Changes in sediment and sediment interstitial water characteristics in Lake Fertő/Neusiedler See

E. Ágoston-Szabó and M. Dinka[1]

Abstract. Changes in the C, S, N, P concentrations, organic matter content and electron transport system activity (ETS) of the sediment and in the NO_2^-, NO_3^-, PO_4^{3-} SO_4^{2-}, NH_4^+ concentrations of water and sediment interstitial water were studied in the Hungarian part of Lake Fertõ/Neusiedler See during the vegetation period. Sediment samples were collected in healthy and die-back reed stands and in the open water area from the 0-5 cm sediment layers. Organic matter content, C, N, S, P concentrations and ETS-activity were significantly higher in the sediment of the degraded reed stand. Higher electrical conductivity and SO_4^{2-} concentration were found in the second part of the vegetation period, when the water level was lower. The seasonal variation in PO_4^{3-} and NO_3^- concentrations of the surface water showed an antagonistic pattern. Higher PO_4^{3-} and NH_4^+ concentrations were measured in the sediment interstitial water in summer, when the temperature and the decrease in SO_4^{2-} concentration, which indicate the SO_4^{2-} reduction processes were greater. The higher ETS-activity values in September were probably due to the decaying mass of macrophytes.

Wetland ecosystems are among the most productive ecosystems of the biosphere (Mann & Wetzel, 2000), biogeochemical nutrient cycling in these ecosystems is critically influenced by the interaction among water, sediments and macrophytes. Macrophytes have functionally adapted to the anaerobic conditions in the sediments by translocating oxygen into the rhizosphere. Oxygen moving from the rhizosphere into the surrounding sediments changes the redox potential of the sediment (Armstrong & Armstrong, 1988) and favours the chemical oxydation of the reduced chemical components in the interstitial water and the microbial oxydation processes (Roden & Wetzel, 1996). The concentration of dissolved organic and inorganic nutrients in surface and sediment interstitial water and their spatial and temporal changes provide key data to reveal how these systems function at the biogeochemical level (Pakulski et al., 1995). From interstitial water profiles it is, in some cases possible to identify zones of consumption and zones of production of reduced and oxidized form of the elements (Glud et al., 1998).

Functional evaluation of wetlands in nutrient cycling, requires knowledge of differences in microbial processes between different sampling sites. Community respiration is one of the most commonly measured functional attributes of ecosystems (Hill & Gardner, 1987; Hill et al., 2000). The activity of electron transport system (ETS), which reflects the metabolic activity of respiring microorganisms (Christiansen & Packard, 1977; Broberg, 1985), can be used in sedimentological studies as a measure of the total anaerobic and aerobic respiration (Hakanson & Jansson, 1983). The ETS-test developed by Packard (1971), Kenner & Ahmed (1975), Owens & King (1975), and Broberg (1985) yields the maximum potential respiratory activity.

The aim of this study was to evaluate the differences in the chemical composition of the sediment (C, N, P, S, and organic matter content), sediment interstitial water (NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-} concentrations) and sediment ETS-activity of degraded and healthy reed stands and a reedless area of Lake Fertő/Neusiedler See during the vegetation period.

[1]*Edit Ágoston-Szabó* and *Dr. Mária Dinka,* MTA ÖBKI Magyar Dunakutató Állomás (Hungarian Danube Research Station of the Hungarian Academy of Sciences) H-2163 Vácrátót, Alkotmány u. 2-4., Hungary. E-mail: edit@botanika.hu and dm@botanika.hu
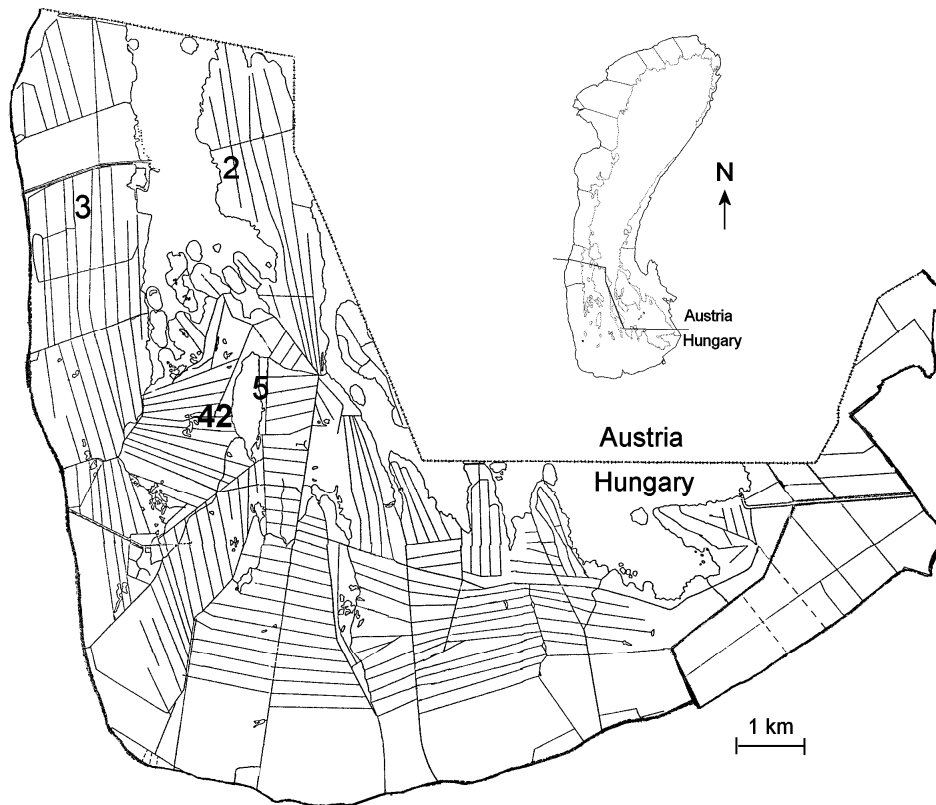
Figure 1. Sampling sites at Lake Fertő/Neusiedler See

Sampling sites

Lake Fertő/Neusiedler See, situated on the Hungarian-Austrian border (47 42' N, 16 46' E, Fig. 1), is the westernmost and largest steppe lake in Eurasia, declared as a biosphere reserve by UNESCO in 1977 and 1979. It has a surface area of 309 km^2 (Hungarian part 75 km^2), with a mean depth of 1.1 m and 54 % of the whole lake, 85 % of the Hungarian part is covered by reed (*Phragmites australis* Cav. Trin. ex Steud.). Within the reed belt, there are numerous reedless ponds of variable size. According to the characteristic ionic ratios the water of Lake Fertő/Neusiedler See can be characterised as hydrogencarbonate-sulphate and sodium-magnesite mixed water type, the sediments of the lake are characterised by autochthonously formed minerals, Mg-calcite and protodolomite (MOLNÁR & DINKA, 1997, JUNGWIRTH, 1979).

