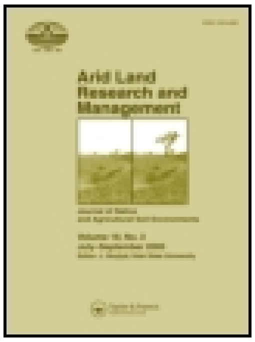

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Longer-term monitoring of a degrading sodic lake: landscape level impacts of hydrological regime changes and restoration interventions (SE Hungary)

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ABSTRACT

The diminishing number, extent and degradation of soda lakes were reported from the lowland area of the Carpathian Basin in the past two decades due to anthropogenic impact and climate change. This study provides a detailed spatio-temporal assessment of a degrading alkaline sodic lake ecosystem (13.5 ha) in Southeast Hungary. It discusses the results of spatially detailed topsoil and vegetation surveys from 2009 and 2018 to understand the changes among the current natural and anthropogenic conditions to support a future possible ecological water management. Habitat mapping and laboratory measurement of EC2.5, soda and calcium carbonate content from 199 topsoil samples provided the basis for the assessment. In 2009 the degradation of the naturalness was observed according to the vegetation survey, and the topsoil parameters reflected steppification, leaching and desalinization. Between 2009 and 2018 the loss in extent of Puccinellia swards and the spread of salt meadow species along the channel continued due to the changing salt content. According to the 2018 snapshot of the topsoil, higher salt (from 0.7 to 1.3 mS/cm) and soda content (from 0.08 to 0.12%), furthermore decreasing $CaCO_3$ content (from 25.89 to 20.08%) were characteristic, meaning that there was a changing water and salt regime in the lakebed. The past decade was partly favourable in the point that humid years could rehabilitate the natural conditions in certain parts of the lakebed, but they did not prove to be enough to sustain this alkaline sodic lake.

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KEYWORDS
Changing habitat pattern; changing saline ecosystems; degrading sodic lake; steppification

Introduction

Due to human impact and climate change, saline wetland ecosystems became endangered in the last decades all over the world (Aladin and Plotnikov 1993; Poiani, Johnson, and Kittel 1995; Williams 2002; Timms 2005; Harvey, Ayers, and Gosselin 2007; Pitchford et al. 2012; Boros, Ecsedi, and Oláh 2013; Kertész et al. 2020) resulting in challenges for ecology, economy and society. The changes in supply, movement and chemical attributes of water, furthermore topography and climate determine the nature of these wetlands (Smith, Rollins, and Shinn 1994), therefore, their monitoring is an important step toward proper wetland management.

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The preservation of Pannonic salt steppes and salt marshes is of high importance in the European Union (Natura 2000 habitat type, code: 1530, IMEUH 2007), their occurrence is only related to the Carpathian Basin, mostly to Hungary, Austria, Slovakia and Romania. The Pannonian salt steppes, salt marshes and shallow salt lakes are highly influenced by Pannonian climate, the salt accumulation in the topsoil is due to the intense evaporation of groundwater during the summer. Compared with other salt lakes and marshes of the world, the alkaline lakes here are characterized by lower salt content but higher alkalinity (Šefferová Stanová, Janák, and Ripka 2008).

Among saline habitats Last and Ginn 2005 distinguish lakes, wetlands and grasslands. Following the classification of Pannonian salt-affected areas which was utilized by Dítě et al. 2023, the following habitats can be distinguished; hypersaline open swards (lakeside vegetation of soda pans, soda pans (or salt lakes), salt marshes and alkali meadows, as well as salt steppes (or grasslands). In the paper we used the following tentative definitions, listing the studied habitats from the highest to lowest. Salt steppe is a (semidry) grassland composed of salt-tolerant and halophyte plants, used typically as a graze land for sheep, cattle or horse. Puccinellia stands are a kind of transition between steppe and meadow habitats. Salt meadow is composed mainly of grasses, but also sedges with short duration of waterlogging and very small patches of open water; the habitat is used typically as a hayfield. Salt marsh is another type of wetlands with extended waterlogging and larger patches of open water, being composed of reeds, cattail, sedges and some grasses; it is used typically as a sedge hayfield or grazed by swine or buffalo. Shallow salt lakes have temporary water cover above the bare lake bottom, which are often drying out after dry summers.

Based on the salt and water supply, halophytic plant communities follow a characteristic zonation from dry steppes across wet salt meadows to annual plant communities of periodically flooded salt lakes (Tóth and Kertész 1996; Tóth 2002; Zalatnai, Körmöczi, and Tóth 2008; Deák et al. 2014) in relation to micro-relief conditions. Shallow salt lakes in Hungary (also called alkaline lakes, alkaline sodic lakes, soda lakes, soda pans depending on the salt content and water cover) due to their highly diminishing number, are protected by the Act on Nature Conservation No. LIII. of 1996. The degradation processes, as diminishing number (Hoyk and Sipos 2010), decreasing coverage (Biró et al. 2008, Molnár 1997, Deák and Kevei-Bárány 2006), unfavorable changes in hydrologic (Tóth, Kuti, and Fügedi 2003, Ladányi et al. 2009, Rakonczai 2011) and salt condition (Rakonczai et al. 2008, Füleky et al. 2013), altering in biodiversity (Török, Kapocsi, and Deák 2012) were monitored by several authors in the past decades in Hungary. In addition, there have been numerous publications on the drivers of change (Valkó et al. 2014, Molnár et al. 2019), and restoration possibilities (Boros, Ecsedi, and Oláh 2013) of salt lakes, as well.

Zadereev et al. (2020), Mile and Unyi (2017) stated that there are no universal causes for the degradation of saline lakes by continents, regions or climatic gradient, but a combination of several global/local factors. Wurtsbaugh et al. (2017) emphasize the importance of human impact on the decline of saline lakes, namely surface inflow diversions. Global warming has two major effects on saline lakes, as increased evaporation and decreased runoff into the lakes, both decreasing water volume and increasing salinity. Williams (2002) predicted a significant decrease in the area of saline lakes in the near future.

