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EVOLUTION OF A SALT-AFFECTED LAKE UNDER CHANGING ENVIRONMENTAL CONDITIONS IN DANUBE-TISZA INTERFLUVE

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Abstract: There are many shallow, environmentally sensitive salt-affected lakes in the Danube-Tisza Interfluve, Hungary. Because of long-term tendencies in regional and local hydrological and meteorological conditions (e.g. channelization, precipitation extremities, consecutive droughts) significant changes occurred in the state of these shallow lakes (or soda pans) in the last decades. In the example of Lake Szappanos the changes were studied that have taken place over the last three decades, such as the quality of surface water, groundwater and soil condition, transformation of vegetation, in 2014/2015 - repeating a survey in 1982. In the observed points, the average depth of groundwater level slightly dropped, away from the lake the differences became more pronounced, while the extension of the lake surface decreased. The soluble salt content of the groundwater decreased by one order of magnitude. The saline groundwater lies deeper, getting to lose its role as the source of salt. The rainfed near-surface water can act as a „freshwater cushion", which results in freshwater-like conditions, accompanied by changes in the vegetation. The „desalinization" process can be reversed to some extent and the Smaroglay's (1939) lake-evolutionary stages („white" to „black" lake toward freshwater marsh) could be interchangeable in both directions by changing the influencing factors.

Keywords: soda pans, desalinization, land cover change, lake-evolution, rapid succession

1. INTRODUCTION

The Danube-Tisza Interfluve, as the wider environment of the study area, is a part of an extended, deep Neogene sedimentary basin, called the Pannonian Basin. According to the earlier hydrogeological studies (Erdélyi, 1976, Tóth & Almási, 2001), the whole basin can be considered as a hydrologic continuum, in which the main factor of direct salinization is groundwater (Salama et al., 1999, Fan et al., 2012). The central part of the Danube-Tisza Interfluve is the topographically uplifted Danube-Tisza Ridge, which is built up mostly by aeolian sand and acts as a regional discharge area. Between the sand dunes small, local flow systems can be embedded in the hierarchical flow system and on the bottom of the valleys where the temporary wet surface "trapped" the fine, wind blow material, small lakes could formed, often without outlets, but with remarkable soluble salt concentration (Sümegi & Boros, 2013, Molnár, 2015).

Over the last decades long time tendencies were detected in the shallow groundwater level changes in the territory. There was a strong decreasing trend from late 80s to the middle of 90s, but after 1995 it is rising to the beginning of 2000s (Simon et al., 2011). Lakes and ponds are often studied for the purpose of reconstructing past events (Riera et al., 2004, Kienel et al., 2009, Mees et al., 2011, Stockhecke et al., 2014).

Salt-affected lakes are unique natural formations, they can occur in many countries in the world, as the Great Salt Lake in USA, Lake Urmia in Turkey, Lake Eyre in Australia, in Eastern Europe (Hammer, 1986), but in many places they are getting to disappear (Shadrin et al., 2015, Wurtsbaugh et al., 2017), due to changes in their special environment (e.g. biogenic succession) and anthropogenic effects (channelization, more intensive water use, afforestation etc.) see Romanescu et al., 2010, Dickson et al., 2013, Habeck-Fardy & Nanson, 2014 and Tóth et al., 2014 for special cases.

According to Smaroglay's theory (1939), interdune salt-affected lake in the Danube-Tisza Interfluve forms, where the saline groundwater level reaches the bottom of the valley in July, which feeds the lake in summer. The strong evaporation leads to precipitate amorphous lime mud ($CaCO_3$) at first and after complete desiccation of soda (Na_2CO_3). Sodium chloride also occurs (NaCl). This process leads to the „white lake" stage. Due to the gradual thickening of the almost impermeable lime mud, the groundwater supply of lakes decreases, so the strength of salinisation also decreases. At this time, the salt-tolerant plants can already settle in the lake bed and the formation of organic matter begins. This is the "black lake" status. Finally, the salinisation process stops, the former lake becomes a freshwater swamp, and later a wet pasture. Thus, the development of lakes is described by a slow (hundreds or thousands of years) succession process where environmental conditions can be considered constant.