Sampling sites were selected in the Hungarian part of Lake Fertő/Neusiedler See also taking into consideration the lake configuration and the condition of the reed stands in the process (Fig. 1). Sampling site 42 (S42) is a deep water (60-80 cm) reedless pond within the reed belt, sampling site 2 (S2) is a homogenous healthy reed stand (water depth: 20-40 cm), both sites have a silty-clay sediment. Sampling site 3 (S3) is a degraded stand with clumped distribution of the culms and callus occlusions in their gas space, (ARMSTRONG et al., 1996) (water depth: 30-50 cm), there are several areas of open water. The sediment is a sandy-silty-clayey sapropel rich in organic matter, in which negative redox relationships frequently develop. It is characterised by high S^{2-} concentrations (ARMSTRONG et al., 1996). Sampling site 5 (S5) is a homogeneous, loose healthy reed stand in deep water (80-120 cm), with silty-clay sediment.

In the last two years the water level was lower in early spring than in the same periods of previous years and a further 20-30 cm decrease was observed in the second part of the vegetation period in 2001, as compared to spring values (Fig. 2, data obtained from the Hydro-meteorological Station, Fertőrákos).
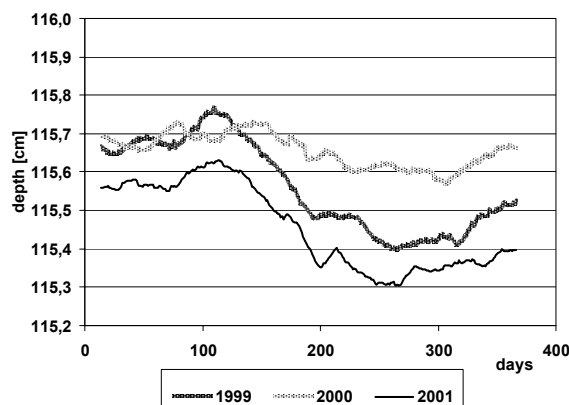

Figure 2. Water level fluctuations at Lake Fertő/Neusiedler See

The samples were collected on April 23th, July 23th, September 5th 2001 at S5 and S42 and on March 26th, April 23rd, June 20th, July 23rd, September 5th 2001 at S3 and S2.

MATERIAL AND METHODS

Sediment sampling and separation

Sediment cores were collected at each sampling site with a 40 cm Gilson sampler diameter of 5 cm, in three replicates. After slicing the sediment in 1 cm thick layers in the laboratory, it was placed in a crucible and dried to constant weight at 105 ^{o}C for 24 h for the determination of the moisture content, then combusted at 450 ^{o}C (Molnár & Dinka, 1997; Jungwirth, 1979; Sutherland, 1998) for 4 h in a muffle furnace for determination of organic matter content by loss on ignition method (OM$_{LOI}$).

Total nitrogen (TN), total sulphur (TS) and organic carbon (OC) concentrations of the sediment samples were determined with a Fison

NA-1500 NCS analyser, total phosphorus (TP) concentration by photometry using the molybden-blue complex method, after combustion of the sediment at 450 ^{o}C and 12 hours digestion with 1n HCl (Aspila & Agemain-Chau, 1976). Sediment ETS-activity was determined by the tetrazolium reduction test introduced by Packard (1971) and modified by Broberg (1985).

Surface and sediment interstitial water analysis

Temperature, electric conductivity (at in situ temperature), pH, of the surface water, the redox potential of the surface and bottom water (3-5 cm above the sediment) were established on the spot with a Hydrolog 2100 field equipment. The interstitial water from the upper sediment layers (0-1, 1-2, 2-3, 3-4 and 4-5 cm) was filtered (Sartorius cellulose acetate filter, pore diameter: 0.4 μm) with the help of a vacuum pump. The NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, SO_4^{2-} concentrations of the interstitial and surface water were measured with a Dionex DX-120-ionchromatograph after filtering (Chromafil filter, pores: 0.2 μm).

Data analysis and statistical methods

An analysis of variance (Statgraf 1.0 for Windows) was used for the statistical evaluation of the individual data ($p < 0.05$).

The relationships between the sampling sites (objects) and the chemical features of the surface water, sediment, sediment interstitial water and the sediment ETS-activity (variables) were determined with standardized Principal Component Analysis (PCA) (Podani, 1997). The ordinations of sediment and water samples taken in different seasons were compared using the Procrustes analysis, which compares ordinations after rotating the two configurations and rescaling them so that the square total of the distances between the corresponding pairs of points should be minimum (Podani, 1997).

RESULTS

Surface and sediment interstitial water characteristics

In situ water parameters

The electrical conductivity of surface water ranged from 1.99 to 4.57 mS cm^{-1}, higher values were measured in the second part of the vegetation period. The electrical conductivity in September was twice as high as in spring at S3 and it was 1.5-1.8 times higher than at S42, S2 and S5 (Table 1).

The pH of surface water ranged from 8.2 to 9.6 and at all sampling sites it was one order of magnitude higher in early autumn than in spring (April: 8.2-8.6; September: 9.2-9.6).

The redox potential of surface water ranged between 24-210 mV, the lowest values were measured in summer months (S3: 24 mV). There were no significant differences between the water parameters measured at the surface and above the sediment except of the redox potential values. In summer the redox potential of the bottom water reached –27 and –40 mV values at S3 and S5, respectively.

The temperature of surface water at S3, shallow water, thinning reeds, varied between 11.7 and 20 ºC, from March to September, and it was by 2.1-4.6 C° higher than in the shallow water, homogeneous reeds (S2) and by 2.3-4.4 C° higher than at the deep water sampling sites (S42, S5). Differences in surface water temperature of different sampling sites were minimum in July (1.7 C°) and maximum in April and September (4.7 C°).

