

Long-term Water Regime Studies of a Degraded Floating Fen in Hungary

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Abstract

Historical trends in water management and recent climatic variations put wetlands in the Carpathian basin under strong pressure and led to their degradation. The lack of extended site specific environmental data series inhibits the understanding of long-term eco-hydrological processes. This undermines the success of restoration and/or management efforts. As a precedent we analyzed a recently degraded Hungarian lowland wetland, the Nyárjas fen in order to identify the main cause of its drying. Our method is based on one-dimensional simulations of a variably saturated soil column representing the dominant hydrological conditions of the wetland. To properly define the necessary soil hydraulic parameters, soil sampling, laboratory measurements and inverse modelling were carried out. The hydrological simulations for the 1961–2010 period clearly suggest that (i) the wetland degraded due to a temporal unfavorable combination of regional groundwater depletion and decreased precipitation, (ii) and could not recover afterwards despite the improvement of hydrological conditions. The ecological water demand of the Nyárjas fen can be explicitly expressed in terms of groundwater level. However, water availability is a necessary, but not sufficient criteria of good habitat status. The elaborated methodology provides the basis of bottom-up type environmental water demand estimation on a regional/national scale.

Keywords

groundwater dependent ecosystems, water balance analysis, vadose zone modeling, eco-hydrology, SVAT, Hydrus-1D

1 Introduction

Wetlands have significant socio-economic importance: as a major component of the natural capital, their ecosystems are aiding us through various ecosystem services (ESs). The major ESs of wetlands are regulating ones e.g. climate mitigation, carbon sequestration, flood prevention, groundwater recharge, water purification [1–3]. The wildlife and biodiversity of wetlands are mostly the best out of their region, so recreation and tourism services of wetlands are also relevant [4–5]. At the same time, biodiversity of freshwater ecosystems declines rapidly along with the increasing human water consumption, and climate change [6–8]. As a consequence, the global area of wetlands decreased by 35 % in the past ~50 years and over 80 % of inland wetland species populations had declined globally [9].

Recognizing the growing threats, national regulations and international conventions and directives (e.g. Habitats Directive, Water Framework Directive) stipulate the conservation and restoration of wetlands. Conservation and restoration planning require knowledge of wetland hydrology [10].

Flooding or inundation depth, duration and frequency can be considered as the most important hydrological indicators for wetlands [11–13] as hydroperiod and its variations have determinant role in enhancing or constraining vegetation. The quality of wetland ESs mostly depends on optimal water availability [4]. The presence of high groundwater levels (GWLs), frequent soil saturation and surface water cover are essential for ESs such as carbon sequestration or maintenance of biodiversity [4, 14–15].

Beside long-term monitoring, hydrological modelling is a useful approach to estimate the water demand indicators of wetland habitats. The selection of the appropriate modeling tool is usually a tough decision burdened by the tradeoff between the model efficiency, uncertainty and complexity [16]. There are several concepts, methods and models to describe the water regime in wetlands and their catchments. These differ mainly in the spatial and temporal resolution and the complexity of the processes in focus [17]. Ultimately, cell based three-dimensional

hydrological models (like Mike SHE) offer the best conceptual solution to describe the complex spatio-temporal characteristics of wetland hydrology, see e.g. the case studies of [18–20]. These modeling tools were used in several wetland hydrology related studies with good results [21]. However, such models have high computational and input data demand, while in many practical applications they proved to be overfitted due to the large number of parameters to be calibrated [22–23].

In contrast, one-dimensional soil-vegetation-atmosphere transfer (SVAT) [24] models can offer viable alternatives with reduced input data requirements. However, the one-dimensional approach strongly limits the applicability of the model to simple hydrologic systems, i.e. where vertical fluxes (e.g. infiltration, percolation, evapotranspiration) dominate the wetland hydrology, or surface/subsurface lateral flows can be handled via appropriate boundary conditions. Hydrus-1D [25] is a popular one-dimensional model, which was used in several research to model wetland hydrology [26–28].

In this research, we analyzed the long-term hydrological conditions and water regime of a degraded peatland in the Great Hungarian Plain (GHP) with a modified Hydrus-1D model. Soil hydraulic parameters were derived from in-situ soil sampling, laboratory measurements and inverse modeling. Modelling was supported by a self-developed software framework, which allowed us to automatically fit the calibration model parameters and to practically manage the input data.

The aim of our research was (i) to test the applicability of the one-dimensional approach used to describe the water balance of the aquatic habitat in addition to the simplifications we have assumed and (ii) to test the applicability of the self-developed novel lower boundary condition. Besides methodological issues, our practical goal was (iii) to answer questions, why and how the wetland dried out and what were the barriers that prevented its regeneration.

1.1 Study area

The Nyárjas lies in an inland dune slack, a typical landform in the Nyírség sand ridge of the GHP (Fig. 1). The average relative relief in the wetland's 0.3 km² subcatchment is moderate, some 11 m/km² (the embodying catchment is around 450 km² with 78 meters relief). Despite the varied topography of the incorporating ridge, the bed of the wetland is relatively flat: the largest difference in elevation is less than three meters. Similarly to the most parts of the ridge, the surrounding environment can be characterized by

