations resulted in relatively extensive water cover, while the majority of these areas were characterised by good-excellent soils, and therefore, excluded from the zonal selection of wetland restoration potential.

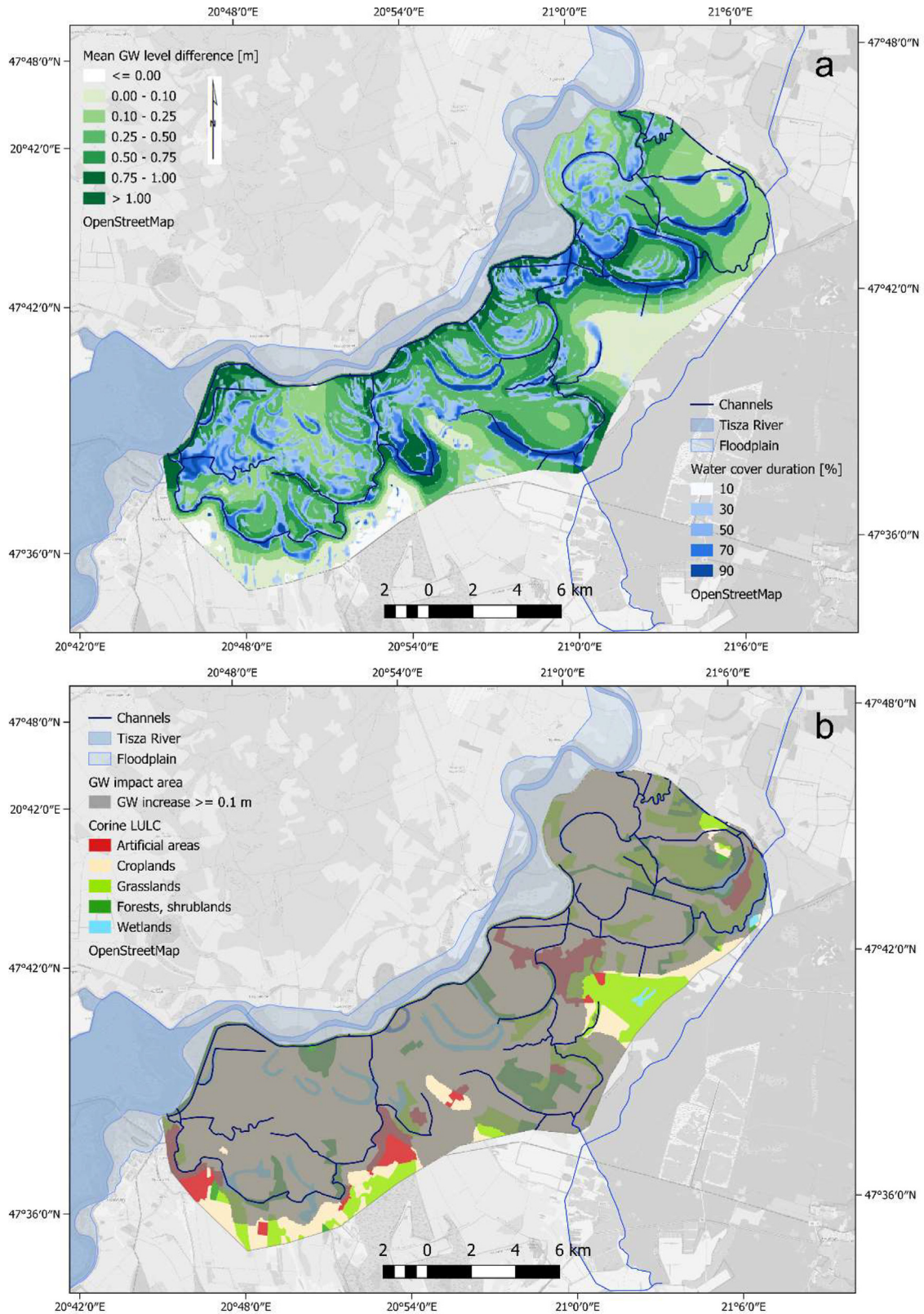


Fig. 5. (a) Water coverage duration and the impact area of ‘active’ water management scenario on average groundwater levels at the Ohat simulation area. Both simulated overland water coverage durations and groundwater level averages were processed for the May–August period, 2000–2010. (b) Land use and land cover (LULC) map of the simulation area with the area where ‘active’ water management scenario has significant impact on May–August average groundwater level, 2000–2010.