Table 1. Chemical characteristics of the surface water at Lake Fertő/Neusiedler See in 2001(n.d.=not detected, Eh= redox potential, T=temperature)

Sites	Data 2001	Conductivity mS cm^{-1}	pH	T °C	Eh mV	PO$_4^{3-}$ mg l^{-1}	NO$_2^-$ mg l^{-1}	NO$_3^-$ mg l^{-1}	SO$_4^{2-}$ mg l^{-1}	NH$_4^+$ mg l^{-1}
Site 42	23.04	2.37	8.2	8.6	210	0.16	n.d.	0.09	327.96	n.d.
	23.07	2.64	9.1	17.1	108	0.45	n.d.	0.19	621.44	n.d.
	05.09	3.16	9.2	19.6	205	0.04	n.d.	n.d.	522.74	1.13
Site 2	26.03	1.99	8.6	10.0	206	0.00	n.d.	1.80	331.27	n.d.
	23.04	2.13	8.4	9.7	209	0.38	n.d.	0.26	328.51	n.d.
	23.07	2.53	8.8	17.7	84	0.17	0.48	n.d.	529.60	n.d.
	05.09	2.44	9.4	19.3	205	0.02	n.d.	0.32	491.55	n.d.
Site 3	26.03	2.20	8.5	11.7	206	0.00	n.d.	0.20	219.88	n.d.
	23.04	2.52	8.3	12.9	142	0.38	n.d.	0.49	334.64	n.d.
	23.07	3.55	8.8	19.9	24	0.22	0.74	0.08	791.64	n.d.
	05.09	4.57	9.6	20.0	205	0.00	n.d.	1.13	461.78	n.d.
Site 5	23.04	2.36	8.6	8.4	208	0.16	n.d.	0.19	333.41	n.d.
	23.07	2.74	9.4	17.3	125	0.09	n.d.	0.06	431.80	n.d.
	05.09	3.02	9.4	19.4	195	0.00	n.d.	0.57	520.72	n.d.

Nutrients in surface and interstitial water

Higher SO_4^{2-} concentrations of surface water were measured in the second part of the vegetation period (Table 1). The SO_4^{2-} concentration in the upper 5 cm sediment layer decreased with increasing depth, the highest decrease was observed in the 4-5 cm sediment layer e.g. at S3 the pore water SO_4^{2-} concentration was lower by 57-63 % and at S5 it was lower by 46-62 %, than that of surface water (Fig. 3). Spatial pattern in pore water SO_4^{2-} concentration profiles was evident, a higher decrease was observed at sites S3 and S5 with higher organic matter content. The pore water SO_4^{2-} concentration showed obvious seasonal changes,

at S3 its value was 2.1 times higher in September than in March (Fig. 3), this ratio was 1.6 at S5, 1.2 at S42, and 1.0 at S2 where the water level changes were smallest.

The NO_2^- concentrations in the surface water of most sampling sites were below detection limit, they were detectable only at S2 and S3. NO_2^- was only found in spring and summer in the examined upper 5 cm sediment layer of the sampling sites, its concentration varied from 0.76 to 3.49 mg l^{-1} at S5, from 0.15 to 3.57 mg l^{-1} at S3, from 0.18 to 3.23 mg l^{-1} at S2 and from 3.14 to 3.35 mg l^{-1} at S42 (Table 2). The NO_2^- concentrations did not show any evident spatial pattern.

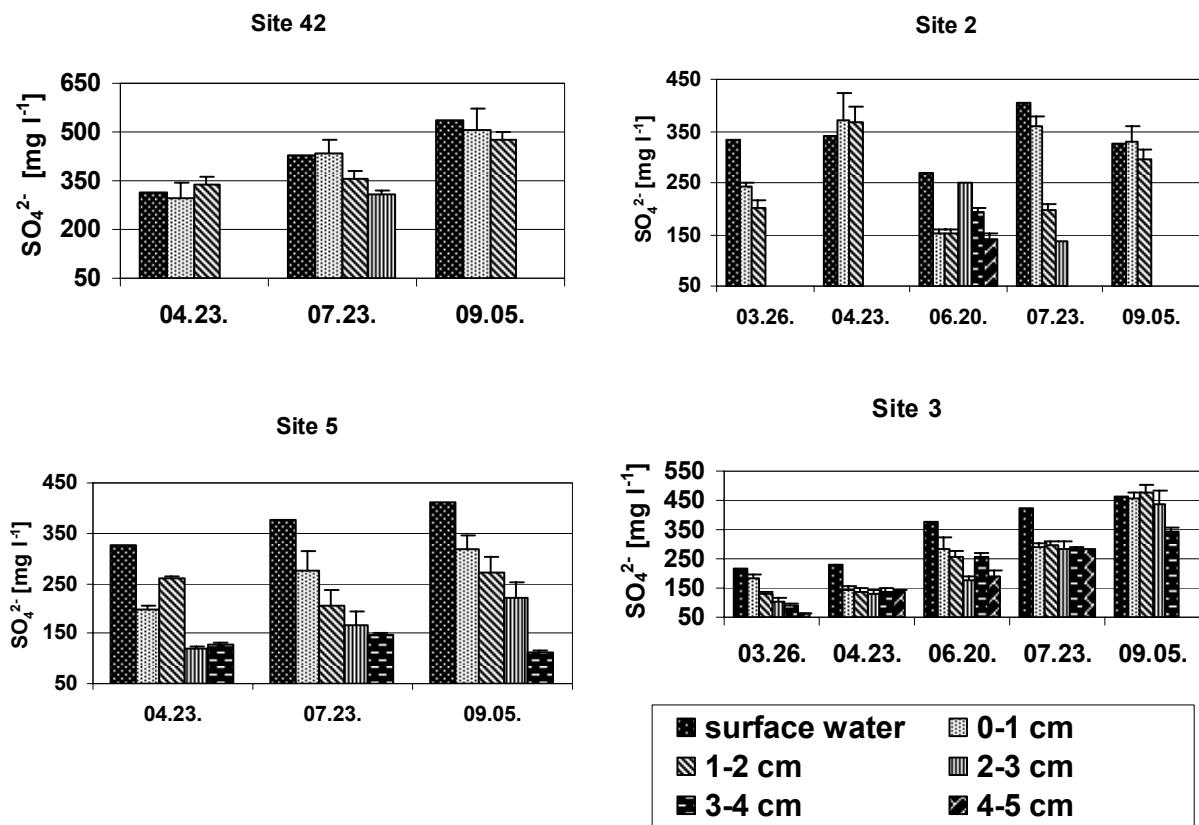**Figure 3**. SO_4^{2-} concentration of the surface and sediment interstitial water in Lake Fertő/Neusiedler See in 2001 (means±SE, n=3).