This study aims to provide a detailed spatiotemporal monitoring of the valuable saline ecosystem in a small degrading alkaline sodic lake (13.5 ha) in Southeast Hungary to support its future preservation. The lakebed has no surface water cover since decades, steppification, desalinization and leaching became dominant processes mostly due to (and in the lack of) anthropogenic interventions and the impact of climate change, the more frequent drought years lowering the groundwater table. The current study discusses the results from the 2018 soil and vegetation survey campaign and describes the differences between 2009 and 2018. The reason for the spatially detailed soil and vegetation monitoring is to understand the changes among the current natural and anthropogenic conditions to support a future possible ecological water management in the lakebed.

The investigated small lake still preserves the valuable ecosystem of the alkaline lakes and the spatial extent of reed spread, thus, ecological water management can bring fruitful results in long term to preserve the valuable ecosystem. In the past decade, the lakes in the immediate vicinity of the sample area were managed differently (Table 1). Studied Lake Kancsal (1), is still drained by a channel and there is no water retention to stop drying and degrading of the halophytic vegetation. Lake Nagyszéksós (2) is under a buffalo-driven complex rehabilitation project, started in 2010, with water retention and water supply managing the reed and water levels in the lakebed. Lake

Table 1. Water quantity and quality data of the Lake Kancsal and the neighboring sodic lakes in South-East Hungary from the early 1970s (Andó 1975), their current state and management status (Ladányi et al. 2016; Ladányi 2017).

Surveyed parameters		1 Lake Kancsal	2 Lake Nagyszéksós	3 Lake Kisszéksós	4 Lake Madarász
1970s	Extent	13.5 ha Open water surface	120 ha Open water surface		36.9 ha Open water surface
	Water level	0.6 – 1.5 m	0.5 – 0.8 m		0.8 – 1.2 m
	Annual water level dynamics	0.8 m	0.8 m		0.8 m
	pH	9.5	9.2		9.5
	Dissolved salt content	2500–3000 mg/l	2500–4000 mg/l		2000–3000 mg/l
2010s	Open water surface in spring	No	Yes	No	Yes
	Naturalness	Degrading naturalness, no water cover, changing soil and vegetation, no restoration	Improved naturalness in the past decade due to restoration (water retention, reed management, buffalo reserve since 2010)	Degrading naturalness, high reed cover, no restoration	Reed spreading, open water surface due to water supply
	Water retention or supply in the canal	No	Yes	No	Yes
	Management	Mowing (once per year, several owners)	Complex water management, buffalo reserve (with more than 150 buffalos)	Reed harvesting	Reed management

Kisszéksós (3) is under the monodominance of reed (like Lake Nagyszéksós was before 2010) and there is no water retention in the channel (Ladányi 2017). Lake Madarász (4) degraded the least in the past decade due to water supply and recreational purposes. However, in the past few years reed spread was also characteristic, threatening its existing valuable wildlife.

In the lakebed of Lake Kancsal 5 main habitat types can be determined (Ladányi and Rakonczai 2012, Ladányi et al. 2016), where the year-by-year changes are driven by the horizontal and vertical salt and water transfer, furthermore other physical impacts like trampling or disturbance (Table 2). The hypothesis of the study is that the changing habitat pattern is determined by the exact location and the changes of the background factors. These conditions may contribute as criteria for identifying appropriate management options.

Table 2. Major physical and chemical factors influencing habitat stability.

Factors	Annual salt pioneer sward	Puccinellia sward	Salt meadow	Salt marsh	Sand steppe grassland
Precipitation	+	+	+		
Level of the groundwater (of high salt content)	+	+	+	+	
Disturbance, treading		+			+

Materials and methods

Study area

The studied area, called Lake Kancsal, is a degrading lake located in Southeast Hungary near the Hungarian-Serbian border (Figure 1), being one of the highly valuable alkaline sodic lakes in the region preserving steppe and wet inland halophytic vegetation of the

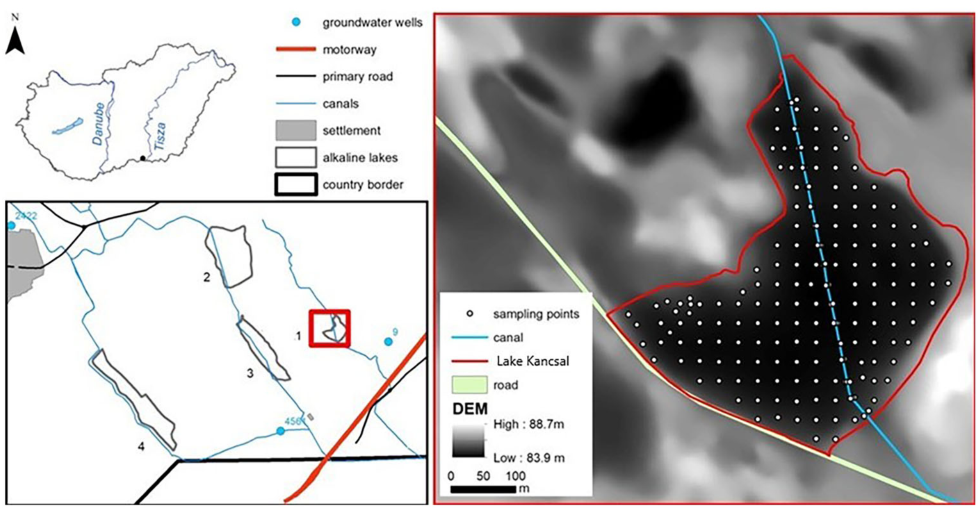

Figure 1. Location of the study area (1: Lake Kancsal) in Hungary, the neighboring alkaline sodic lakes (2: Lake Nagyszéksós; 3: Lake Kisszéksós; 4: Lake Madarász).

Pannonian Biogeographical Region. These lakes were formed by the prevailing north-western winds in a blown-sand area between the Danube and the Tisza River, resulting in a landscape determined by deflation hollows (allowing the lakes to be formed), residual ridges and sand sheets. The main water sources of these lakes are precipitation and local and regional groundwater flows coming from the higher elevated parts of the Danube–Tisza Interfluve. The depressions of the area were drained in the 1970s by several canals to remove surplus water from the surrounding arable land matrix. Furthermore, due to climate change, more drought years were experienced after the 1980s. As a result of the experienced changing water (and salt) regime and mostly the lack of wise water management, the wet inland halophytic vegetation of these lakes started to change: reed spread and steppification, thus degradation of the naturalness could be observed (Ladányi et al. 2016). Apart from the fact that data were available on the degradation from the past decade, the restoration has not been started because the land belongs to several private owners and the channel is managed by the water authorities.