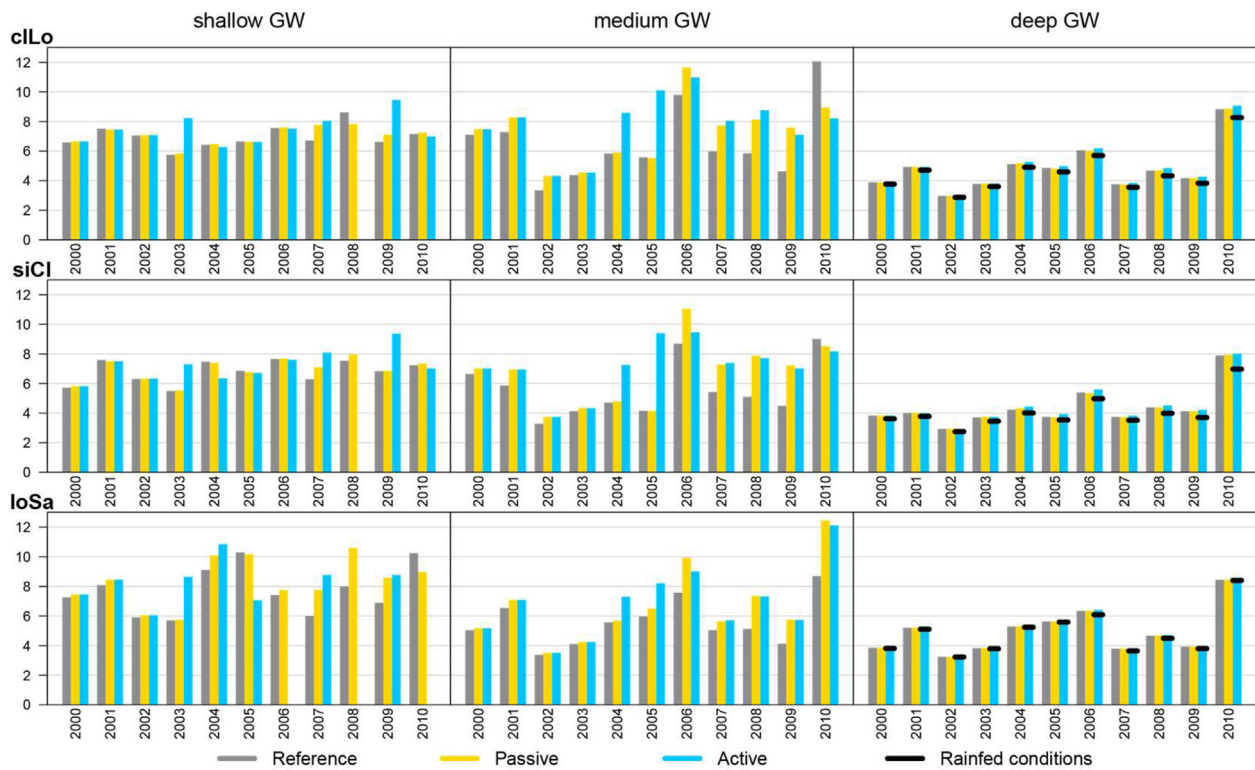


Fig. 6. Simulated yields of maize in different soil profiles (cLo = clayey loam, siCl = silty clay, and loSa = loamy sand) under three groundwater conditions (shallow, medium, and deep) of the three water management scenarios (reference, passive, and active) in 2000–2010. *t*-test results are available in Table S6.