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Table 2. Changes in NH_4^+, NO_2^-, NO_3^-, PO_4^{3-} concentrations of the surface (0-5cm) sediment interstitial water at Lake Fertő/Neusiedler See (S.E.=standard error, n.d.=not detected)

		26.03	23.04.	20.06.	23.07.	05.09.	23.04.	23.07.	05.09.
		Site 2					**Site 42**		
NH_4^+	Min	n.d.	n.d.	0.87	n.d.	n.d.	n.d.	n.d.	1.13
$[mg\ l^{-1}]$	Max	n.d.	n.d.	1.72	n.d.	n.d.	n.d.	n.d.	5.61
	Mean			1.30					3.37
	S.E.			0.60					3.17
NO_2^-	Min	n.d.	n.d.	0.18	3.13	n.d.	n.d.	3.14	n.d.
$[mg\ l^{-1}]$	Max	n.d.	n.d.	0.53	3.23	n.d.	n.d.	3.35	n.d.
	Mean			0.33	3.18			3.25	
	S.E.			0.17	0.07			0.11	
NO_3^-	Min	0.45	0.15	0.36	n.d.	0.64	0.09	n.d.	0.13
$[mg\ l^{-1}]$	Max	0.41	0.38	0.82	n.d.	0.72	1.01	n.d.	0.11
	Mean	0.43	0.27	0.52		0.68	0.55		0.12
	SE	0.03	0.17	0.26		0.33	0.65		0.01
PO_4^{3-}	Min	n.d.	n.d.	0.46	0.17	0.01	0.16	0.12	0.04
$[mg\ l^{-1}]$	Max	n.d.	n.d.	2.14	1.84	0.02	0.21	0.45	0.17
	Mean			1.30	1.01	0.02	0.19	0.28	0.11
	S.E.			1.19	1.18	0.01	0.04	0.23	0.09
NH_4^+		**Site 3**					**Site 5**		
$[mg\ l^{-1}]$	Min	n.d.	n.d.	0.94	2.99	n.d.	n.d.	0.60	5.65
	Max	n.d.	n.d.	2.43	3.89	n.d.	n.d.	7.99	8.05
	Mean			1.72	3.44			3.45	6.85
	S.E.			0.75	0.45			3.29	1.70
NO_2^-	Min	0.00	n.d.	0.51	3.25	n.d.	0.00	1.56	n.d.
$[mg\ l^{-1}]$	Max	0.15	n.d.	0.61	3.57	n.d.	0.76	3.49	n.d.
	Mean			0.54	3.40			2.96	
	S.E.			0.04	0.12			0.93	
NO_3^-	Min	0.11	0.08	n.d.	n.d.	0.10	0.15	n.d.	0.57
$[mg\ l^{-1}]$	Max	0.37	0.53	n.d.	n.d.	1.34	0.24	n.d.	0.63
	Mean	0.10	0.29			0.87	0.26		0.60
	S.E.	0.38	0.21			0.76	0.12		0.03
PO_4^{3-}	Min	0.14	0.15	0.32	0.22	0.17	0.60	0.33	0.74
$[mg\ l^{-1}]$	Max	0.16	0.38	0.89	0.46	0.28	1.99	3.06	4.21
	Mean	0.15	0.27	0.61	0.34	0.23	0.98	3.61	3.55
	S.E.	0.01	0.12	0.29	0.12	0.06	0.68	1.65	0.94

The range of NO_3^- concentrations in the surface water was 0.06-1.80 mg l^{-1} (Table 1) and in the sediment pore water it varied between 0.15 and 0.63 mg l^{-1} at S5, between 0.09 and 1.01 mg l^{-1} at S42, between 0.11 and 1.34 mg l^{-1} at S3 and between 0.15 and 0.82 mg l^{-1} at S2 (Table 2). It changed with the season, with lower values in the first part of the vegetation period, except with S42.

Comparing the sampling sites, the highest pore water NH_4^+ concentrations were measured in summer and early autumn, from 0.60 to 8.05 mg l^{-1} at S5, from 1.13 to 5.61 mg l^{-1} at S42, from 0.94 to 3.89 mg l^{-1} at S3 and from 0.87 to 1.72 mg l^{-1} at S2. The pore water NH_4^+ concentration increased with depth. NH_4^+ was not detectable in the surface water except S42 in September.

Higher PO_4^{3-} concentrations were measured in summer and early autumn (Table 1). The PO_4^{3-} concentration of sediment interstitial water increased in the function of depth, the highest increase was observed at S5, it was by 70-89 % higher than the appropriate sediment surface values (Table 2).

Sediment characteristics

The following discussed characteristics were measured in every sediment layer of the upper 5 cm. Average values are presented in Table 3 with an indication of significant ($p < 5$ %) differences between the sites.

There were significant spatial changes in the organic matter content (OM_{LOI}) of the upper 5 cm sediment layers. S3 had the significantly highest OM_{LOI} from spring to autumn. Summer (OM_{LOI}) samples were highest at all sites, except with S2. Significant differences were observed among the OC values measured in the sediment of different sampling sites. The OC concentration was significantly higher at S3 than at the other sampling sites at each sampling time.

Total nitrogen (TN) value was also significantly higher at S3 than at the other sampling sites. TN concentration differences in the sediment were not significant among the other sampling sites. Significant seasonal and spatial differences in the C:N ratio were recorded between the sampling sites. The greatest changes were measured at S3 (mainly due to N concentration alterations during the vegetation period).

Similarly to other element concentration TP concentration was significantly highest in the sediment of S3. TP concentration of the sediment decreased from April to September at S2 and S3. The significantly lowest average TS concentration was measured at S42 at each sampling time. At S3 the S concentration was significantly (up to 22 times) higher than at the other sites.

Temporal changes of the characteristics in the 1 cm layers at S3 can be seen in Fig. 4. With the exception of the early spring samples no considerable spatial changes were recorded in the organic matter content, OC, TN and TS concentrations of the sediment. TP and TN concentration had a decreasing tendency from cm to cm in the upper part of the sediment, especially in summer months. A similar pattern was detected in the individual characteristics at the other sites.