Because of their environmental values, the about 460 salt-affected lakes have been protected „ex lege" since 1997 in Hungary. One of the typical members of the Kiskunság-region soda pans is the Lake Szappanos, where a soil and vegetation condition survey was taken in 1982. The changes were studied that have taken place in the lakes and the surroundings since then. Based on earlier observations (Molnár & Kuti, 1987) and records (aerial and satellite photographs, maps etc.), following the terms of Smaroglay's lake succession theory, the Lake Szappanos was in „white lake" stage in the 1950s and 60s, turning into „black lake" in 1980s, while it reached the freshwater swamp stage by 2014/2015, which change can be regarded rather a quick succession. Desiccation of the lake accelerated in the 80s, when extended drop of the groundwater level was observed in the region. The temporal drying out of the lake was boosted by the effect of the close Bócsa-Bugac channel, which had deepened in the early-1970s. Neighboring Lake Szekercés had changed more quickly, it turned into "black lake" stage by 50s and became a swamp by 70s.

Present paper studies the main driving factors which can result the observed changes in Lake Szappanos environment, its accelerated evolution towards the marsh/meadow stage complementing the preliminary paper (Tóth et al., 2015).

2. MATERIAL AND METHODS

In 1982 summer, within the territory of Kiskunság National Park, the soil and vegetation cover of Lake Szappanos and surroundings (Bócsa area) was surveyed, investigating a catena with the most typical geomorphological sites from the deepest lake towards the elevated position. This area has been selected for further comparative studies, not only because of the archive dataset, but its relatively undisturbed protected environment of the National Park.

In 2014 November and 2015 July four observation points were georeferenced based on the original survey- and topographic maps and site descriptions. 20 m diameter spots were delineated around the points, which were considered homogenous based on the electromagnetic induction probe field data. Vegetation description, soil and groundwater sampling were performed within these spots, and the lake water was sampled also. Both dominant and subordinate plant species were described. As opposed to the genetic layer-based soil pit sampling in 1982, the soil boreholes in 2014/2015 were sampled equidistantly, every 10 cm till 120 cm depth, and every 20 cm to groundwater level were also recorded. The height of the surface was determined by geodetic leveling.

Electric conductivity (EC), pH and pNa (negative logarithm of molar concentration of Na, by ion-selective electrode) were measured in 1:2.5 soil/water suspension. Dissolved salt content was estimated based on EC (Tóth et al., 2015). Grain size distribution for standard fractions was determined by pipette method (MSZ 1978). Ion composition of water samples were determined by ICP and titrimetric methods. Sodium adsorption ratio (SAR) was calculated, which is a measure of the sodicity (US Salinity Laboratory Staff, 1954).

The lakebed was dry in 1982 and 2015 July, but waterlogged in 2014 November, so in addition to the groundwater samples taken in the transect points, surface water sample was taken also.

To analyze the regional factors on lake evolution, time series groundwater data (depth, chemistry) of the Hungarian Groundwater Monitoring Wells Network (source: General Directorate of Water Management, Hungary) and CarpatClim meteorological data (Szalai et al., 2013) were used.

3. STUDY AREA

Lake Szappanos lies on a moderately warm and dry Bugac microregion, Bócsa area (Dövényi et al., 2010), southern Hungary. Mean annual temperature shows an upward trend in the last decades. It led to mostly droughty years in 1983-1995, as well as in 2001-2003, when the annual temperature was above the thirty-year average (10.2-10.3°C) with 1.5-2°C, while the annual precipitation remained unchanged (520-550 mm). Based on CarpatClim Database, largest precipitation extremes occurred in 1999 (882 mm) and 2010 (1002 mm).

3.1. Genesis of the Lake

Lake Szappanos formed on the middle of the Danube-Tisza ridge, on the former Danube alluvial fan. During its Quaternary evolution, following the cessation of the alluvial deposition, eolic sedimentation, mostly loess and the redeposited Danube-sediment as blown sand became decisive.