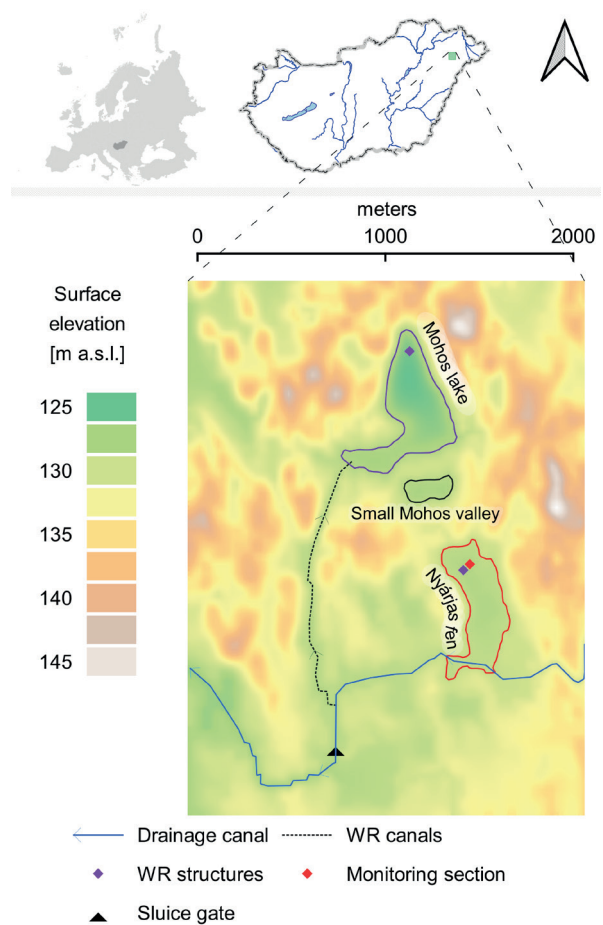


Fig. 1 Study area

Table 1 Changes in the open water surface of Nyárjas fen [32]

The date of the survey	Water covered area of the Nyárjas fen [ha]
1763–1787	102
1806–1869	118
1869–1887	98
1941	45
2016	0 (15 peat meadow with non-permanent water cover)

quasi-homogeneous stratigraphy, where the dominant soil type is sand of aeolian origin [29–31]. Contrary, on-site soil sampling revealed five different soil layers in the upper two meters at the deepest patch of the Nyárjas, indicating determinant role of biogeochemical factors in soil formation.

Up to the middle of the 19th century the Nyárjas was a fen with around 120 ha regular water cover [30]. As a result of region-scale drainage [32–34], extent of open water surfaces reduced by ~75 % by the mid-twentieth century (Table 1) [32]. The drying was deteriorated by sand accumulation caused by deforestation induced wind erosion. The Mohos Lake (a more explored floating fen about 500 meters north of the Nyárjas) underwent identical changes.

The degradation of the fen continued in the late 20th century. Significant changes in plant community composition are evident from repeated (1981, 1983, 1987, 2009, 2014) coenological surveys [34]: species indicating regular inundation in the 1980s became extinct or went through remarkable population decline, while the extent of the habitat shrunk to about 15 ha. Previous studies [34–35] linked the drying process to reduced annual precipitation as well as to decreasing GWLs from the middle of the 1980s. Even though groundwater regime generally reflects climatic changes, annual precipitation and average GWLs are only moderately correlated ($R^2 = 0.64$) in the region. GWLs decreased by 1.2 cm/year in the 1961–2013 period [36], vigorously in the mid '80s, partially due to increasing groundwater withdrawal for drinking water. In contrast, time series of annual precipitation show no significant trend, though the decade from 1984 was relatively dry. Overall, the relative importance of the two factors is of question.

Even though the Nyárjas went through substantial hydrological and ecological transformation, it is still particularly valuable according to botanical records, as it still shows traces of its former floating fen character, and is habitat to several specialized protected plant species [35, 37]. Recognizing its ecological value, artificial water replenishment (WR) was implemented in order to restore the wetland, utilizing two sources: (i) groundwater from a nearby deep (>80 m) groundwater well and (ii) water diverted from the adjacent temporarily impounded drainage channel. The measures resulted in increasing GWLs [34], however, wet habitats did not regenerate.

2 Methods

2.1 Overview

Hydrological processes in the study area were simplified to a one-dimensional soil-vegetation-atmosphere transfer system [24]. They were simulated with a modified version of the Hydrus-1D model for the 1961–2010 period with daily time steps. The following processes were taken into account: (i) surface water transfer including infiltration, evapotranspiration, interception and surface ponding, (ii) WR considered as precipitation, (iii) single porosity matrix water flow in the vadose zone with root water uptake, (iv) head-dependent recharge/discharge bottom boundary flux, and (v) heat transport (to facilitate snow hydrology). The numerical model was based on various data sources: (i) official hydro-meteorological records from the vicinity of the fen, (ii) a spatially interpolated climate database of the 1961–2010 period, (iii) a long-term

but irregular in situ monitoring program maintained by an independent local biologist (Dr. Mihály Vas), (iv) and three in situ soil samplings and laboratory measurement carried out as part of this research. The model of the fen was calibrated for locally measured groundwater/surface water levels covering a 12 years long period.

Hydrological indicators were derived from the simulated daily water coverage, groundwater depth and soil moisture time series. As these variables are linked to each other through site-specific non-linear relationships, it is worth comparing them. The derived statistical measures were used to characterize the hydrological conditions of the wetland and to evaluate the water supply of the ecosystem.

Inverse modeling, the automatic set up and simulation of scenarios as well as the statistical evaluation of simulation results were supported by the self-developed BHR-algorithm (Batched Hydrologic Runs Algorithm) [38]. The algorithm applies the *nlopt* open access program library [39] to aid the nonlinear local-global optimization tasks.