ETS-activity in sediment

The ETS activity values obtained at each individual sampling site were, however, very different (Fig. 5). In several cases there was a decrease with depth in the upper 5 cm sediment layer. In spring ETS-activity in the sediment was low and did not change considerably from the sediment surface to the 5 cm layer. In summer and especially in autumn ETS activity values often decreased with sediment depth. At S5 and S42 in September only 50 % and 12 % of ETS activity of the upper 1 cm layer, respectively were measured in the 5 cm layer.
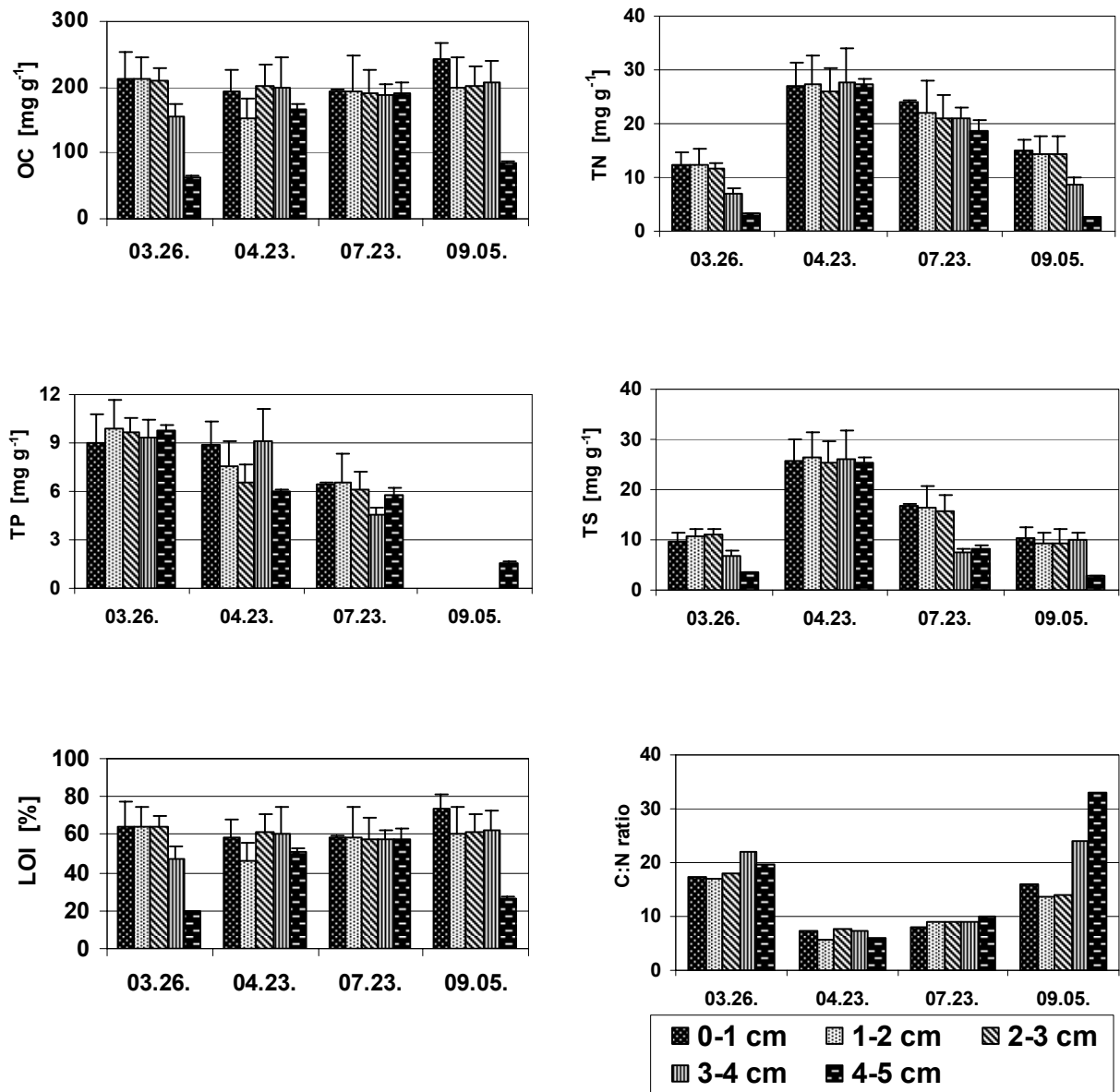
Figure 4. Chemical characteristics of the sediments at Lake Fertő/Neusiedler See, sampling site 3 in 2001 (means±SE, n=3).

The highest ETS-activity values were measured at S3 (0.31-2.2 mg O_2 g_{dw}^{-1} h^{-1}), this was 5-15 times higher than the ETS activity values measured at other sampling sites. The ETS activity at S3 showed a relatively strong positive correlation (r^2=0.63) with OM_{LOI} and a negative correlation with the C:N ratio of the sediment (r^2=0.62), whilst it did not correlate significantly with OM_{LOI} at S42, S2 and S5. The lowest mean values were found at S42 (range 0.01-0.11 mg O_2 g_{dw}^{-1} h^{-1}, Table 3).

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Table 3. Characteristics of the surface sediment layer (0-5 cm) at Lake Fertő/Neusiedler See (values followed by different letters are significantly different at the 0.05 probability level) (mean±SE, n=3).
(LOI=loss of ingnition, OC=organic carbon, TN=total nitrogen, TS=total sulphur, TP=total phosphorus)
(a, b, c -significant differences for the columns)