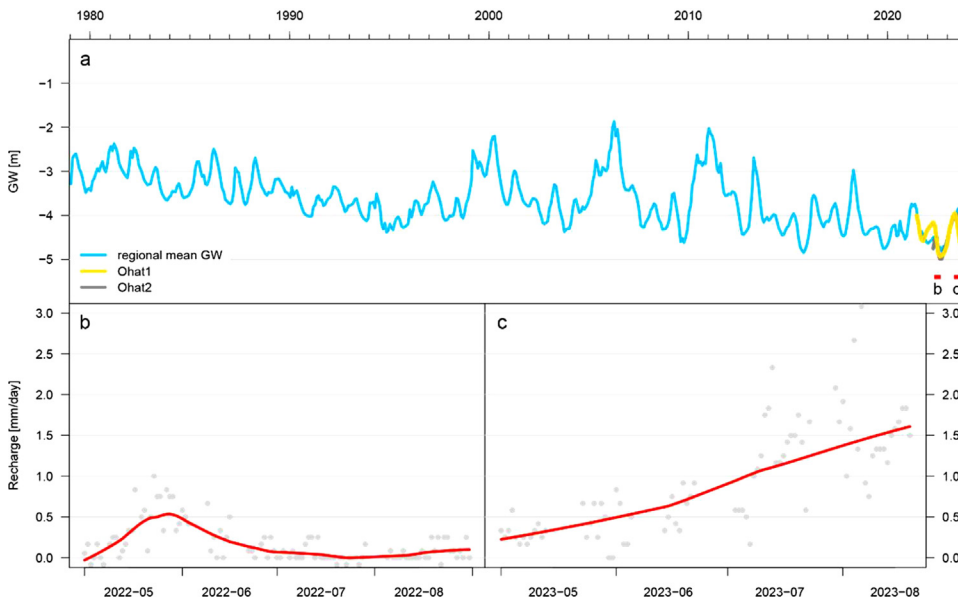


Fig. 7. Groundwater table beneath the Ohat Forest. (a) Regional long-term monthly groundwater table time series (light blue) scaled to Ohat 1 monitoring well (grey). Daily groundwater recharge rate estimated based on diurnal fluctuation in the Ohat 1 and Ohat 2 monitoring wells in the growing seasons of (b) 2022 and (c) 2023.

4. Discussion

4.1. Hydrological aspects of the study

The results revealed that the hydrological restoration of wetlands in the Hungarian Plain would have increased groundwater stock with a significant positive impact on (semi)natural ecosystems and crop plantations in their surrounding areas between 2000 and 2010 (Fig. 4; Fig. 5a–b). As a result of the passive water management measures (inland excess water retention) and active ones (managed inundation), water covered an estimated 67 % of the Ohat simulation area and its duration was >10

% on average in the May–August period (Fig. 7a). This surface water would have increased groundwater storage both horizontally and vertically, and groundwater levels would have risen by an estimated 0.42 m on average over the simulation area (Fig. 4; Fig. 5a–b). Similarly to other managed aquifer recharge interventions, e.g., in the Ramganga basin (India) (Chinnasamy et al., 2018), in Arizona and California (North America) (Scanlon et al., 2016), the simulated impact of the passive and active water management measures may potentially counterbalance the historically reconstructed 0.25 m decrease of shallow groundwater table in the plain (Pinke et al., 2020). The ‘edge effect’ of wetlands on subsurface waters was not uniform but depended on terrain morphology, the