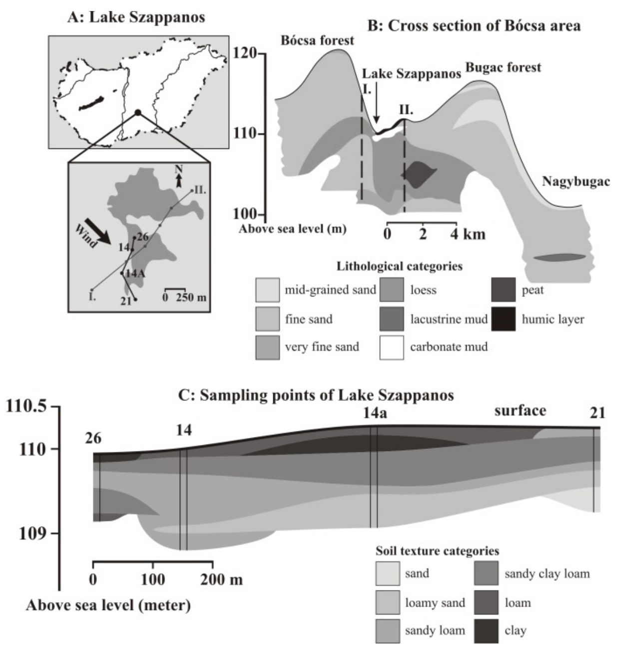

Figure 1. A) Location of the study area, observation points (26, 14, 14a, 21) direction of geological cross section (I.-II.). B) lithological cross section (based on Molnár and Kuti 1987)

There are continuous transitions among the Late Pleistocene deposits, but the sequence is always closed by blown sand or sandy loess, which provide the basis of ridge lakes (Fig. 1). The uppermost sandy loess layer is sometimes divided by peat or blown sand, accepted as the indicator of end of Pleistocene (Molnár & Kuti 1987).

Parallel with the loess deposition, in morphologically deeper positions, the surface could be covered occasionally with periodic water in ponds. In such cases peat or transformed, swampy loess layers have been interbedded in loess deposit. The snail fauna of these interlayers have great ecological tolerance, such as in the recent salty lakes, which refers to similar formation conditions (Jenei et al., 2007).

During the Holocene, in such ponds where the groundwater table was close to the surface and the pond was only a few decimeter deep, the strong evaporation in summer led to water became oversaturated and the carbonates precipitated in soft mud form. Where in the Holocene the pond became more permanent because of the more precipitous rainfall, carbonate mud formation was replaced by peat formation, so calcareous peat grew over mud.

In the Szappanos lakebed Pleistocene and Holocene clastic sediments as loess and windblown sand build up the young geological formation of the area, with interbedded clay, mud and organic-matter rich lacustrine/swampy lenses and coarse alluvial sediments in depth. The 20-80 cm thick carbonate mud is a characteristic sediment of the lakebed (Fig. 1).

3.2. Hydrological characteristics of the Lake

The nearest groundwater level monitoring wells to Lake Szappanos are the No. 2361 (112.9 m) and No. 1412 wells (113.5 m). Their fluctuation shows similar tendencies, with slightly different amplitude (Fig. 2). The nearest No. 2361-Bocsa well is situated ca 1500 m eastwards from the Lake, the surface between them is flat (slope < 1%). Supposing hydrological continuity, the tendencies of the groundwater level changes below the Lake Szappanos should be similar to the 2361-Bocsa well's hydrograph. Here the groundwater level reached its earlier (1981) stage by the late 1990s.

After 2000 a fluctuating period started with short sections (2-3 years), probably related to extreme rainfall. Two peaks can be identified on the hydrograph in 2000 April and 2011 January (Fig. 2), at circa one-year lag after highest annual precipitation in accordance with previous observation of Kohán & Szalai, (2014). The hypothetic shoreline level of Lake Szappanos is at about 110 m (Baltic).