2.2 Variably saturated flow - governing equations

Hydrus-1D simulates water movement in variably saturated soils by solving the Richards equation [25]:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(h) \left(\frac{\partial h}{\partial z} + 1 \right) \right] - S(h), \quad (1)$$

where θ is water content [L^3/L^3], t is time [T], z is the vertical space coordinate [L], $K(h)$ is the unsaturated hydraulic conductivity [L/T], h is the water pressure head [L] and $S(h)$ is the root water uptake sink term [$L^3/L^3/T$]. The Mualem-van Genuchten soil hydraulic models [40] were used to approximate the $\theta(h)$ water retention curve (Eq. (2)) and the $K(h)$ unsaturated hydraulic conductivity (Eq. (3)):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha \cdot h|^n \right]^m}, \quad h < 0, \theta_s, \quad h \geq 0, \quad (2)$$

$$K(h) = K_s \cdot S_e^l \left[1 - \left(1 - S_e^m \right)^{\frac{l}{m}} \right]^2, \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad (4)$$

where θ_r and θ_s are the residual and saturated water contents [L^3/L^3], α [1/L] and n [-] are empirical shape parameters ($m = 1 - 1/n$), S_e is the effective saturation [-] and l [-] is the pore connectivity parameter.

2.3 Boundary conditions (BCs)

Daily precipitation (P), temperature (T) and relative humidity (RH) for the simulation period were derived from the Carpatclim database [41]. Using T and RH, potential evapotranspiration (PET) was calculated with the Varga-Haszonits formula [42]. The advantage of the Varga-Haszonits model is its simplicity and limited data need, which was a great advantage as only the required T and RH were available for the whole simulation period. This is probably also a source of error, as it has been proven that the reduction of meteorological variables taken into account may introduce considerable bias to the estimation [43].

P, T and PET were applied as atmospheric BC on the top of the model (Fig. 2). Estimated specific flow rate of WR [33] was added as surplus water, assuming that the discharged volume was spatially uniformly distributed in the wetland. Due to topographic and soil conditions, overland surface runoff from the catchment was neglected. This is supported by the fact, that the annual surface runoff is estimated to be ~2 % of annual P (550 mm/y) in the embodying catchment: i) the total (surface-subsurface) runoff is only ~7 % of P (data source: General Directorate of Water Management), and ii) the baseflow index (ratio of subsurface runoff to the total runoff) is more than 70 % [44].

Groundwater table in the region moderately follows the ground surface [45] and annual PET exceeds P in all, but five extremely wet years. Thus, it is lateral groundwater inflow that maintains permanent or prolonged surface water cover in interdune wetlands, i.e. groundwater discharge to wetlands covers the climatic water deficit [46]. However, the one-dimensional approach limits the degree to which non-vertical hydrological processes can

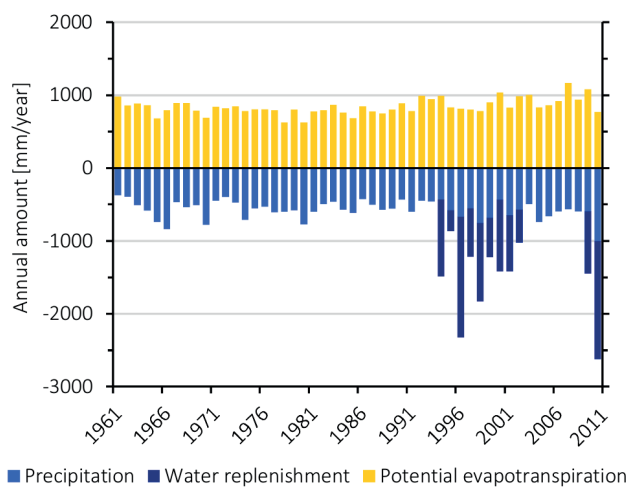


Fig. 2 Annual sum of PET, P and WR in the study interval

be considered. Generally, in case of shallow groundwater, either GWLs are known (Dirichlet type BC) and fluxes at the model bottom are to be calculated, or inversely, the model calculates GWLs corresponding to the prescribed bottom fluxes (Neumann type BC). GWL measurements in the wetland were sparse and the records cover only about third of the entire simulation period, while specific subsurface inflow/outflow rates were unknown. On the other hand, even though shallow groundwater monitoring wells in the 3–12 km proximity of the wetland provided consistent and sufficient data, the periodic WR induced local groundwater rises were naturally not reflected in their records. To resolve this frequently occurring problem, a head-dependent-flux (Robin type) BC was developed and incorporated into the open-source Hydrus-1D code. The new BC assumes horizontal flow from or to the modelled soil column depending on the relation of actual GWL at the wetland and known (prescribed) GWL at a certain distance from the modeled soil profile. Lateral groundwater flow is calculated based on Darcy's law (Eq (5) and Eq. (6)):

$$Q_{GW} = \frac{(h_{BC} - h_{bot})}{d_{BC}} \cdot K_{s,BC} \cdot (h_{bot} + m) \cdot \tau \quad (5)$$

and bottom BC flux is expressed:

$$q_{bot} = \frac{Q_{GW}}{A} = \frac{(h_{BC} - h_{bot})}{d_{BC}} \cdot K_{s,BC} \cdot (h_{bot} + m) \cdot \frac{\tau}{A}, \quad (6)$$

where Q_{GW} is lateral groundwater flow to/from the model domain, h_{BC} [L] is the prescribed GWL above the model bottom at d_{BC} [L] distance from the modeled soil profile, h_{bot} [L] is the actual pressure head at the model bottom, $K_{s,BC}$ [L/T] is saturated hydraulic conductivity of the medium through which water flows into or out from the soil profile, m [L] is additional thickness to virtually extend the model domain to account for the entire depth in which inflow/outflow occurs, τ [L] is the perimeter of the soil profile, q_{bot} [L/T] is the bottom flux and A [L²] is the surface area of the soil profile. A practical restriction of this BC is that the height of the modeled soil profile should be such that $h_{bot} > 0$ is satisfied at any time step of the simulation, or in other words, calculated groundwater depth should never fall below the model bottom. Averaged and vertically adjusted GWL time series of nearby monitoring wells were applied as h_{BC} in the model. The parameters d_{BC} , $K_{s,BC}$, τ , A (aggregated to one parameter) and m were subject to calibration, while actual GWLs (h_{bot}) in the wetland were calculated by the Hydrus-1D.