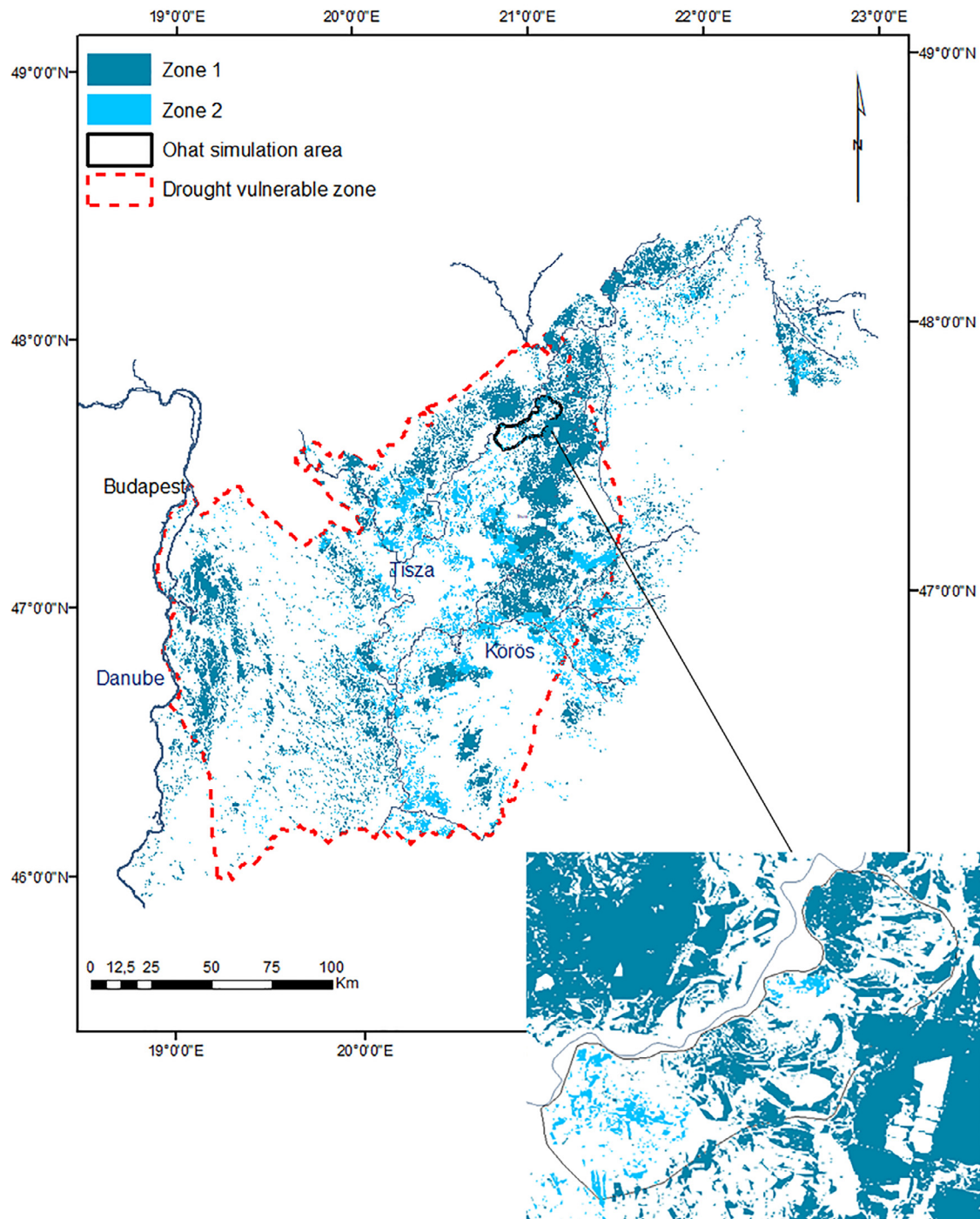


Fig. 8. Zones of wetland restoration potential in the Hungarian Plain. Zone 1: Areas prone to inland excess water and nitrate vulnerable areas of the Pan-European Ecological Network with low and moderate agro-suitability. Zone 2: Areas prone to inland excess water with low and moderate agro-suitability without ecologically valuable criteria or nitrate vulnerability. Red line indicates the drought-prone zone the most in the plain.

vicinity of the drainage channels, vegetation and land cover, and soil characteristics.

