

Changes of phytoplankton communities in Lakes Naivasha and Oloidien, examples of degradation and salinization of lakes in the Kenyan Rift Valley

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Abstract Increasing degradation of the water quality, caused by overuse and salinization, leads to considerable changes of the phytoplankton composition in Kenyan Rift Valley lakes. Exemplarily, the phytoplankton communities and biomasses of deteriorating freshwater Lake Naivasha and salinizing Lake Oloidien were studied between 2001 and 2005, accompanied by physico-chemical measurements (pH, total phosphorus and nitrogen, alkalinity, conductivity). Over the last three decades, the ecology of these two water basins has been subjected to dramatic changes, caused by excessive use of water and catchment area by man. In L. Naivasha a shift in

the dominance of coccoid cyanobacteria towards dominance of Chlorophyceae (*Botryococcus terribilis*) was observed. Lake Oloidien exhibited a shift in the dominance of coccoid Chlorophyceae towards dominance of cyanobacteria (*Arthrospira fusiformis*, *Anabaenopsis elenkinii*). Phytoplankton findings and chemical data demonstrate that L. Naivasha has developed towards a eutrophic freshwater lake while L. Oloidien has progressed towards a hypereutrophic alkaline-saline lake.

Keywords Lake Naivasha · Lake Oloidien · Eutrophication · Salinization

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Lake Naivasha is the largest freshwater lake in the Kenyan Rift Valley. This shallow body of water remains fresh due to inflow from three river systems (Malewa, Gilgil, and Karati) and underground outflow through seepage (Beadle, 1932; Gaudet & Melack, 1981; Becht & Harper, 2002). Lake Oloidien is a former bay of L. Naivasha with a hydrologically closed basin. Its water level is maintained only by rainfall, evaporation, and subsurface inflow from L. Naivasha through a permeable sill (Verschuren et al., 2000). For geomorphological features of the lakes see Table S1.

The first studies on the Naivasha-basin were conducted by Jenkin (1929) and Beadle (1932). Subsequent studies were done in 1960s (Evans, 1962; Lind,

1968; Richardson, 1968), end of 1970s (Kalff & Watson, 1986), beginning of 1990s shortly after the separation of both lakes (Uku & Mavuti, 1994), and in 1997–1998 (Hubble & Harper, 2002). Over the last three decades, the Naivasha-basin ecology has been subjected to dramatic changes caused by excessive use of water and catchment area by man (Harper, 2006). Consequently, the phytoplankton community exhibited substantial fluctuations whose magnitude needs to be documented to assess further development of protection and restoration strategies for the lake ecosystem.

The aim of this study was, therefore, to investigate (a) changes in salinity/conductivity and nutrient concentrations, and (b) changes in phytoplankton community. This study was carried out from June 2001 to May 2005. Physico-chemical data and methods of measurements are given in Table S2. Phytoplankton methods were applied according to Ballot et al. (2004).

Lakes Naivasha and Oloidien showed clear differences in physico-chemical conditions. Secchi-depth never exceeded 0.62 m, with median values of 0.50 m in L. Naivasha and 0.22 m in L. Oloidien. The pH ranged from 8.0 to 9.4 in L. Naivasha and from 9.3 to 9.9 in L. Oloidien. Conductivity values between 282 and 374 $\mu\text{S cm}^{-1}$ in L. Naivasha and 3,890 and 5,270 $\mu\text{S cm}^{-1}$ in L. Oloidien were measured. Total alkalinity ranged from 2.6 to 5.0 meq l^{-1} in L. Naivasha and from 39 to 65 meq l^{-1} (1,970–3,250 $\text{mg CaCO}_3 \text{l}^{-1}$) in L. Oloidien. Total phosphorus (TP) concentrations ranged from 0.07–0.20 mg l^{-1} in L. Naivasha and from 0.4–1.0 mg l^{-1} in L. Oloidien. Total nitrogen (TN) concentrations ranged from <0.5–2.4 mg l^{-1} in L. Naivasha and from 0.9–6.3 mg l^{-1} in L. Oloidien.

The phytoplankton community of L. Naivasha was dominated by cyanobacteria, Chlorophyceae, and Bacillariophyceae (Fig. 1a). A list of identified taxa is presented in Table S3. Coccoid cyanobacteria e.g. *Cyanocatena planctonica*, *Chroococcus limneticus*, and *Aphanocapsa* sp. were responsible for 83–98% of the cyanobacterial biomass. Throughout 2002/2003, the Chlorophyceae was the most abundant group. A maximum phytoplankton biomass of 56.6 mg l^{-1} was recorded during a bloom of *Botryococcus terribilis* in September 2002. Other groups that temporarily reached high biomass were Desmidiaceae (*Gonatozygon* sp.) and Bacillariophyceae