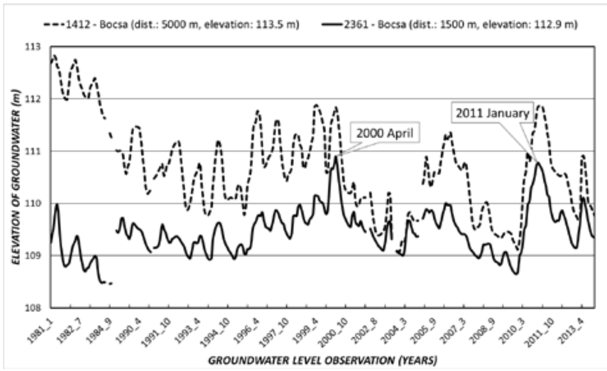

Figure 2. Hydrographs of the nearest wells (location is indicated on map, Figure 4). Groundwater levels are in monthly averages between 1981 and 2013.

4. RESULTS

4.1. Hidrogeochemistry

In the summer of 1982 and 2015 the Lake Szappanos was desiccated. The lake bed (no. 26) was waterlogged in 2014, where the total salt content of the surface water (10 meq/l) and the SAR (0.11) were low. The ionic composition was dominated by Ca^{2+} and Mg^{2+} and HCO_3^-. The surface water chemistry was clearly distinct from the composition of the groundwater at the same place (44 meq/l, SAR 2.40, with Na^+ and HCO_3^- dominancy). Therefore, the accumulated water in the lake bed originated mostly from rain.

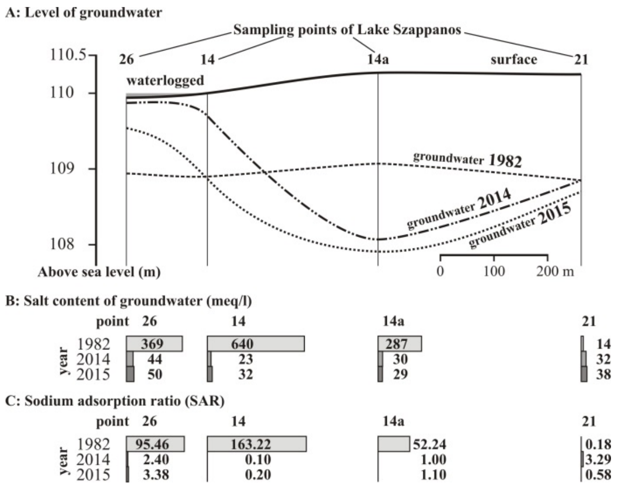

Figure 3. Changes in groundwater level (A), salt content (B) and SAR (C) at the sampling sites.

Table 1. Ionic composition of ground- and surface water (sw); expressed as % total cation/anion equivalent concentrations (meq/l)

Point / Ion	26 1982	26 2014	26 2014 sw	26 2015	14 1982	14 2014	14 2015
Ca^{2+}	0.01	4.57	**45.05**	2.88	0.04	16.68	13.94
K^+	1.57	4.26	3.23	8,66	1.43	2.76	4.64
Mg^{2+}	0.33	27.00	**41.97**	18.37	0.15	**69.18**	**71.23**
Na^+	**98.09**	**64.17**	9.75	**70.10**	**98.39**	11.38	10.19
SO_4^{2-}	6.33	2.72	2.89	0.61	4.77	1.79	0.66
CO_3^{2-}	19.76	7.10	0.00	13.20	28.64	3.42	4.99
HCO_3^-	**61.26**	**87.85**	**95.03**	**84.99**	**56.90**	**93.90**	**91.12**
Cl^-	12.65	2.33	2.08	1.20	9.69	0.90	3.22