The passive and active water management scenarios had an immediate and significant effect on groundwater levels in 2003 (Fig. 3), right after the managed inundation of the deep floodplain when an extreme drought hit the landscape (Ciais et al., 2005). On the contrary, passive water management measures (inland excess water retention) alone generated a more significant rise in groundwater in two other years of drought, 2007 and 2009 (Fig. 3c, 3d). Some points need to be made concerning this result. Although 2007 and 2009 also saw serious

droughts, due to permanent positive temperature and negative precipitation anomalies in 2000–2002 and early 2003, the groundwater table had decreased to an extreme degree by May 2003. As a consequence of the winter and spring drought of 2003 the storage of surface water and the recharged groundwater were significantly less than in 2007 and 2009. The floods of the Tisza and its tributaries supply plenty of water for lowland wetlands by bringing precipitation and snow melt from the mountainous watershed (Jánosi et al., 2023) even in such serious dry years as was 2003. Nevertheless, water flow is bidirectional in lowland riparian systems. A key to drought mitigation capacity is when

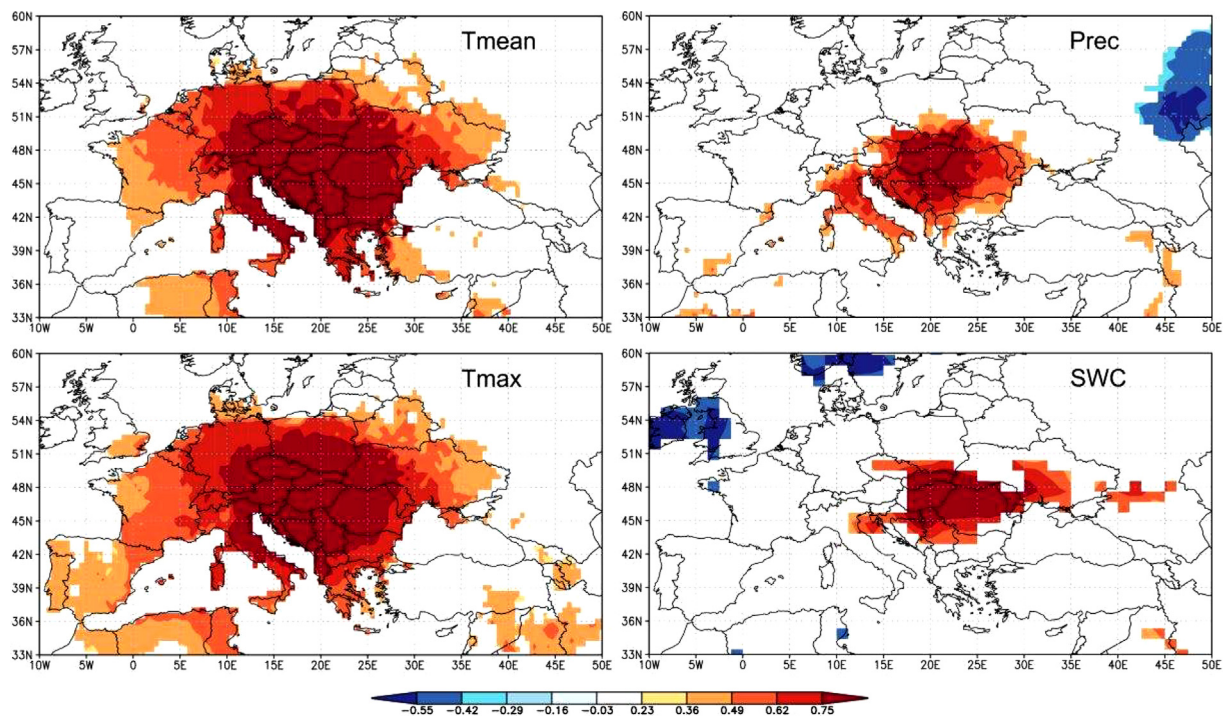


Fig. 9. Spatial correlation computed between the meteorological parameters averaged for May–August gridded variables for the Ohat simulation area and gridded data in the 33°N to 60°N and 10°W to 50°E domain. Pearson correlation coefficients significant at $p = 0.1$ level are displayed according to the colour scale. Tmean: mean temperature; Prec: precipitation sums; Tmax: mean of daily maximum temperatures (CRU TS 4.08) for the period of 2000–2023; and SWC: 0–1 m soil moisture (CLM/ERAi) for the period of 2000–2016. Data were processed using Climate Explorer (Trouet and Van Oldenborgh, 2013).