The survey campaign in 2018 was a repetition of a detailed survey performed in 2009 (Ladányi, Rakonczai, and Deák 2011, Ladányi et al. 2016) to get a snapshot from the topsoil conditions in the lakebed of Lake Kancsal with a very high spatial resolution, and it was a part of a longer term vegetation monitoring of the lakebed (2002–2018).

Soil resampling was executed from the topsoil (0–10 cm) along the same network of 199 points in November 2018 as in 2009. Points were predefined in a regular network of 30 m intervals, and refined at the channel to monitor both sides and the bottom. Furthermore, some additional points were allocated during the sampling to get into more details around the salt efflorences. The lakebed is dry almost all year (except for early spring water inundations in humid years, e.g., 2010), the canal (built-in 1972) still drains the water from the area preventing water accumulation in the lakebed. The sluice gate set in the channel to control the outflow from the lakebed is still not operable at present. Salt-affected soils (mostly Solonchak according to the Hungarian Soil Classification System) are typical in the lakebed (Kreybig 1943). A small degree of spatial inhomogeneity can be seen within the lakebed, however, the area having the highest salinity corresponds to the Solonchak Reference Soil Group of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015), meeting the salinity, pH and thickness criteria.

For the detailed temporal assessment of the habitat pattern, a habitat map of the sample area was drawn in 2018 using the categories of the General National Habitat Classification System, complementing the existing data series (Ladányi et al. 2016). The boundaries of patches were allocated using a Trimble Mobile Mapper ($p = 0.5$ m) and high-resolution aerial photos (0.1–1 m) – the minimal area of a polygon was 35 m^2, similar to the previous studies. According to the categories of the General National Habitat Classification System of Hungary (A-NER, Bölöni et al. 2007; Bölöni, Molnár, and Kun 2011), the most extensive natural habitat in the lakebed is Puccinellia sward (F4) (a community of *Lepidio crassifolii-Puccinellietum limosae* dominated by *Puccinellia limosa* (Schur)Holmb, *Lepidium crassifolium* Waldst et Kit, *Aster tripolium ssp. pannonicus* (Jacq.) Soó). The abiotic preferences for F4 are the high level of groundwater with high salt content, furthermore a relatively longer-term surface water cover. They generally occur on Solonchak soils (according to the Hungarian Soil Classification System and WRB 2015). Annual salt pioneer sward (F5) (community of

Lepidio crassifolii-Camphorosmaetum annuae), dominated by *Lepidium crassifolium* occur only at the edges in small extensions. The abiotic preferences are same as of F4, however, they are permanently covered by water with a high salt content that cannot allow perennial vegetation to survive, salt accumulation on the surface is typical, and furthermore they frequently occur on trampled or steeper slopes. Salt meadows (F2), belonging to the *Agrostio-Caricetum distantis* association dominated by *Agrostis stolonifera*, appear at the edge of the lakebed and along the channel representing the degradation process due to the changing water regime. F2 typically occurs on Solonetz meadow soils (according to the Hungarian Soil Classification System), Gleysols (according to the WRB 2015) where the waterlogging is characteristic only until springtime and became totally dry for summer. The salt accumulation is generally observed in the B horizon of the soil, the humus content is higher in the A horizon. Salt marshes (B6) dominate the deepest parts of the lakebed (communities: *Bolboschoenetum maritimi* and *Bolboschoeno-Phragmitetum*), where water logging with high salt content is the most permanent compared with the previously mentioned habitats. Sand steppe grasslands (H5b) can be found on the sand ridges at the edges of the deflation hollow (Ladányi et al. 2016), where the parent material is mostly aeolian sand with a lower ratio of clay particles and higher humus content compared to the open sand steppes.

The information about the precipitation of the studied period based on Szeged station data (8 km in the NE direction) and groundwater table level changes based on well data (no. 2422 2 km in SW direction, no. 4561 7 km in NW direction, and no. 9 1.5 km in W direction) were assessed.

Laboratory methods and data processing

Laboratory measurements were carried out for soil physical and chemical parameters in 2018: EC2.5, soda content (%), calcium carbonate content (%). The total salt content (EC 2.5) was characterized by measuring the electric conductivity of 1:2.5 soil:water extract. Soda alkalinity (soda%) was determined from soil suspension, titrated with 0.1 M $KHSO_4$ till the red color of phenolphthalein disappears. The calcium carbonate content was determined via Scheibler-type calcimeter.

Result maps were compiled by ArcGIS 9.3 and for visualization the data was classified with the natural breaks method. Boxplots were also calculated with ArcGIS 9.3.

Results

Changes of hydrological conditions following the 1970s

The annual precipitation shows more frequent extremities in the past two decades compared to the 1970–1980s in the region (Figure 2). The lowering of the groundwater table, was slightly experienced here too, however, the decrease was not so intensive as in the higher elevated part of the interfluve region. The changes in the hydrological regime, the draining impact of the established canals in the wetlands resulted in a degradation process for the alkaline sodic lakes: desalinization, steppification, drying out started. As a result of the humid years of the past decades, groundwater table started to increase (Figure 2). In the investigated period (between 2009 and 2018) 2010 and 2014

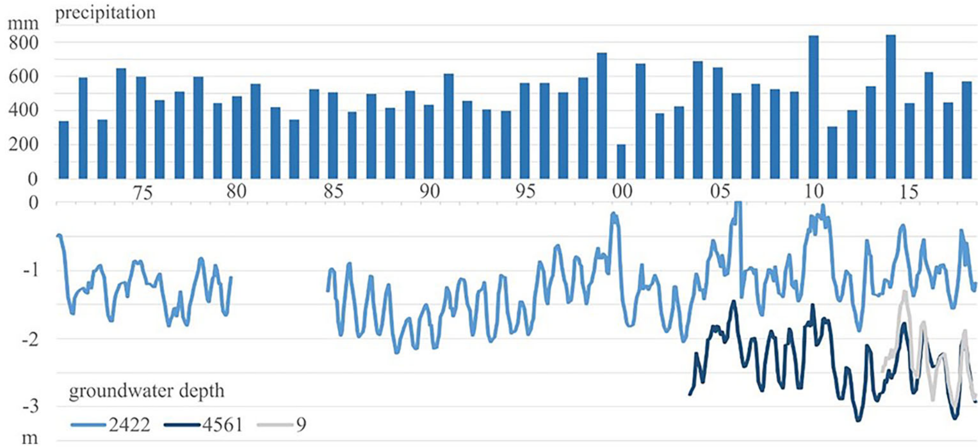

Figure 2. Precipitation and groundwater changes in the neighborhood of the lake since the 1970s (data: precipitation from Szeged station (in 8 km in the NE direction) and groundwater table level (wells no. 2422, 2 km in SW direction, no. 4561, 7 km in NW direction, and no. 9, 1.5 km in W direction, see Figure 1).