2.4 Soil and vegetation parameters

Although 3D soil databases and thematic soil hydrologic maps become increasingly available with improving spatial resolution and overall reliability [47–48], these data sources still cannot represent site specific soil hydraulic characteristics typical to special habitats as the Nyárjas fen. Work and time intensive local soil sampling and laboratory measurements provides the most reliable information.

In order to reduce the number of independent unknown parameters, the saturated hydraulic conductivities and the water retention curves of soil layers in the wetland were determined by robust and simple laboratory tests and inverse modeling. Saturated hydraulic conductivities were measured with standard falling head method, while saturated water contents gravimetrically. To determine the remaining van Genuchten parameters of the water retention curve we applied a test that was similar to the one described by Ganot et al. [49]. A 220 cm deep soil profile in the fen was sampled with DN110 mm diameter plastic tubes. The samples were stabilized with permeable geotextile at the bottom end and then fully saturated ex situ. A 2 cm water column was imposed on the top of each soil sample, while atmospheric pressure was maintained at the bottom.

As a result of free drainage, the soil column went through a saturated-unsaturated phase shift. This shift is indicated by the nonlinear temporal variation of the measured bottom flux, thus it provided a solid basis for the approximation/validation of the saturated hydraulic conductivities.

The observed process was simulated with Hydrus-1D. Automated calibration was used to adjust soil hydraulic (van Genuchten) parameters so that the model results best fitted the measured bottom flux. Fig. 3 shows a typical result of

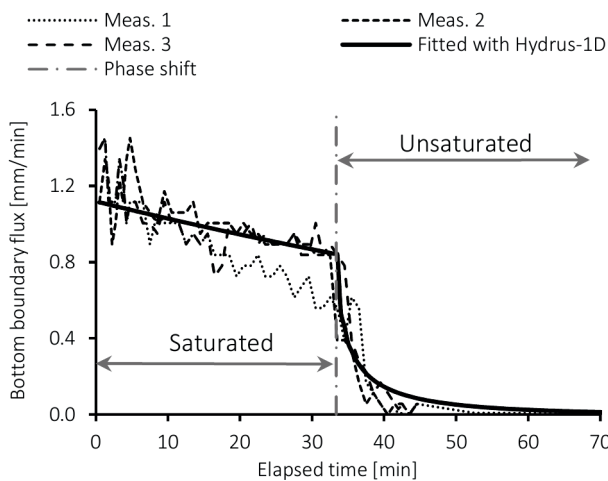


Fig. 3 Measured and fitted bottom boundary flux time series of the soil sample from the depth between 1.02 and 1.12 m

measured and simulated fluxes. Nash-Sutcliffe Efficiency (NSE) values were between 0.71–0.98. Fig. 4 illustrates the vertical distribution of saturated hydraulic conductivities and typical values of the water retention curve.

The hydraulic conductivity and the saturated water content clearly delineate the depth of the surface peat layer. This depth (~70 cm) is in line with the experiences of recent field observations. However, the drying of the wetland in the last four decades apparently affected the structure of the topsoil. Prolonged oxidative conditions resulted in the degradation and compaction of peat as it was observed and measured several times by Vas [34]. There is no reliable quantitative information about the spatio-temporal evolution of soil hydraulic properties for the analysis period, therefore the effects of this phenomenon were disregarded and the above introduced values were applied throughout the whole simulation.

Vegetation parameters were estimated indirectly, based mostly on the previous botanical surveys of the habitat [34]. For numerous reasons we did not have the possibility to directly quantify the leaf area index (LAI) for the whole simulation period with a consistent methodology. On site measurement would yield data only for present conditions missing most species formerly living at the site. The LAI variation of wetland habitat species appears to be scarcely studied [50–51] except for recent remote sensing technique-based research [52–54]. However, satellite imagery databases provide easily accessible infor-

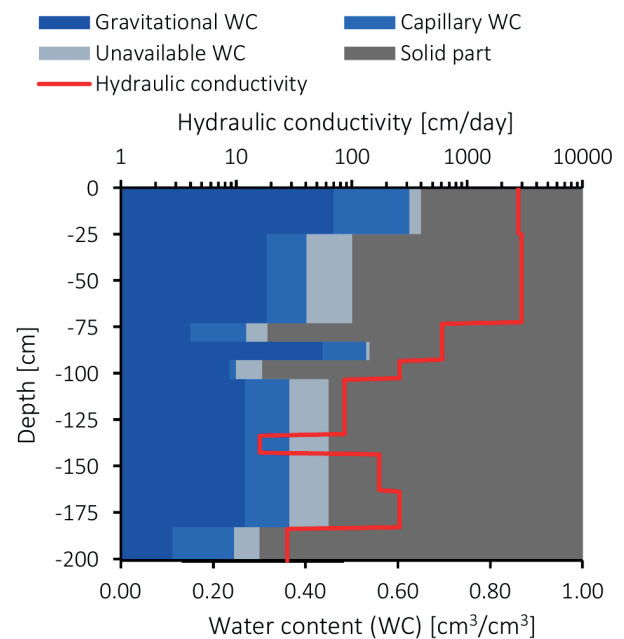


Fig. 4 Soil profile – Depth distribution of saturated hydraulic conductivity and water content