	Dates	site 42	*SE*	site 2	*SE*	site 3	*SE*	site 5	*SE*
LOI [%]	26.03			**13.32** [a]	*2.14*	**51.83** [b]	*7.16*		
	23.04	**6.51** [a]	*0.97*	**13.73** [b]	*4.51*	**55.57** [c]	*8.90*	**9.39** [ab]	*2.70*
	23.07	**10.09** [a]	*2.05*	**13.43** [a]	*1.24*	**58.00** [b]	*7.64*	**22.96** [c]	*1.63*
	05.09	**6.49** [a]	*0.06*	**13.28** [b]	*1.83*	**56.70** [c]	*8.31*	**18.70** [d]	*4.27*
OC [mg g^{-1}]	26.03			**42.76** [a]	*10.71*	**170.76** [b]	*23.19*		
	23.04	**20.12** [a]	*4.83*	**44.11** [b]	*22.57*	**183.18** [c]	*29.33*	**29.70** [a]	*13.50*
	23.07	**32.00** [a]	*10.23*	**43.11** [b]	*6.20*	**191.27** [d]	*25.20*	**74.80** [c]	*8.15*
	05.09	**20.06** [a]	*0.31*	**42.62** [b]	*9.17*	**186.94** [d]	*27.40*	**60.64** [c]	*21.35*
TN [mg g^{-1}]	26.03			**3.13** [a]	0.30	**9.33** [b]	1.49		
	23.04	**1.70** [a]	0.22	**2.94** [a]	0.34	**27.10** [b]	4.28	**2.15** [a]	0.66
	23.07	**2.60** [a]	0.79	**3.14** [a]	0.19	**21.40** [b]	2.79	**4.60** [a]	0.92
	05.09	**2.08** [a]	0.62	**2.25** [a]	0.24	**11.02** [c]	1.99	**6.50** [b]	0.49
TS [mg g^{-1}]	26.03			**3.07** [a]	0.59	**8.37** [b]	0.79		
	23.04	**1.13** [a]	1.06	**2.00** [a]	1.15	**25.74** [b]	4.04	**0.55** [a]	0.70
	23.07	**0.48** [a]	0.38	**3.14** [b]	0.22	**12.95** [c]	2.21	**4.79** [b]	0.48
	05.09	**0.20** [a]	0.19	**2.71** [b]	0.58	**8.30** [d]	1.64	**5.28** [c]	1.52
TP [mg g^{-1}]	26.03			**1.48** [a]	*0.42*	**9.66** [b]	*1.18*		
	23.04	**0.82** [a]	*0.06*	**1.41** [ab]	*0.34*	**7.63** [c]	*1.26*	**1.86** [b]	*0.69*
	23.07	**0.90** [a]	*0.08*	**1.18** [ab]	*0.25*	**5.89** [c]	*0.79*	**1.87** [b]	*0.13*
	05.09	**0.66** [a]	*0.09*	**1.15** [ab]	*0.11*	**1.61** [b]	*0.44*	**1.92** [b]	*0.13*
C:N ratio	26.03			**13.67** [a]	*0.77*	**18.30** [a]	*26.44*		
	23.04	**11.86** [a]	*8.35*	**14.99** [b]	*1.54*	**6.76** [a]	*0.45*	**13.80** [b]	*19.02*
	23.07	**12.29** [b]	*8.59*	**13.74** [a]	*4.34*	**8.94** [a]	*1.84*	**16.26** [b]	*6.07*
	05.09	**9.66** [b]	*0.06*	**18.91** [b]	*3.35*	**16.97** [b]	*47.84*	**9.33** [a]	*1.48*
ETS **[mg O$_2$ g$_{DM}^{-1}$ h^{-1}]**	26.03			**0.03** [a]	*0.02*	**0.21** [b]	*0.13*		
	23.04	**0.01** [a]	*0.00*	**0.05** [a]	*0.03*	**0.34** [b]	*0.11*	**0.03** [a]	*0.02*
	23.07	**0.07** [a]	*0.04*	**0.06** [a]	*0.03*	**0.29** [a]	*0.15*	**0.28** [a]	*0.09*
	05.09	**0.11** [a]	*0.09*	**0.17** [a]	*0.07*	**1.07** [c]	*1.73*	**0.76** [b]	*0.25*

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The seasonal variation of the ETS-activity was characteristic and similar at each sampling site, it started with lower values (0.01-0.34 mg O_2 g_{dw}^{-1} h^{-1}) in spring and increased continuously till autumn (0.11-1.07 mg O_2 g_{dw}^{-1} h^{-1}).

After conversion of oxygen to carbon (1 mg O_2= 0.5 mg C, WINBERG 1971), the respiratory energy loss of the sediment from the degraded reed stand (S3) ranged between 1274.26–6605.85 mg C $m^{-2}h^{-1}$, it was 1.64-4.93 times higher than the respiratory energy loss measured in sediment of healthy reed stands (S2 and S5).

PCA comparison of sampling sites

The ordinations of water samples taken in April, July and September were compared using the Procrustes analysis. The square total of the distances between water samples was 0.092 between April and July, 0.562 between April and September, and 0.656 between July and September.

The distribution of the differences between the two random ordinations was examined and compared to the distance square totals. As a result, significant differences were recorded between April and September and also July and September but not between April and July.

Because of the similarity of samples taken in April and July (demonstrated by the Procrustes analysis) only the data from July are presented here (on PCA axes 1 and 2) emphasising differences with the PCA of the autumn (September) samples (Fig. 6). In July the first principal component showed a positive correlation with NO_3^-, ETS-activity, TN, OC, TP, TS, LOI and a negative correlation with the C:N ratio and NO_2^- concentration. SO_4^{2-} showed a positive correlation with the second principal component of the variables, while PO_4^{3-} showed a negative correlation, it could be interpreted as an axis indicating the redox conditions of the sediment. The first principal component showed relationships with more variables than the second principal component. Altogether 75.4 % of the

total variance was accounted for by the first component and 17.6 % by the second component. In September the first principal component showed a positive correlation with ETS-activity, TN, TS, LOI and none of the variables showed negative correlation with this component. The second principal component showed a positive correlation with TP, PO_4^{3-} and a negative one with OC, C:N ratio and SO_4^{2-}.

In each case S3 showed a positive correlation with the first principal component. Among the variables NO_3^-, ETS-activity, TN, OC, TP, TS, LOI played an important part in its separation. In each case the separation of S5 was mainly determined by PO_4^{3-}. S42 positively correlated with the second principal component in July and negatively correlated with the first principal component in September, in each case the SO_4^{2-} pointed in its direction. S2 correlated negatively with the second principal component and its separation was mainly determined by the C:N ratio in every sampling time.

DISCUSSION

Surface and sediment interstitial water characteristics

The seasonal variation of electrical conductivity and SO_4^{2-} concentration was largely influenced by water level fluctuations. The seasonal changes in surface and sediment interstitial water characteristics showed similar tendencies but in different values. The changes are mainly due to the shallowness of the lake, hydrometeorological conditions and accelerating eutrophication processes, which is demonstrated well by the PO_4^{3-} concentration of the surface water. The chemical composition of the lake water is characterised by remarkable seasonal and spatial changes (DINKA & BERCZIK, 1992; TAKÁTS et al., 1997).