wetlands delay baseflow, i.e., water seeps from the wetlands to the low level streams and reduces the likelihood of meteorological-driven hydrological drought formation, e.g., by an estimated 18 %–19 % in the basins of the Gan River (humid subtropical China) and the Nelson River (sub-Arctic Canada) (Wu et al., 2023a). This baseflow support function of wetlands strongly depends on wetlands' degree of riparian connectivity as was confirmed by the example of the Nenjiang River Basin (China), situated in the northern temperate zone (Wu et al., 2023b). Therefore, linking riparian wetlands and their streams is an unavoidable element of landscape-level wetland restoration. As a result of climate change and channelisation of rivers in the Plain (Kiss et al., 2025), in a way similar to other drought-prone regions in North America (Scanlon et al., 2016) flood water supply will be less predictable, as happened in 2022, when the annual flood simply never took place. Therefore, retaining and reserving surface waters generated by local lowland processes is justified as a strategy in dry plains of Europe (Fig. 9). It is necessary to draw attention to the importance of water retention because according to the regional water management protocol a vast amount of inland excess water is drained into the river system: an average of $1.4 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ being channelled was recorded between 1971 and 2001 (Hungarian Hydrological Yearbooks, 1971–2002). The channelisation of inland excess water has taken place even in the driest years, as happened in 2022 (Hydrological Management Yearbook, 2022), when an extreme drought hit the landscape (Biella et al., 2025).

4.2. Edge effect of the hydrological restoration of wetlands on the croplands of the surrounding transition zones

The results of the cereal yield simulations confirmed the strong groundwater dependency of maize production in the simulation area. The edge effect of the hydrological restoration of wetlands may benefit croplands in the surrounding transition zones between the high terraces and the wetlands the most resulting in balanced year-to-year yields on fine-grained soils (Fig. 6). Furthermore, the positive impact of the passive and active water management measures was 3–11 times

higher (!) under medium groundwater conditions (2.44 m below surface) than shallow ones (depending on soil type). In fact, this effect was so pronounced that maize yields may have increased by an estimated 20 %–28 % and reached or even exceeded those typical of low-lying areas where a shallow groundwater table already provided quasi-optimal moisture conditions for crops. The positive impact of groundwater rise on maize yields was not negligible, but only modest on the high terraces during the driest years, when the groundwater table was well below a level at which it could foster capillary rise. Farmers growing maize in areas where the water table is shallow (11-year average: 1.26 m below surface) may have harvested 44 %–67 % more maize on average than fields with a deep groundwater table (4 m below surface) between 2000 and 2010 (Fig. S1d; Fig. S5). These findings confirm the results of previous experiments with lysimeter measurements and model calculations (Gao et al., 2017; Kahlown et al., 2005), which also defined the optimum groundwater depth for maize as 1–2 m below the surface. Besides, the continuous availability of groundwater in the zone with shallow groundwater may substantially attenuate the drought sensitivity of maize. For example, shallow groundwater could have even reduced the drought damage to zero in 2002 and 2003, yet in those years yield loss of rainfed maize reached an estimated 25 % to 47 %, respectively, in the Hungarian Plain (KSH, 2025). Presumably, the drought mitigation impact of the higher groundwater table may have been significant in 2022, when the drought caused record losses to Hungarian agriculture, particularly in the Hungarian Plain, where maize loss reached an estimated 70 % (Biella et al., 2025).