mation (e.g normalized difference vegetation index - NDVI or directly LAI) only from 1982 (Landsat 4), when the Nyárjas habitat had already undergone some degradation. Furthermore, early satellite images have a coarse resolution relative to the extent of the wetland, leading to over-estimation of the LAI: The presence of open water surface was frequent and widespread with mostly submerged or floating vegetation, while satellite image cells covering the wetland enclose not only terrestrial plants in the epilittoral zone but trees in the close vicinity of the habitat. Therefore, we defined the LAI time series on the basis of four coenological surveys between 1981 and 2009 and on relevant literature data. The temporal variation of LAI was characterized by trapezoidal curves, reflecting the seasonal pattern as well as the long term changes in species composition and abundance of plants: (i) from 1961 to 1984 between the minimum of $0.5 \text{ m}^2/\text{m}^2$ and maximum of $2.5 \text{ m}^2/\text{m}^2$, (ii) from 1990 to 2010 from $0.8 \text{ m}^2/\text{m}^2$ to $3.5 \text{ m}^2/\text{m}^2$, and (iii) curves linearly interpolated between 1985 and 1989. The maximum of the 1990–2010 period is the typical value of common reed (*Phragmites australis*) based on [50, 54], while maxima of the two earlier periods were estimated. Even though the formal validation process for LAI could not be done, we carried out a simple sensitivity analysis. This indicated that there was no significant change in simulation results for different LAI time series. Root distribution was adjusted according to field observations: root density was assumed to linearly decrease from surface to 1 m depth.

By default in Hydrus-1D, Feddes water stress response function [55] inhibits plant transpiration under near-saturated conditions (when water content in the root zone exceeds the user defined "anaerobiosis point" P_0) and in case of surface water coverage. Even though, generally this is an adequate approach in field hydrology, it means a conceptual fault when simulating wetlands as saturated root zone or water coverage mean near optimal physiological conditions for the vegetation typical in wet habitats. The S shaped stress function [56] theoretically would allow transpiration under fully saturated/inundated conditions, but in practice this option proved to be numerically unstable and led to significant water budget errors. To aid this issue, we modified the Hydrus-1D source code so that it allows transpiration under saturated-ponding conditions: as part of this modification, positive pressure heads (indicating saturation) can also be entered for parameters P_0 , P_{opt} , etc. of the Feddes stress function.

3 Results and discussion

The model was calibrated against locally measured groundwater/surface water level time series [35] by adjusting the parameters of the head-dependent flux BC. Overall, 357 measurements were available that cover the 1994–2003 and the 2007–2010 periods with an average 14 days frequency. According to the guidelines of the American Society of Agricultural and Biological Engineers [57], calculated and measured GWLs (Fig. 5) show good agreement in the calibration periods ($NSE = 0.77$ and $R^2 = 0.81$). However, in case of extremums the model sporadically over/underestimated the actual GWLs. The differences probably can be attributed to data uncertainties: (i) the biased estimation of the replenished water volumes due to intermittency of measurements, (ii) the assumed seasonal and long-term dynamics of vegetation and the corresponding changes in related parameters that could not be taken into account in details in the absence of specific data; and finally (iii) even though the agreement for the adjusted soil parameters was good ($NSE > 0.71$ for all samples), the introduced measurement method provides information only about the region of the water retention curve between saturation and field capacity (gravitational bottom flux occur only in this domain). As the method gives uncertain estimates for the higher pF values (in practice the drying part of the curve), we plan to carry out an uncertainty analysis for the soil parameters.

The relation of the input bottom boundary and the calculated GWLs (Fig. 6) illustrates the capabilities of the newly developed bottom BC. Simulated GWLs generally