were extraordinarily humid years, which helped the groundwater to reach periodically the near-surface soil horizons. An additional attempt in the region was the complex rehabilitation of the Lake Nagyszéksós (water supply and retention, ensuring the appropriate seasonal lake level changes) that also contributed to the rise of the local groundwater table.

Figure 3 represents a West-East cross-section of the lakebed and the characteristic habitats (except for salt marsh in the clay-mining pits) and the characteristic water table stages from the past decade schematized for three different water and salt conditions in

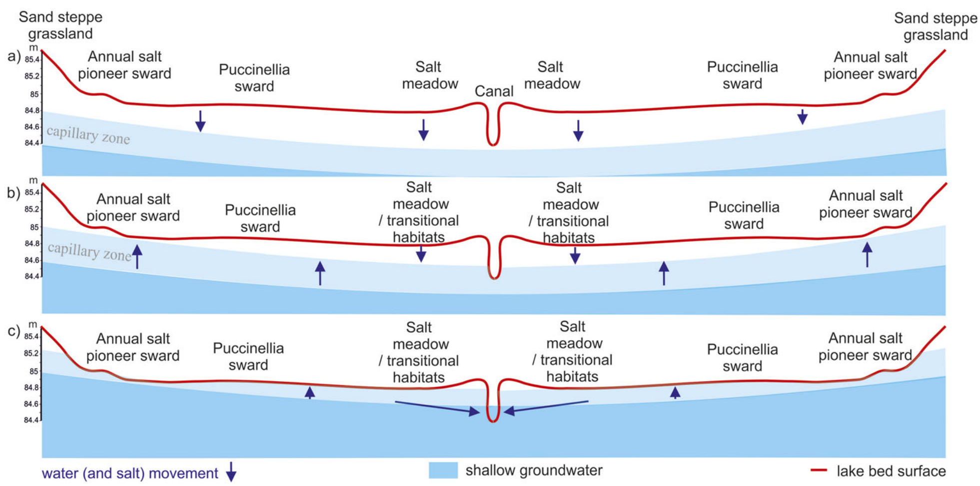

Figure 3. Schematic cross-section of the lakebed and the characteristic habitats (except for salt marsh in the clay-mining pits in the western part of the study area) and the characteristic water table stages from the past decade in case of (a) low water levels (e.g., 2009), (b) better salt and water supply for annual salt pioneer swards and Puccinellia swards (e.g., 2018), (c) better salt and water supply for all habitats, but draining impact of the channel, removal of water and salts due to the lack of water retention (e.g., 2010).

the lakebed including low water levels after dry years, the impact of humid years without water control in the channel. The figure represents how sensitive and mobile the system is at present and how vegetation adapts to the changing water and salt supply in the different years.

Assessment of habitat changes between 2009 and 2018

Previously, a widening zone, where changing vegetation conditions occurred due to the changing salt and water regime was allocated along the channel which was caused by the canal draining, and the drying-out process. According to the habitat map made in 2018 (Figure 4) the widening of zone along the channel continued, where transitional