Point / Ion	14a 1982	14a 2014	14a 2015	21 1982	21 2014	21 2015
Ca^{2+}	0.26	26.79	21.19	14.09	6.62	12.59
K^+	1.89	1.82	2.37	1.92	3.14	1.23
Mg^{2+}	0.55	29.19	30.98	**68.64**	10.86	**60.75**
Na^+	**97.30**	**42.20**	**45.46**	15.34	**79.37**	25.44
SO_4^{2-}	3.33	22.79	16.72	3.16	2.36	3.17
CO_3^{2-}	23.76	0.00	12.81	10.70	4.43	12.42
HCO_3^-	**61.79**	**73.80**	**69.00**	**85.61**	**90.87**	**82.81**
Cl^-	11.12	3.40	1.47	0.53	2.33	1.60

At the points 26 and 14a, the salt content of groundwater dropped to approximately one tenth of the 1982 value in 2015, while at the former most salty point (14) it dropped to twenty times (Fig. 3). Changes in groundwater ionic composition are shown in Table 1. A small increase in the salinity of groundwater at point 21 was observable. The oscillation of the groundwater level was the largest at 14a point, lakeshore (14a point), coupled with strongly decreasing SAR value (Fig. 3).

In all samples the Na^+ (and Mg^{2+}) and HCO_3^- ions dominate in the groundwater, Na+Mg ratio in 2014 and 2015 decreased by 10%, while the ratio of Ca^{2+} shows opposite tendency (except point 21, where the salt content did not change drastically) Under the dry lakebed (site no 26) in 2015 summer the groundwater was sampled at 0.4 m and 4 m depth, also. Comparing the deeper and shallower groundwater, it has been found that the total salt content (68 meq/l), SAR value (12.03) are higher in depth, than in the near-surface (50 meq/l; SAR 3.38), indicating a rainfed “freshwater-cushion” formation.

For 2000-2012, the recorded EC values in the nearest Groundwater Quality Monitoring Wells show different tendencies in their filtered depth, 7.5-8 m. The k104 well (with high EC values) has shown a decreasing trend, in case of k118 well the EC increased, while the k035 and k032 wells have quite the same low values, indicating the spatial rearrangement of salinization pattern (Fig. 4).

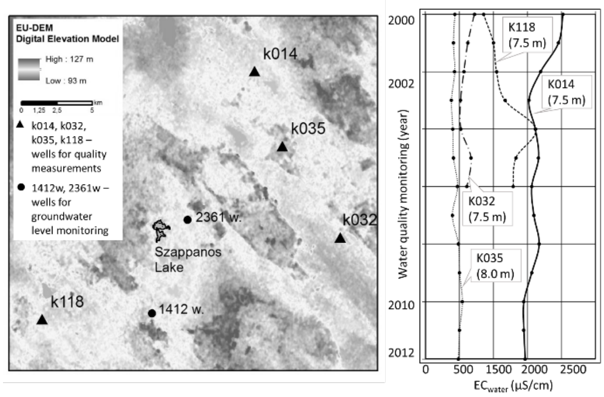

Figure 4. Observed changes around the Lake in EC_{water} between 2000 and 2012 (mid of filtered depth in brackets).

4.2. Birds and vegetation

Bird population indicate the changes in the fauna of the Szappanos Lake. Based on the Kiskunság National Park records, the number of species associated with sodic habitats has radically decreased (Acrocephalus scirpaceus, Larus ridibundus, Larus melanocephalus, Egretta alba, Ardea cinerea lapwing, common tern, curlew), while the number of species associated with swamp habitats has grown (Acrocephalus scirpaceus, Larus ridibundus, Larus melanocephalus, Egretta alba, Ardea cinerea reed warbler, mediterranean gull, great egret) in the last decades.