The chemical characteristics of surface and sediment interstitial water are greatly influenced by the organic matter content of the sediment (THRESH et al., 1944). In our study, the lower
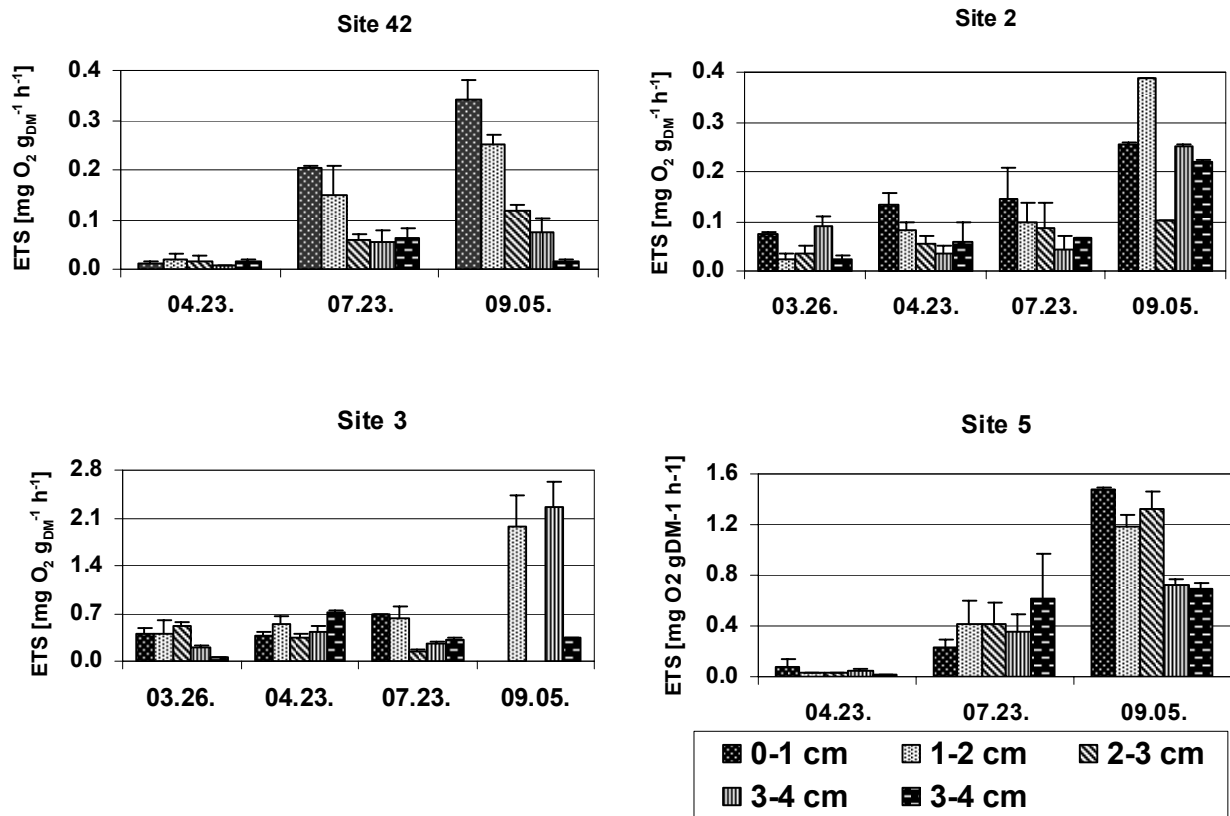
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Figure 5. Seasonal changes of the ETS-activity of the sediment in Lake Fertő/Neusiedler See in 2001. (means±SE, n=3).

organic matter content at S2 and S42 resulted in lower concentration of nutrients in the sediment (Table 3) and the interstitial water.

The decrease in SO_4^{2-} concentration with sediment depth can be explained by sulphate reduction, which is one of the most important processes in the decomposition of organic materials (JØRGENSEN, 1977). Spatial patterns in the interstitial water SO_4^{2-} concentration profiles differed according to the sampling sites (Fig. 3). The high SO_4^{2-} concentration decrease at S3 and S5 indicates that there was a substantial sulphate reduction activity in the sediments of these sites, which probably is due to the highly reducing conditions and to the organic rich sediments (51.8-58.0 %, 9.4-23.0 %, respectively). SO_4^{2-} concentration and temperature strongly influences the PO_4^{3-} release from the sediment (CARACO et

al., 1989; NIXON et al., 1980). When sulphate reduction activity is lower, PO_4^{3-} is stored in the sediment. This phenomenon was well illustrated by our results.

NH_4^+ was detectable in higher concentrations in the upper 5 cm interstitial water only in summer months. These high summer NH_4^+ concentrations were probably caused by elevated NH_4^+ generation rate and higher temperature values. In summer, high PO_4^{3-} concentration was often associated with high NH_4^+ concentration, which was also observed by ANDERSEN, 1974; BENGTSSON, 1975; GOEL et al., 1980. The NH_4^+ concentration of the interstitial water varied spatially, it was always higher than the corresponding values in the overlying water and the NO_3^- concentration in the interstitial water but it was similar with the NO_2^- concentration values