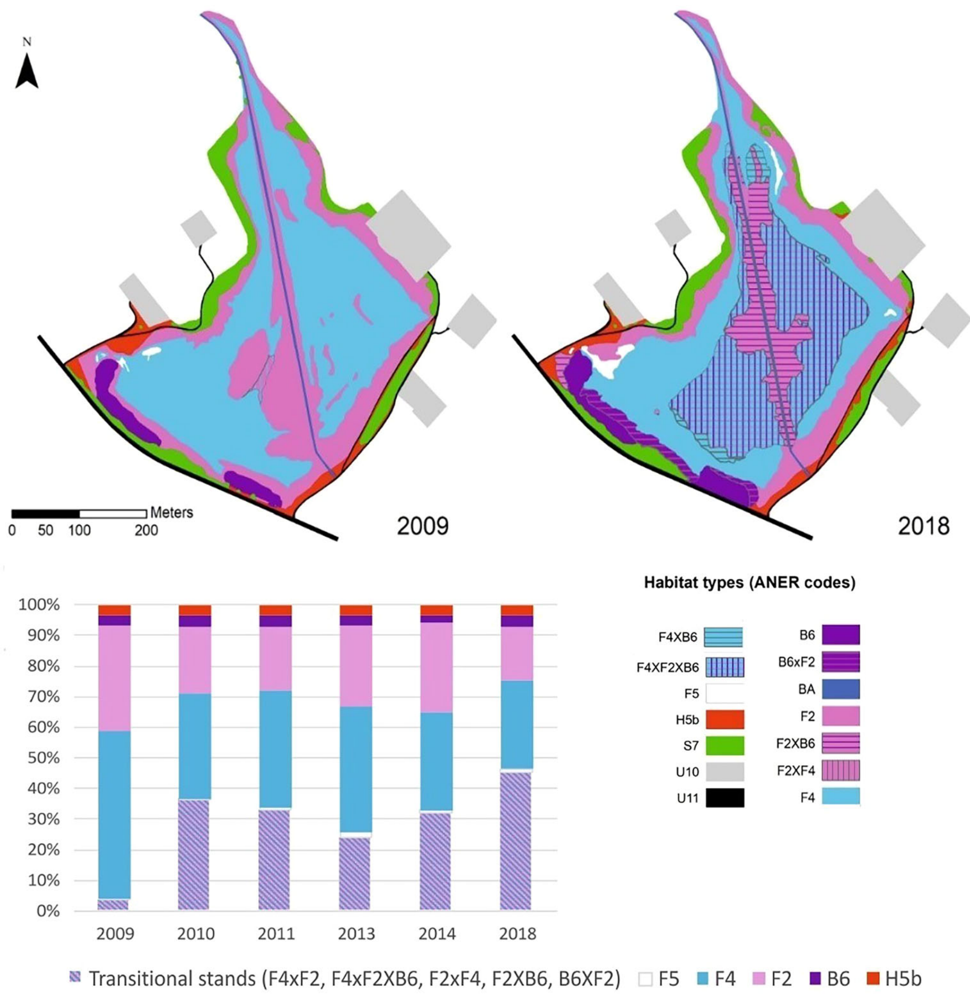

Figure 4. Habitat types in the lakebed using the nomenclature of the General National Habitat Classification System (Bölöni, Molnár, and Kun 2011) – spatial (from years of the detailed soil assessment, 2009 and 2018) and temporal changes of the habitat types between 2002 and 2018. (B1a: reed; B6: salt marsh; BA: channel; F2: salt meadow; F4: Puccinellia sward; F5: annual salt pioneer sward; H5b: sand steppe grasslands; P2c: Invasive shrub dominated stands; S7: Non-native tree species; U10: hamlet; U11: road, transitional habitats indicated by 'x').

stands expand as a result of low salt content and water cover. There is a further decrease in the extent of the natural Puccinellia swards, and more salt meadows (and in humid year salt marsh) – Puccinellia sward transitional stands can be observed. There is an increase in the number of patches and extent of the annual salt pioneer swards (N and SE parts). There is a spread of reed in B6, especially in humid years. The Northwestern part of the area is managed by the local farmers against reed spread and invasive species (e.g., *Solidago canadiensis L., Asclepias syriaca L.*) on the edges (Ladányi and Rakonczai 2012, Ladányi et al. 2016). The extent of the salt meadow is changing from year by year, it spreads mainly along the channel, while its decrease is only observed in the salt marsh due to the spread of reed.

Dynamic change in the habitats along the canal could be observed in the past decades. The reason for the change is the different water (and salt) supply, thus the varying drought and humid years produce different and variable habitat patterns. The habitat change overlaid with the soil sampling network shows those points where vegetation change occurred between 2009 and 2018 (Figure 5). It seems that most of the changes are in the middle of the lakebed related to the channel, and the western part of the area connected to the changes of salt marsh. Invasive species cannot be seen in the lakebed in 2018, the farmers do mowing in the area, and utilize the hay. Due to the machines used for management purposes and for crossing the area reaching the farms,

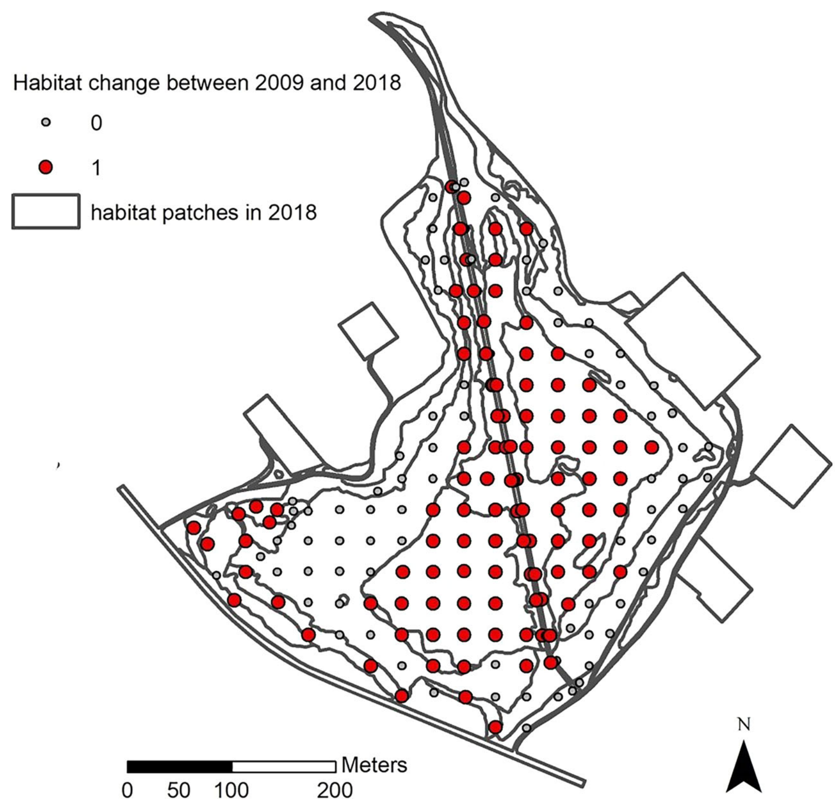

Figure 5. Detected habitat changes between 2009 and 2018 at the soil sampling points. White dot means no change, while red dot means change.

the trampling resulted in very small patches of surface salt efflorescence in the south-western edges too.

Assessment of changes in soil processes between 2009 and 2018

Based on the box-plot diagrams of all measured point data, a significant change of the upper soil layer chemical features could be observed based on the laboratory measurements in 2018 compared to 2009 (Figure 6). Increasing soda content, but decreasing calcium-carbonate content was observed in the lakebed.

In 2018 EC2.5 and soda content showed lower values along the channel (Figure 7). The highest values were represented between this zone and the edges, and at the bottom of the channel (except for soda content). The soil sampling points on the highest elevated edges could be described by similar values compared to the zone along the channel. If we compare the western and eastern parts of the lakebed, the previously mentioned parameters (EC and soda) showed not exactly the same pattern, which was probably due to the impact of the NW-SE groundwater flow, which could enhance the salt accumulation near the slopes, and can foster the degradation/leaching out near the channel.

The pattern of the calcium carbonate content was different compared to the previously described (EC and soda) parameters. The lowest values were characteristic only for the edges (especially on the southern part of the lakebed), and there was no zone along the channel where a decreased pattern could be observed. The highest carbonate content occurred in a large part of the lakebed and also at the bottom of the channel.