In 2015 summer, within a 5 m radius of the observation points the main floral elements were described at species level. Instead of the earlier (1982) described sparse, salt-tolerant plant communities with small cover (Agrostis-Caricetum distantis, Artemisio santonici-Festucetum pseudovinae and Lepidio-Camphorosmetum annuae associations) a rich, less salt-tolerant, swamp-like vegetation was descibed, covering the whole surface (*(Achillea millefolium, Agrostis stolonifera, Bolboschoenus maritimus sensu lato, Cirsium vulgare, Elymus repens, Festuca pratensis, Galium verum, Linum hirsutum, Melandrium viscosum, Ononis spinosa, Phragmites australis, Plantago lanceolata, Poa pratensis, Rhinanthus minor)*creeping bentgrass, saltmarsh bulrush, couch grass, common reed). Both vegetation and land use changes follow the desiccation process in the region the cropping approached the coast of the pans. The recent dense plant cover results in great transpiration, reduces wind speed on ground and traps fine windblown sediments, thereby reducing water infiltration. These kind of changes are common in the arid area. Similar processes have been identified by Zhang et al., (2017) in the Xinjiang region, Northwest China.

5. DISCUSSION

The salt content of the shallow groundwater has decreased in Lake Szappanos. Changes fit well with processes in similar soda pans (Ladányi et al., 2016, Kovács et al., 2017). The observed change is quite rapid, which modifies the earlier Smaroglay's theory (1939) on the slow lake-evolution. The largest measured salt content of groundwater below other soda pans, as the Szappanszék-, Hattyús-, Kondor- and Szívós Pan were 9532, 4080, 1698, 1638 (mg/l) in 1972 (Molnár, 2015), showing that different evolutionary stages of soda pans existed parallel in the region.

The driving force behind the change of lake is the large drop of the salt content of the lake water. If the salty and alkaline groundwater cannot rise and evaporate in the lake bed, the saline nature of the lake became reduced or even disappeared (Jobbágy et al., 2017). Intake of salty groundwater into the lake is reduced not only because of the formation of a gradually thickening surface mud layer (Smaroglay, 1939) but other changes in hydrological conditions (Fig. 5).

The geometry and salt-concentration of the near-surface groundwater basically determines the salt accumulation processes. Because of regional water depletion, channelization and warming climate, the spatial salinization pattern, the water- and salt supply of the lake, and the composition of groundwater have significantly changed in the last decades. Above the deep salty groundwater the rainfed shallow water can act as a „freshwater cushion", resulting in freshwater-like conditions in the lake water.

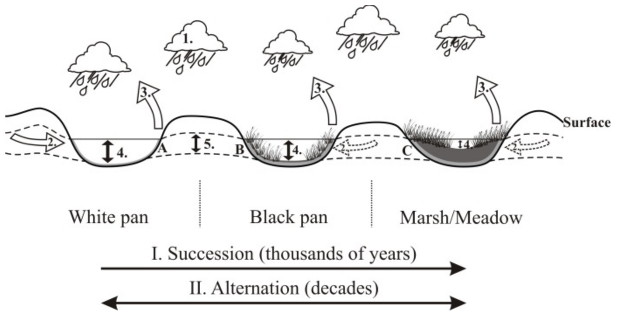

Figure 5. Basic processes in the lake evolution and Smaroglay's stages (1939) in the slow lake-evolution (I.). Modified theory with more rapid alternation (II.).
Legend: 1. precipitation, 2. infiltration (limited in black pan and marsh stages), 3. evapotranspiration, 4. annual lake water fluctuation, 5. annual groundwater fluctuation; A: thin lime mud, B: thick lime mud, C: thick, almost impermeable lime mud and organic rich layer

The natural succession process has been accelerated by human intervention (e.g. intensification of cultivation and extraction of deep waters). The „desalinization" process is quite fast and could be reversed to some extent and -by changing the influencing factors- the Smaroglay's (1939) lake-evolutionary stages could be interchangeable in both directions within a quite short period of time (Fig. 5).

6. CONCLUSION

It is concluded that the main factors in the changes in the state of the Lake Szappanos are the decrease in the salt content of the lake's water and water supply, change in groundwater level geometry, increase in plant cover and sedimentation. The external environmental conditions determine which steady state of the lake can last longer. Due to the current processes (depletion, warming, etc.) the short term disappearance of the former soda pans and the emergence of wet meadows in their place is the predictable scenario. With adequate water regulation, restoring salty lakes of very significant natural value would be possible.

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