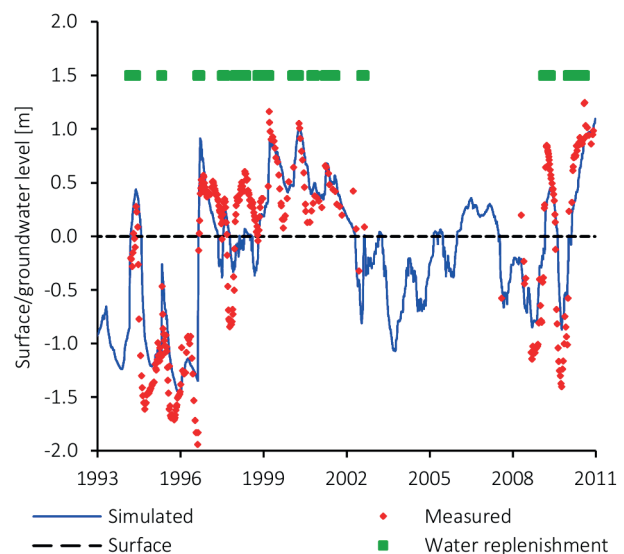


Fig. 5 Measured and simulated relative GWLs in the calibration period

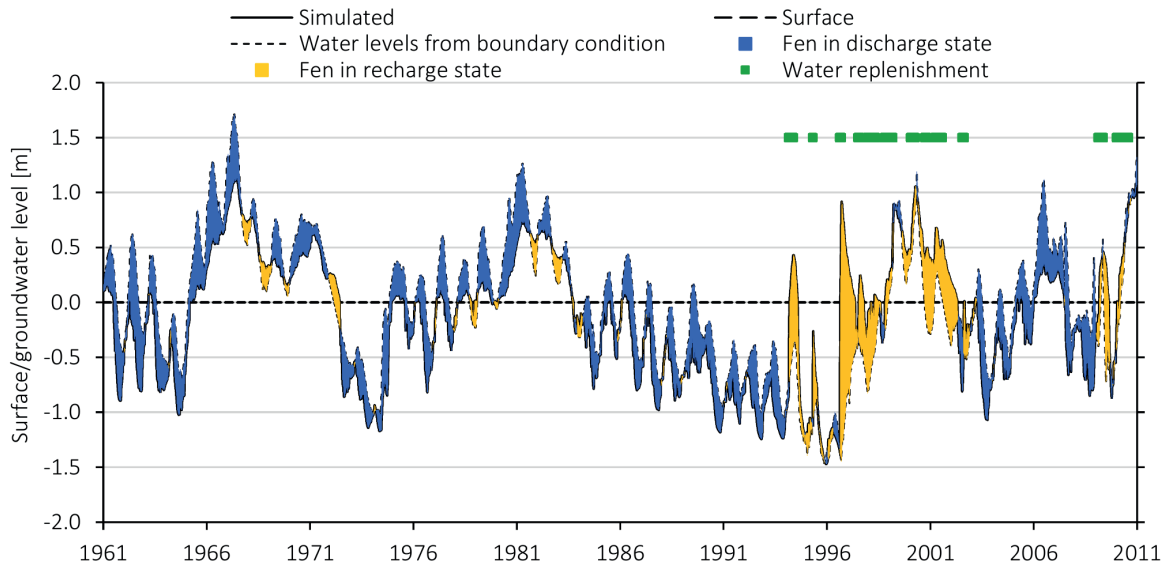


Fig. 6 Calculated and boundary relative GWLs and the direction of groundwater flow

follow those prescribed as h_{BC} , but, at the same time, flexibility of the applied BC allowed local hydrological drivers to produce their effects: (i) under natural conditions (from 1961 to the 1980s), due to almost continuous lateral groundwater inflow, range of GWL fluctuation was somewhat moderated within the wetland compared to the regional regime represented by measured GWLs in the monitoring wells, and (ii) local peaks caused by artificial water replenishment from 1994 could develop in the model, albeit these are not reflected in the h_{BC} time series.

On the basis of calculated GWLs in the wetland, the simulation period was divided into three distinct hydrological phases: (i) 1961–1983, (ii) 1984–1994 and (iii) 1995–2010. Statistical measures of GWLs (Fig. 7(a)) as well as frequency of inundation (Fig. 7(b)) in the growing season, and soil moisture dynamics (Fig. 8) within the range of plant available water content were calculated for each period. These measures express water availability and were used as hydrological indicators of the actual wetland status.

In the first period the typical range of relative GWLs was between -40 cm and $+40$ cm with an average of 0 cm (groundwater table is at the surface) and the wetland was inundated for about 156 days between March and October. Multiannual water covers developed twice and lasted for seven and three years. Correspondingly, full soil saturation in the upper 40 cm prevailed (its relative frequency was some 70 %) and soil moisture in this zone did not reach permanent wilting point at all.

Contrary, in the middle decade (1984–1994) the groundwater table was gradually declining and was found between -45 cm and -100 cm in 50 % of the vegetation periods with

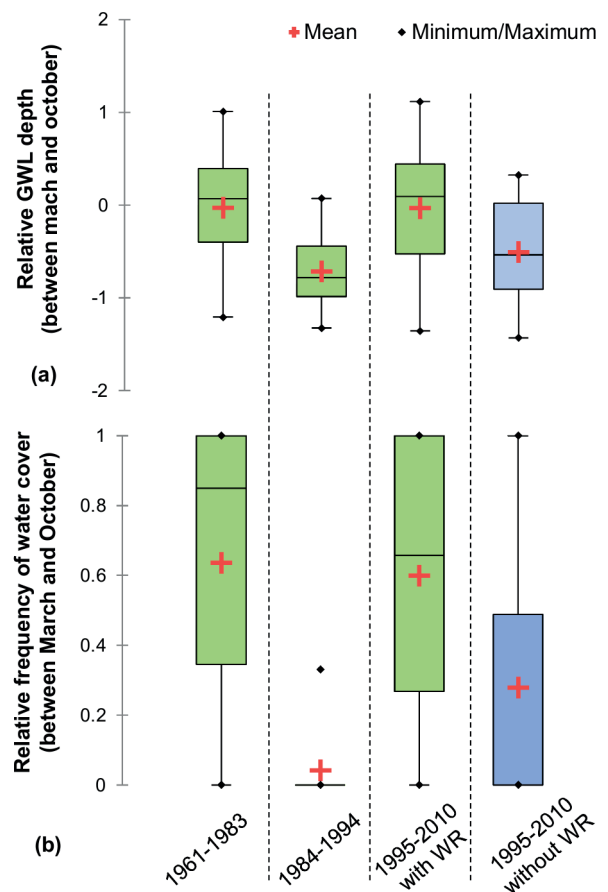


Fig. 7 Statistical measures of simulated relative GWLs (a) and frequency of inundation (b) in the growing season

an average of -71 cm. Surface water cover formed only in two years (in 1985 and 1986, echoing the antecedent wet period) and lasted for 13 % and 33 % of the growing season. Full saturation in the upper root zone (10 cm, 20 cm