The changes in the parameters between 2009 and 2018 showed different patterns. Decrease in EC2.5 was characteristic in the bottom of the channel and near the edges in the southern part of the lakebed (Figure 8), furthermore near the salt accumulation zone toward the edges in the north-western part. At several points in the flat lakebed

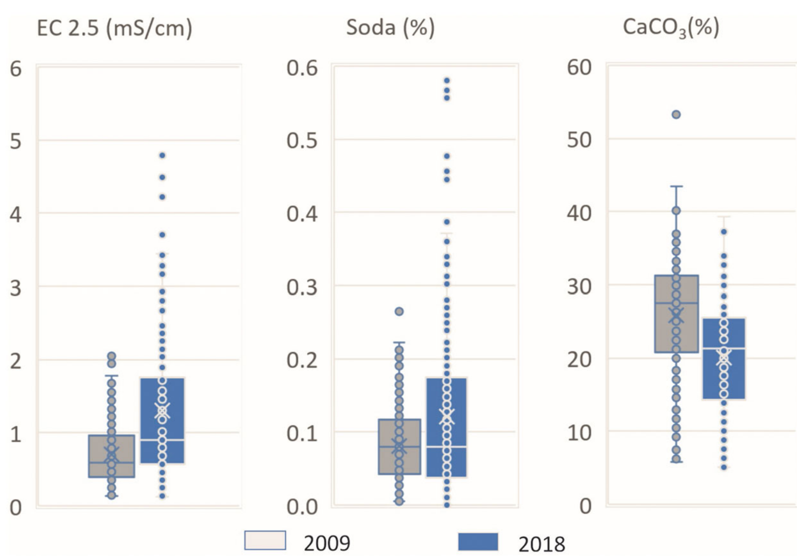

Figure 6. Changes of main soil chemical parameters of topsoil layer between 2009 and 2018.

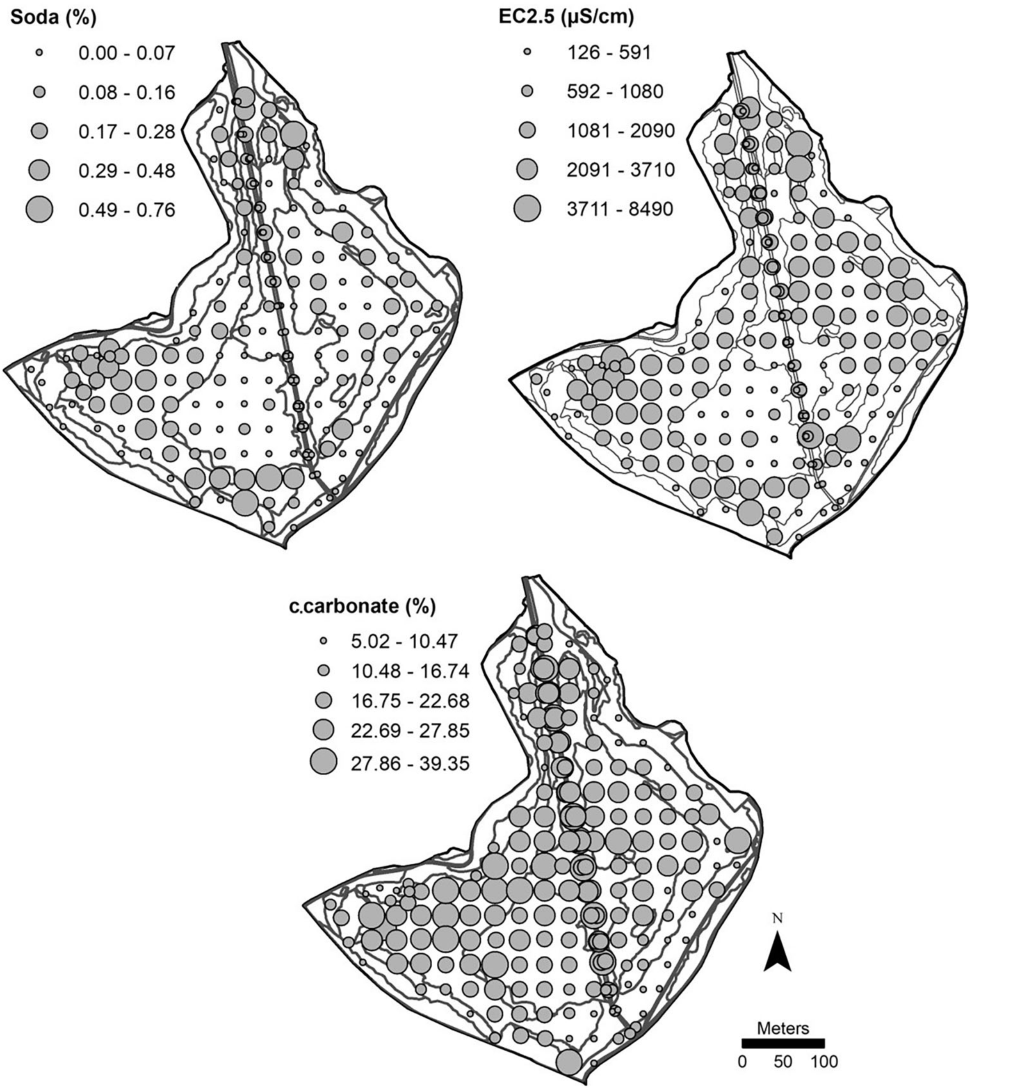

Figure 7. Spatial representation of EC2.5, soda and calcium carbonate content of the topsoil measured in 2018 along a regular network in the lakebed.

(mostly near the channel), there were no significant changes in the measured EC2.5 values, and the increase was characteristic toward the edges and near the surface salt accumulation patches. Soda content changed also in two directions, similarly to the EC2.5. The highest decrease was observed at the bottom of the channel (Figure 8), and a decrease was also characteristic of the leaching-out zone along the channel and the edge zone of the highest elevations. In between these zones, the soda content remained the same or showed a slight increase, especially near the surface salt accumulation patches. In the case of calcium carbonate content, the changes were decreases at all points. The highest decrease was characteristic of the bottom of the channel and the surface salt accumulation patches near the edges.