of the interstitial water. The chemical form of the nitrogen deriving from detritus depends on the oxidizing/reducing characteristics of the sediment. NO_2^- was found in the surface water of S3, where the highest NO_3^- and PO_4^{3-} concentrations were measured. The seasonal variation of PO_4^{3-} and NO_3^- concentrations in the surface water showed opposite tendencies, which has previously been demonstrated by PHILLIPS, (1977) and GOEL et al., (1980).
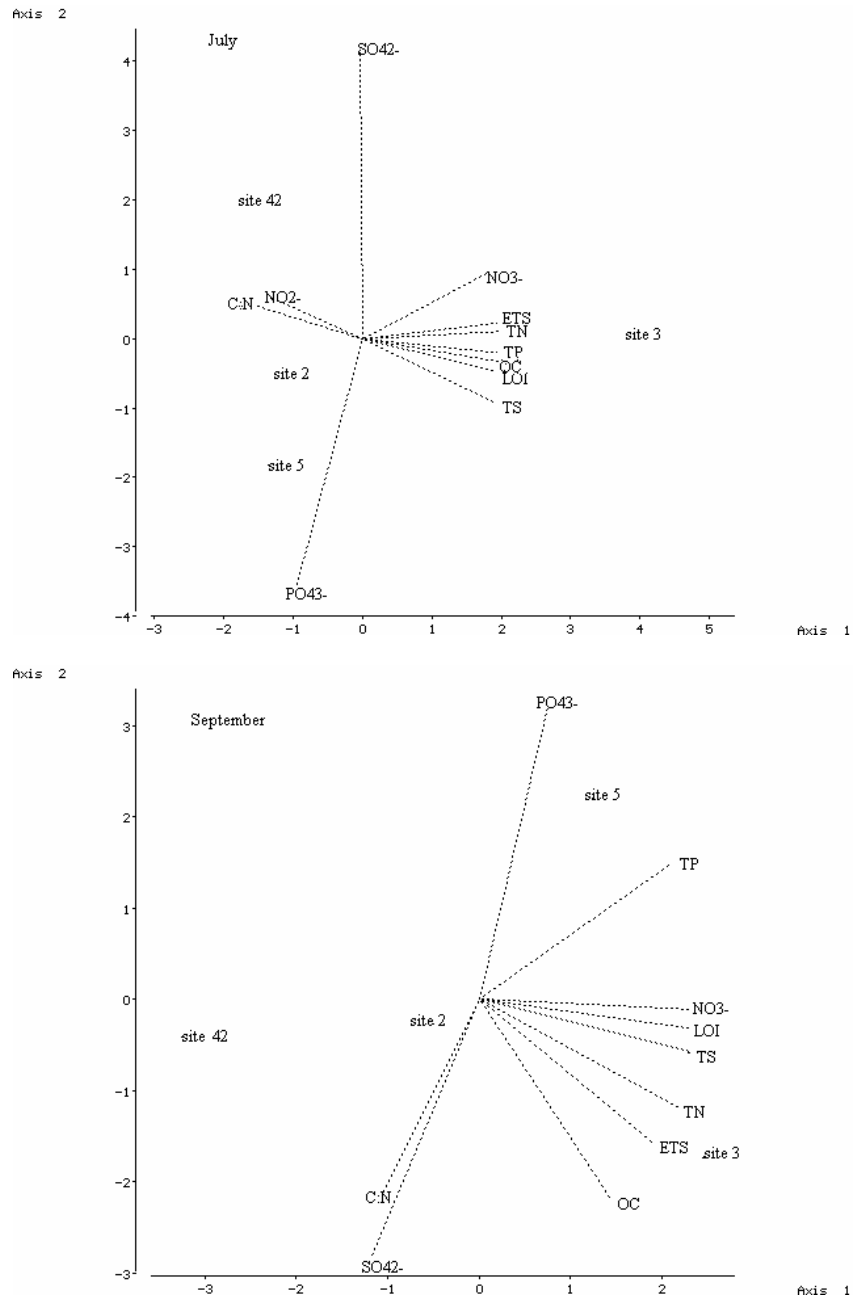

Figure 6. Graphic interpretation of chemical features and principal component analysis of the sampling sites.

In summer negative redox conditions developed in the sediment (unpublished data), which are favourable for anaerobe nitrate reduction (RYSGAARD et al., 1996), therefore the nitrate concentration decreased with depth (DINKA, 2001, SZABÓ, 2001, SZABÓ in press) and PO_4^{3-} increased.

Sediment characteristics

The sediment organic matter, OC, TN, TS and TP content was significantly higher in the degraded (S3) than in the healthy (S2, S5) reed stands or in the inner pond (S42). Increased organic matter accumulation in the upper sediment of degraded reed areas was likely due to the higher annual accumulation rate of wetland plant material and the frequent occurrence of negative redox conditions.

Seasonal changes in the TP concentration of the sediment can be explained by the seasonal pattern of the P release from the sediment. Most P release occurs in summer and is associated with changes in Fe cycling and sulphate reduction (CONLEY, 2000).

ETS-activity in sediment

ETS-activities of the sediment often decreased with depth (Fig. 5), these decreases partly depended on consolidation and stabilization of the sediment and partly on the termination of aerobic metabolism (BROBERG, 1985; SONGSTER-ALPIN & KLOTZ, 1995); benthic algae at the sediment surface, with their photosynthetic ETS, additionally increase measured ETS activity (DEL GIORGIO, 1992). SIMCIC & BRANCELJ (2002) also found decreasing ETS-activities with depth in the sediment of shallow mountain lakes.

Increased bacterial metabolism (increased ETS-activity values) at S3, the degraded reed stand, may be attributed to the increased rates of terminal electron acceptor replenishment (MANN & WETZEL, 2000) due to higher organic matter content than in healthy reed stand areas. In

general heterotrophic bacterial production has a strong positive relationship with the organic matter content of the sediment (SANDER & KALFF, 1993). The higher ETS-activity values in September were probably due to the large decaying mass of macrophytes.

The mean ETS-activity in the uppermost 0-5 cm layer of the Lake Fertő/Neusiedler See sediment (S3: 48.25 mg O_2 g $_{wet\ wt}^{-1}$ h^{-1} and S2: 37.37 mg O_2 g $_{wet\ wt}^{-1}$ h^{-1}) was similar to or higher than that in Central Swedish lakes (L. ERKEN: 38.7 mg O_2 g $_{wet\ wt}^{-1}$ h^{-1}, L. RAMSJÖN: 21.9 mg O_2 g $_{wet\ wt}^{-1}$ h^{-1}, BROBERG, 1985) and it was higher than in Lake Balaton in Hungary (G. TÓTH et al., 1994). This difference can be explained by the differences in organic matter content, pH, temperature, salinity, and redox conditions in the sediment of the investigated lakes.

CONCLUSIONS

The seasonal variation of electrical conductivity and SO_4^{2-} concentrations was influenced by water level fluctuations. Higher values were measured in the second part of the vegetation period when the water level was lower. The seasonal variation in PO_4^{3-} and NO_3^- concentrations of the surface water showed opposite tendencies. PO_4^{3-} release from the sediment was strongly influenced by the SO_4^{2-} concentration and temperature. Higher PO_4^{3-} and NH_4^+ concentrations were measured in the sediment interstitial water in summer, when the decrease in SO_4^{2-} concentration was higher, which indicated the SO_4^{2-} reduction processes.

The organic matter, OC, TN, TS TP content and the ETS-activity of the sediment were significantly higher in the degraded reed stand area (S3) than in the healthy reed stands (S2, S5) or the inner pond (S42). Increased organic matter accumulation in the upper sediment of degraded reed beds was likely due to the higher annual accumulation rate of wetland plant material and the frequent occurrence of negative redox conditions.

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Higher ETS-activity values in September were probably due to the decaying mass of macrophytes. The four examined sampling sites were well discriminated by the chemical composition of the sediment indicating the highest trophic status at S3 (degraded reed stand), an intermediate status at S2 and S5 (healthy reed stands) and a lower status at S42 (inner pond).

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