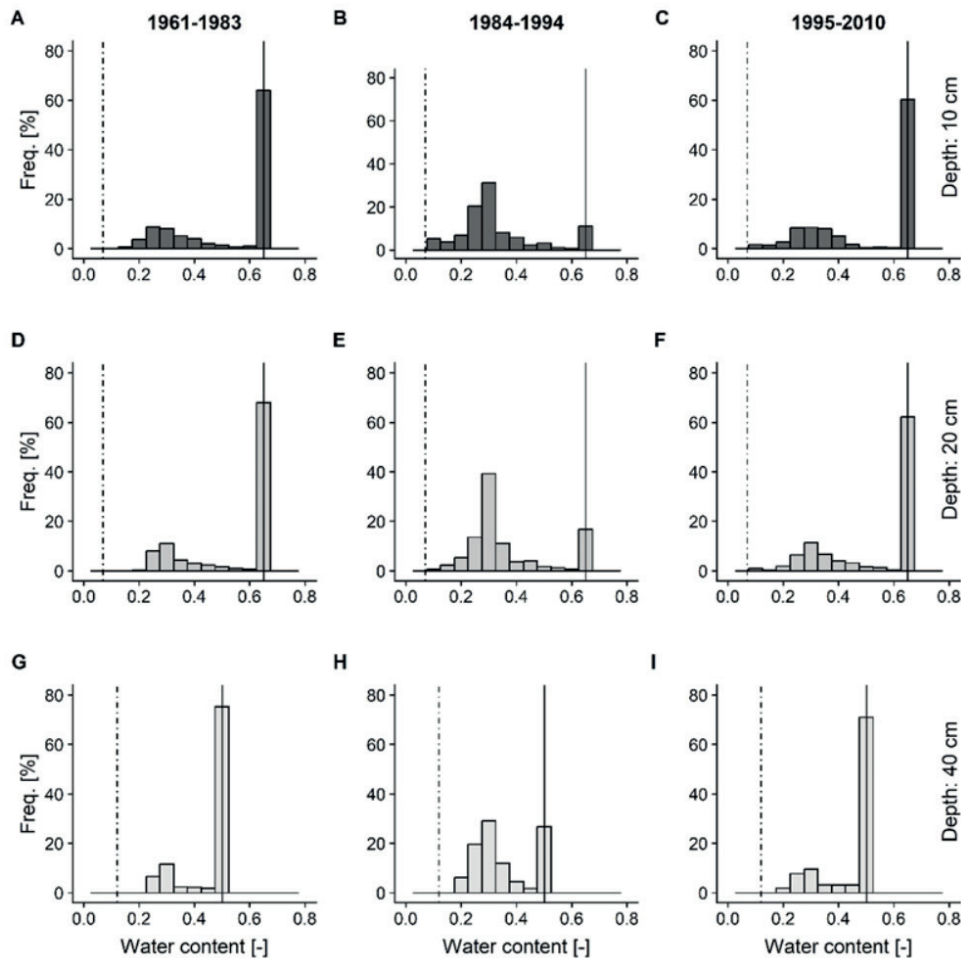


Fig. 8 Water content of various depths 10 cm (A, B, C), 20 cm (D, E, F), 40 cm (G, H, I) in the root zone in the three different climatic conditional periods. The dashed lines are the values of residual WC [-], the continuous lines are the saturated WC [-] values

and 40 cm depth) developed in only 10 %, 20 % and 30 % of the days, respectively, while the mean water content in the root zone was approximately half of the soil porosity. Intermittently wilting point was reached indicating severe water stress for hydrophilic plants.

Statistical measures of hydrological indicators suggest that artificial water replenishment in the third period (1995–2010) provided hydrological conditions highly similar to that of the first period by raising groundwater table by on average 47 cm compared to natural regime. The differences regarding GWL's are minor: range of typical groundwater fluctuation widened by some 15 cm, while the average and median GWL-s are identical. However, inundations occurred less frequently (the difference is more pronounced by the median), and the frequency of saturated soil conditions reduced by 2.6 % within the rooting depth.

It is noteworthy, that unlike other indicators, absolute minimum GWLs in the three phases show only minor deviation (between 1.2 and 1.4 meters below surface),

regardless of the climatic conditions. Therefore, this narrow range of groundwater depth designates the interval of extinction depth (below which root water uptake from groundwater ceases).

Considering regular inundation as the ecologically most determinant hydrological phenomena for a fen, groundwater dependency of the Nyárjas is obvious: the high hydraulic conductivity of peat in the upper 0.7 m makes the development of infiltration excess (Hortonian) inundation impossible, and water cover forms only if the topsoil is fully saturated (Dunnian process), that is the groundwater table rises near to or above the ground surface. The picture is more nuanced in case of soil moisture as the degree of saturation of the peaty topsoil depends on precipitation, potential evapotranspiration and the depth of the groundwater table. According to climatic conditions prevalent in the region, precipitation in itself is insufficient to maintain prolonged saturated topsoil, hence the presence of near-surface groundwater table is essential. With

mild changes in annual precipitation and potential evapotranspiration (9 % decrease and 4 % increase respectively) the role of groundwater was even more emphasized in the second period. In summary, due to the strong groundwater-dependency of the derived hydrological indicators, groundwater depth and dynamics can be considered as ultimate controlling variables. This finding is consistent with the general statement of [10], [12] and [58] concerning the determinant ecological role of groundwater regime in dependent ecosystems.