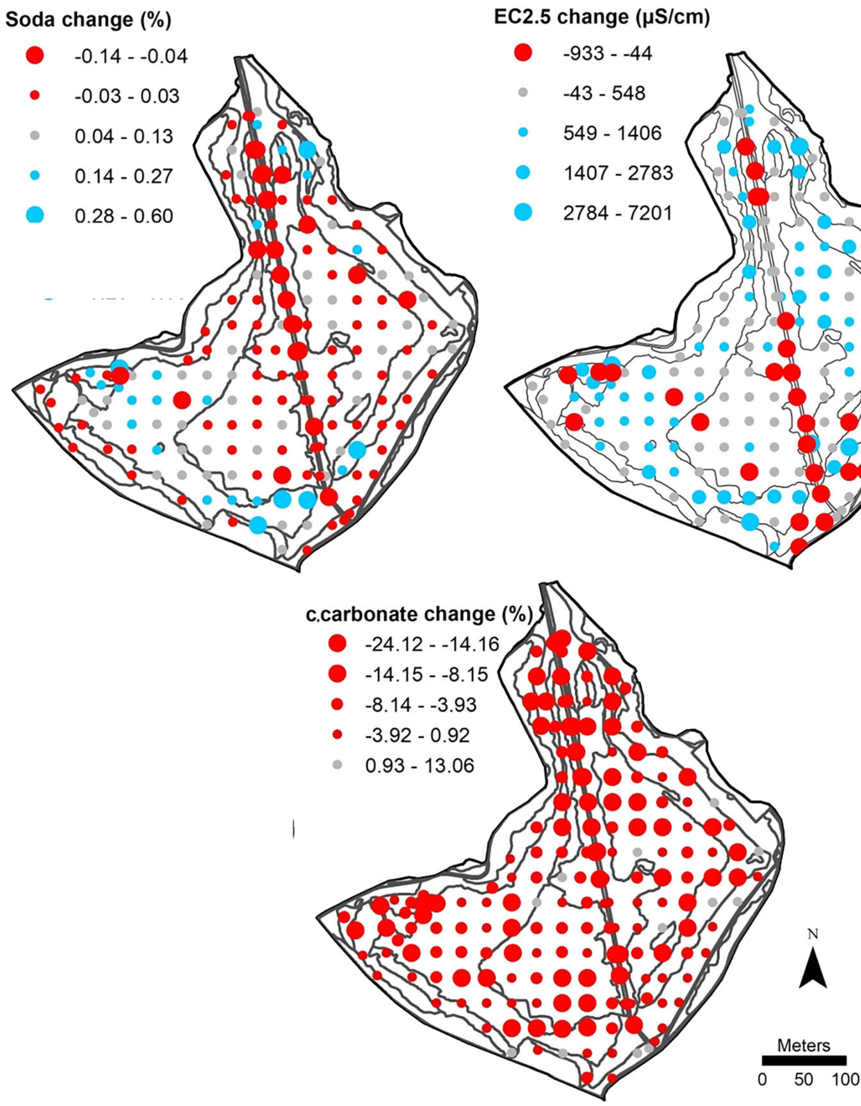

Figure 8. Spatial representation of the temporal changes (2009–2018) in EC2.5, soda and carbonate content of the topsoil along the regular network in the lakebed.

Joint assessment of soil and vegetation changes between 2009 and 2018

Among the investigated soil parameters soda (%) and $CaCO_3$ (%) were selected to investigate the changes in salinization and leaching, which are major processes influencing/shaping the habitats of the lakebed. The highest increase of soda (%) was observed at the annual salt pioneer swards (F5), but it was also characteristic in the Puccinellia swards (F4) (Figure 9). For the transitional habitats along the channel in 2018, it is difficult to explain Figure 8, as there were only a few soil sampling points located in transitional habitats in 2009. Decrease was characteristic for salt meadows on the edges neighboring the sand steppe grasslands, and mostly in the southern part of the study area. The highest decrease could be observed in the canal. The highest decrease of

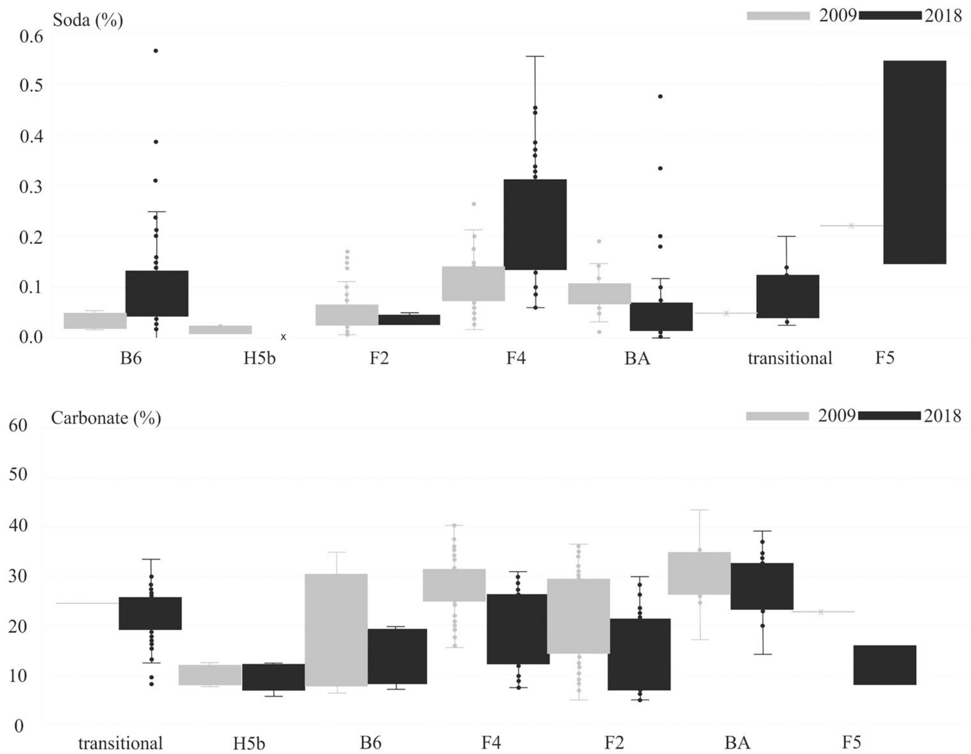

Figure 9. Changes of soda (%) and calcium carbonate (%) content according to the major habitat types in the studied period (2009–2018).

calcium carbonate content was characteristic of the canal (BA), the annual salt pioneer and Puccinellia swards (F4 and F5). The lowest decrease was observed in the case of the sand steppe grassland (H5b) and salt marsh points (B6).