4.3. Wetland restoration: a key to the survival of the last remnants of natural forest-steppe vegetation

Another aspect of water management is a flood and groundwater regulative effect, in which forests delay flood peaks by increasing hydraulic roughness and evaporating soil water. Beyond the obvious engineering solutions, this controlling capacity of forests might be employed to help mitigate the undesired impacts of elevated groundwater table and

fully saturated soil conditions in certain conflict zones. For instance, surrounding settlements with forest strips could reduce the chances of inundation within built-up areas. However, such a buffering capacity is limited both in space and time; furthermore, it depends on the depth of the unaffected groundwater table, local soil conditions, tree species and the size and shape of the forest stand (compare Fig. 4a, 4b). Therefore careful site-specific planning is required in any case of its application.

The positive association between oak growth and the interannual variations in precipitation and groundwater is a general rule over the drought-prone lowlands of the wider region (Garamszegi et al., 2022; Stojanovic et al., 2025), implying that oak growth strongly depends on soil moisture conditions of the growing season in the Ohat Forest (Fig. 7). These oak trees may obtain their water supply via access to groundwater (*phreatophytes*) with their deep root system generating diurnal fluctuations in groundwater table driven by root water uptake. The disappearance of diurnal fluctuation at 4.8–5 m (Fig. 7a; Fig. S10) in the growing season of 2022 (Fig. 7b) strongly indicated that the root system of even the mature and dominant trees of the Ohat Forest were not able to reach the groundwater table under such drought conditions. In 2022, similar disappearance of diurnal groundwater fluctuation was found in a mixed common oak and poplar forest of the plain situated c. 40 km southeast from Ohat (Szabó et al., 2023), supporting the notion that this anomaly could have occurred across the plain. Interestingly, a 5 m depth of groundwater threshold was identified for the degradation of shrub and forest vegetation under semi-arid continental climate (Liu et al., 2024b). Considering that the water demand of forest trees definitely increases during a drought period, the loss of their connection with the vital source of water (i.e., groundwater) is definitely a serious warning concerning their future survival. The simulated groundwater recharge driven by the hydrological restoration of wetlands (Fig. 3) is not simply a factor to increase the productivity of the lowland forest, but is instead also a key to the survival of the last remnants of natural vegetation in the landscape (Mátyás et al., 2018).

4.4. Wetland restoration potential in the Hungarian plain

Too much water for crop farming in wet years and too little in dry years is the main challenge in cultivated wetlands of the Hungarian Plain, generating significant adaptation costs for farmers (Pinke et al., 2018). This conflict between the present land use and the hydrological conditions was identified by selecting the wetland restoration potential of the Hungarian Plain (Fig. 8; Table S1b). An estimated 41 % of ecologically valuable areas with high wetland conservation potential and 88 % of areas where hydrological restoration is economically reasonable are subject to cropland farming today. In these cultivated wetlands, poor soil conditions and the coupled challenges of staple food overproduction and increasing drought sensitivity driven by climate change have brought low profitability to crop farming over the last years (Fabok et al., 2023). In general, economic and/or structural crises are drivers of cropland abandonment mainly on low-productivity marginal lands (Kuemmerle et al., 2016). Cropland abandonment has shown itself to offer a fleeting chance to provide tangible and long-lasting benefits for biodiversity and climate mitigation in several parts of the world. In the Hungarian Plain, socio-ecological investigations indicate that the narrowing prospects of agricultural production in this way have reduced the aversion to the hydrological restoration of wetlands (Farkas et al., 2024). Similarly to other European regions, governance instruments such as subsidies were identified as key motivating factors affecting decisions concerning land use (Fabok et al., 2023; Farkas et al., 2024).

4.5. Limitations of the study

- The hydrological modelling of drained lowland catchments is a challenging and complex task. Characteristic relationships between external drivers (precipitation, potential evapotranspiration, water

transfers) and catchment responses (discharge, water coverage extent, groundwater storage, actual evapotranspiration) are less explored and direct than in the case of hilly or mountainous watersheds. Besides complex hydrological mechanisms, several factors limit the reliability of input data and control variables of the model adjustment, which results in the relatively lower degree of accuracy in the model. Nonetheless, taking these factors into account, we consider the performance of the model presented acceptable.