Regarding the first period as reference in terms of ecological status of the fen, typical GWLs can be associated with quasi optimal/acceptable water supply of the wetland. In other words, its characteristic values were within the range of tolerance of the ecosystem. Concerning the degradation, it is clear from the results that water availability for the ecosystem was severely limited in the middle period. Presumably, it was the second half of the decade when the lowering groundwater table produced its most destructive effect as declining GWL introduces water stress to the vegetation and leads to unfavorable physiological changes [58]. Similar habitat degradation processes were reported in several studies (e.g. [59–61]) in this period in the Danube-Tisza Interfluvium (a sand ridge highly similar to our study area), though groundwater decline was more pronounced in that region. According to the almost identical hydrological conditions, water supply of the ecosystem was seemingly close to optimal in the third period and one could expect regeneration of the fen. However, as botanical surveys pointed out, the wetland did not recover to date. Consequently, water availability was not or not the only factor that recently hindered regeneration.

Several factors may be associated with the continuously deteriorating ecological status of the Nyárjas. These may have acted simultaneously and/or in causality:

The long-lasting sub-optimal hydrological conditions in the second period led to significant habitat transformation, and the flora typical of fens were displaced by more tolerant terrestrial wet meadow-species.

Beside the direct impact of insufficient water supply on the ecosystem in the second period, the absence of regular inundation caused the floating mat of the fen to ultimately attach to the bed of the wetland, while persistent unsaturated conditions led to irreversible peat degradation. Decomposition can heavily reduce peat thickness and water holding capacity [62]. Furthermore, the process leads to the release of nutrients stored in peat biomass [63–64], which may shift the water quality and thus the

trophic status of the habitat. Field experiences of Vas [34] confirms the shrinkage of the peat layer and indirectly the increase of nutrient levels.

Fens are typically discharging type of wetlands [65–66], however, due to the extended periods of WR, there was a fundamental shift in the hydrogeological nature of the wetland as it turned from primarily discharging type to mainly recharging (Fig. 6). This conversion probably altered substance transport and accumulation processes in the soil.

The markedly different water quality of supplemented waters supposedly altered biochemical processes in the wetland. Water from the deep groundwater well has high concentrations of iron oxide (traces are visible at the point of inflow) and probably nitrogen of agricultural origin, while the drainage channel delivered water is rich in nutrients, since arable lands cover the majority of its catchment.

According to the currently available information, the fen's ecological response to changing hydrological conditions is either irreversible or has a significant time lag. The Nyárjas has presumably undergone an ecological regime shift [66] and even though the return of more moist years, up to date it was not able to regenerate after the 1984–1994 dry period. If the habitat will recover in the future, then the water availability (cause) and ecological status (effect) of the fen indicates a path dependent/hysteresis relationship [67]. However, in line with the argument of Gharari and Razavi [67] this behavior is only partially/seemingly hysteresis, in fact it can be explained with other water quality and biological causes (i.e. the above discussed factors). This fact emphasizes the importance of protection measures to conserve good ecological conditions, as the reversion of degradation processes is disproportionately expensive, time consuming or even not possible at all.

Compared to previous research, our analysis offers two novelties: First, the studies focusing on wetland degradation and rehabilitation efforts in Hungary usually deal with riverine, riparian or saline/salt lake habitats [61, 68], while the eco-hydrological investigation of fens is surprisingly under-represented. Second, most analyses use a method (see e.g. [35, 69–71]), which cannot describe groundwater, soil moisture and surface water conditions simultaneously (only one or two of them), even though these have a strong, but not necessarily linear relationship. The presented research overcomes the latter methodological challenge through the example of a fen. Even though it's restricted spatiality, the proposed approach might offer new possibilities in the research of groundwater dependent freshwater habitats.

4 Conclusions and outlook

Using past hydro-meteorological data and SVAT simulations we were able to reconstruct the local hydrological conditions of a degraded fen for five decades, including periods prior to local measurements and botanical evaluations. To do so, we used the Hydrus-1D model with a novel lower boundary condition. The extended one-dimensional approach proved to be adequate to simulate the hydrological processes relevant for the wetland, while its relatively low data requirement enabled us to use it with the available data.

Statistics of inundation, groundwater depth and root zone saturation were derived from simulation results and were used as indicators reflecting the hydrological status of the wetland. Based on the variations of hydrological indicators, the examined 50 years were separated into 3 distinct phases regarding water availability.

Substantial differences in the hydrological indicators suggest that the degradation of the wetland is strongly related to the decreasing precipitation and lowering groundwater table in the 1984–1995 period. It was shown that artificial water replenishment greatly facilitated the restoration of near-optimal hydrological conditions between 1996–2010, however, the wetland has not regenerated. It was concluded that other factors not assessed in this study may have hindered regeneration.

We would like to extend our research of the Nyárjas fen to several directions. We plan to extend the temporal

interval of the analysis both to the past (back to the early 1900s) to track the long-term hydrologic regime shifts and its relationship with ecological changes, and to the future in order to aid restoration efforts in the shadow of climate change. Another strand of the research will focus on the ecosystem services the Nyárjas fen provides and how these services evolved along with the alterations of eco-hydrological status of the wetland.

The applied methodology provides local results for a certain site. The general validity of the mathematical background and the capabilities of the BHR-algorithm enables one to carry out the automated eco-hydrological evaluation for a large number of habitats. Thus, the methodology can serve as a tool for regional/country scale assessment in a bottom-up approach (as did so in the 2nd Hungarian River Basin Management Plans from 2016 [72]).

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