Discussion

The canal construction, followed by groundwater drop—characteristic from the 80s in the region (Fehér and Rakonczai, 2019)—could be the initial point of desalinization. In the past decade the humid years advanced the formation of the transitional habitats, and due to the changing salt content of the topsoil along the channel, the spread of salt meadow species (Ladányi, Rakonczai, and Deák 2011). In 2009 steppification, leaching and desalinization were determined as dominant processes in the lakebed, which was reflected well in the changing soil and habitat pattern along the canal (Ladányi et al. 2016). In 2018 a higher salt and soda content, furthermore decreasing calcium carbonate content was characteristic for the upper soil layer in the lakebed compared to the 2009 soil chemical data (Ladányi and Rakonczai 2012), meaning that there was a changing water and salt regime in the lakebed. As there is no water retention, water supply or even any water cover in the lakebed, the reason for the changes can be searched in the periodically rising shallow groundwater level. Furthermore, the higher groundwater level is facilitated by the rehabilitation of the alkaline sodic lake in the northwestern direction in the same deflation hollow system (see NW-SE pattern of the alkaline lakes,

Figure 1). The restoration there started in 2010, when a significant amount of water was retained in the crossing canal and lakebed and the natural hydrological regime of the lake was restored. The higher water table could generate slightly higher water levels in the neighboring lakes too, and as a complementary to the water table rise in humid years, rose the groundwater table level to reach the capillary zone, thus, the salt and water could reach the upper soil layer and the surface (Figure 3). This process was indicated by the significant increase of the areas where salt accumulation occurs. The high salt content of the groundwater helped the annual salt pioneer swards and Puccinellia swards to regenerate, new patches of salt efflorescence could be observed, however, the higher elevated parts along the edges still show decreasing salt tendencies, and the draining and leaching impacts of the canal still persist.

The detailed analysis of the spatial changes for 2018 along the same sampling network showed a similar decreasing trend of calcium carbonate content, while, on the contrary, the rather increasing tendency of salt and soda content in the lakebed. The contradictory tendencies could reveal more spatially separated processes in the lakebed. The raised level of salty groundwater, furthermore the increased erosion near the edges, since humid years enhance the increase of soda and salt content, and the eroded/washed out material means input to the bottom. In the center part of the lakebed an increasing amount of plant biomass occurs, which contributes to lower calcium-carbonate content.

To sum up, the resampling survey revealed several points where topsoil was less alkaline and showed decreasing salt content, however, near the edges on the slopes, the salt and soda content could increase.

The past decade was partly favorable so that humid years could rehabilitate the natural conditions in certain parts of the lakebed via the somewhat shallower groundwater table, however, the randomly occurring humid years and the impact of the neighboring wetland rehabilitation are not enough to sustain the studied sodic lake. The more frequent and more severe drought years, predicted by several studies (e.g., Szépszó and Horányi 2008, Bartholy, Pongrácz, and Pieczka 2014, Pieczka et al. 2018), can result in a further decrease of the groundwater level, thus the steppification can continue, and in case of humid years without water retention, the draining and leaching processes will strengthen the degradation (desalinization) process. As in the case of Lake Nagyszéksós, the naturalness of the investigated lake could be preserved, that would have high importance due to the valuable habitats of Pannonian interest.

To reflect the hypothesis and Table 2 in the light of the results:

- salt transfer is the most dynamic in the level of the channel, as the impacts of the groundwater level and the precipitation are added up, contributing to habitat changes. On the edges the sand steppe grassland is not sensitive to chemical changes, but disturbance contributes to erosion impacting the habitats.
- annual salt pioneer sward, Puccinellia sward, salt meadow and salt marsh are sensitive to salt and water transfer (via chemical composition change) resulting in the transformation of the habitats along the natural zonation (inducing desalinization or salt accumulation processes)

- Puccinellia swards are sensitive to the trampling of vehicles which caused an increasing number and extent of salt efflorescences (annual salt pioneer swards) by soil compaction. Lavado and Taboada (1987) reported that grazing/trampling increased salt accumulation by enhancing evaporation.

The results show that the joint evaluation of the spatial soil model, the habitat sensitivity and the observed habitat changes can predict ongoing processes. The question is to what extent was such a prediction useful for the conservation and was it worth to be performed? The knowledge of detailed topsoil conditions can inform the decision makers on the progress of certain processes (see here the significant loss of topsoil salt content below the transitional habitats along the channel), as habitats are able to tolerate changes within a certain range, but suitable actions completed on time can prevent (further) degradation. Topsoil parameters (e.g., soil moisture directly (Zhuo and Han 2016; Klinke et al. 2018), salt content indirectly (Yang and Yu 2017; Wang et al. 2018) can be monitored by remote sensing tools, by which refinement can be reached and monitoring costs can be reduced, however, water logging and vegetation may influence the reliability in that case.

Conclusion

Wetlands in the Carpathian Basin have high importance due to the fact that they preserve significant ecological value in the matrix of arable lands. Ecosystems like this small alkaline sodic lake are under the threats of anthropogenic and climate change impacts, thus their maintenance and restoration are priorities to preserve the adjoining wildlife too. There are success stories of wetland restoration in Hungary in the Danube–Tisza Interfluve where the wise ecological water management helped the lakes to restore a more favorable water and salt regime (e.g., Lake Kolon, Lake Nagyszéksós, Böddi-szék). Furthermore, there are wetlands at higher elevations in the dune region, where irreversible processes could also be experienced due to the lack of available groundwater resources (Rakonczai 2011). Groundwater table decline as a result of climate change is a well-known and documented process in the Danube–Tisza Interfluve (Fehér and Rakonczai, 2019), but it is not so advanced in the edge areas, thus, less effort should be necessary to restore those small wetland mosaics (like the investigated lake), where mostly anthropogenic activities are the reason for the degradation (Nagy and Unyi 2016). The results confirmed the hypothesis as the changing habitat pattern is determined by the spatial location and the changes of the background factors. The monitoring of the habitat pattern seems to be the most cost-effective way to follow the changing condition, however, to identify the suitable appropriate management options, repeated soil survey is suggested. Habitat management plans e.g., controlling the vegetation by cutting 1–3 times a year could be recommended in the area. The monitoring should be extended to the groundwater level and vegetation composition in the bottom and edge of the lake.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the first author, upon reasonable request.

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