- The zonal analysis has some limitations due to the fact that we could not get access to some GIS datasets, e.g., the biological state of ecosystems and land ownership (state, local government or private). In possession of these data, a more sophisticated analysis with a higher degree of spatial resolution of wetland restoration potential could be conducted.
- The wetland restoration potential of Zone 1 presented herein is based on the probability of inundation of the National Ecosystem Map of Hungary sites, combined with agricultural suitability and nitrate vulnerability. The National Ecosystem Map of Hungary has a real ambition to address ecological connectivity for the migration of the key species in nature conservation. However, the implementation of a realistic blue network to link wetland patches outlined in zonal analysis demands complex hydrological examinations due to the complexity of hydrological processes, as demonstrated in the Ohat simulation area. Since the identification of blue networks has gradually emerged as a spatial planning issue in the EU over recent decades large-scale hydrological investigations have become topical, and indeed urgent.

5. Conclusions

Considering the methodological limitations, the selected zones of restoration disperse with corridors. As first steps in this direction, hydrological simulations will be essential, as in the case of Ohat, described here, to accurately define the physical framework of the targeted hydrological restoration. Nevertheless, the amount of the ecosystem services explored, especially the recharged groundwater, and the maize yields triggered by increasing groundwater, together strongly support the hypothesis that the hydrological restoration of wetlands may effectively mitigate increasing drought sensitivity in a European hotspot of climate change studied here. These results, taken together with the high amount of other services (e.g., flood regulation) provided by lowland wetlands and the selected pattern of wetland restoration and conservation potential shed light on the intersectoral prospects of the hydrological restoration of wetlands in Europe.

Data availability

Data used for this research are available from: Copernicus (2019). Corine Land Cover 2018 (CLC2018) <https://doi.org/10.2909/71c95a07-e296-44fc-b22b-415f42acdf0>; Copernicus (2025). Water and Wetness status 2018 Europe, 3-yearly. <https://doi.org/10.2909/7992f641-bf77-47b7-b0c1-74fc832b78b1>; Ministry of Agriculture (2022). National Ecosystem Map of Hungary (NEMH). <http://alapterkep.termeszetem.hu/> (accessed 12 May 2022); Department of Energy (2022). Nature protection Data System (TIR). <http://web.okir.hu/map/?config=TIR&lang=hu> (accessed 12 May 2022); National Agricultural Research and Innovation Office (2015). Flood hazard mapping and risk management planning. <https://www.vizugy.hu/vizstrategia/documents/81E46637-D6E2-469B-A482-298613A06132/1.%20melleklet%20Belvizi%20veszelyterkepezes%20eredmenyei.pdf> (accessed 12 May 2022); Hungarian Hydrological Yearbooks (1983–2007). VITUKI, Budapest. (in Hungarian) (accessed 21 February 2022);

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Zsolt Pinke: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization. **Tamás Acs:** Writing – review & editing, Writing – original draft, Software, Investigation. **Bence Decsi:** Validation, Data curation. **Máté Krisztián Kardos:** Validation, Software, Data curation. **Matyas Arvai:** Validation, Investigation. **Veronika Fabók:** Writing – review & editing, Writing – original draft. **Jeno Zsolt Farkas:** Writing – original draft, Conceptualization. **Zoltan Gribovski:** Software, Investigation. **Dora Hidy:** Software. **Peter Kalicz:** Visualization, Validation, Software, Investigation. **Zoltán Kern:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Andras Donat Kovacs:** Writing – original draft, Conceptualization. **Eszter Tormáné Kovács:** Writing – review & editing, Writing – original draft, Conceptualization. **Laszlo Pasztor:** Validation, Software, Data curation. **Zsolt Kozma:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.geosus.2026.100464](https://doi.org/10.1016/j.geosus.2026.100464).

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