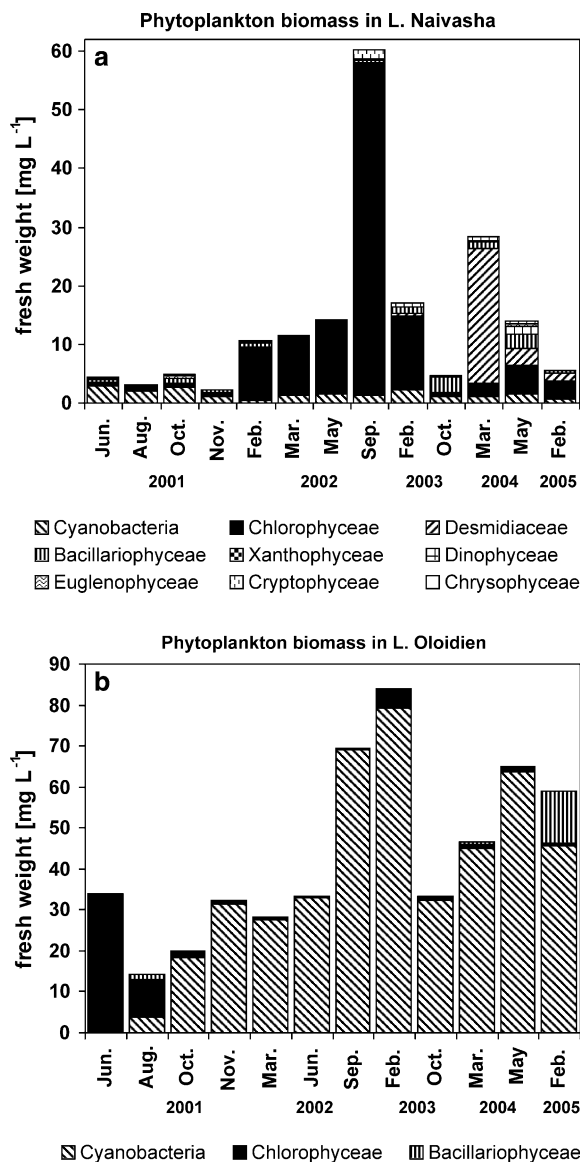


Fig. 1 Biomass (fresh weight in mg l^{-1}) of the main phytoplankton groups in Lakes Naivasha (a) and Oloidien (b) from June 2001 to February 2005

(*Aulacoseira* sp.). Most samples had low biomass of the cyanobacterium *Microcystis aeruginosa*.

The phytoplankton of L. Oloidien was dominated by cyanobacteria and Chlorophyceae (Fig. 1b). Coccoid Chlorophyceae were dominant in June/August 2001 with a percentage of 98.3 and 63.6% respectively. This group was mainly composed of unidentifiable spherical-ellipsoid taxa. Samples from October 2001 to February 2005 showed mass developments of cyanobacteria comprising between 77.5 and 99.2% of

the biomass. The total phytoplankton biomass ranged from 14.4 up to 83.9 mg l⁻¹. Dominant taxa were *Chroococcus minutus*, unidentifiable thin filamentous Oscillatoriales, *Arthrospira fusiformis*, and *Anabaena-opsis elenkinii*.

Our study revealed major differences in the two lakes investigated. Lake Naivasha is characterized by constant freshwater conditions. Only slight variations in conductivity have been recorded over the last 40 years. Talling & Talling (1965) recorded a conductivity of 285 $\mu\text{S cm}^{-1}$ in 1961 while Kalff & Watson (1986) recorded a value of 335 $\mu\text{S cm}^{-1}$ in 1979, both within the similar range to that of 282–374 $\mu\text{S cm}^{-1}$ measured in our study. Only during an eight year long drought period between 1983 and 1991 slightly higher conductivity values of up to 480 $\mu\text{S cm}^{-1}$ were recorded by Harper et al. (1993).

In contrast to L. Naivasha, L. Oloidien has changed from freshwater conditions towards an alkaline-saline lake. Conductivity values measured during our study differed considerably from those reported in former studies. In the period 1979/1980 when the two lakes were connected, the conductivity in L. Oloidien was 660 $\mu\text{S cm}^{-1}$, which was only twice higher than in L. Naivasha (Kalff & Watson, 1986). Over the last 25 years, the conductivity of L. Oloidien has increased almost eightfold, reaching a maximum of 5,270 $\mu\text{S cm}^{-1}$ in 2005.

A progressive increase in nutrient concentrations can be observed in both lakes. Kalff & Watson (1986) measured a mean TP concentration of 0.04 mg l⁻¹ in 1979/80. We measured between 0.07 and 0.2 mg l⁻¹ TP in L. Naivasha and between 0.4 and 1.0 mg l⁻¹ TP in L. Oloidien. These data indicate a shift to higher trophic conditions in both lakes. According to the classification system for warm-water tropical lakes (Salas & Martino, 1991), L. Naivasha can presently be classified as eutrophic while L. Oloidien is hypereutrophic.

Several factors are responsible for increasing nutrient concentrations in both lakes. The water level and volume decrease during dry periods, causing rising nutrient concentrations in L. Naivasha and rising salt and nutrient concentrations in L. Oloidien. At L. Naivasha with a catchment area of around 3,400 km², overgrazing and tilling leading to erosion are common phenomena (Everard & Harper, 2002) hence, inflowing rivers contribute to nutrient enrichment. Another factor is the intensive horticultural

industry, using water of L. Naivasha for irrigation. The horticultural runoff is a source of nutrients and pesticides (Kitaka et al., 2002; Harper, 2006) deteriorating the water quality. Compared to L. Naivasha, the catchment of L. Oloidien is small without inflowing rivers. The main sources of nutrient input are cattle and goat herds watering at the lake and local women washing clothes using detergents. On the other hand, domestic use of water from L. Oloidien is threatened by unsuitable physico-chemical conditions. Waters with pH values above 9 or alkalinity values above 3,000 mg CaCO₃ l⁻¹ are solely suitable for livestock-watering with restrictions (Beede, 2005).

Changes in physico-chemical properties of lake ecosystems are closely linked to changes in the phytoplankton composition. In L. Naivasha, we identified 116 phytoplankton taxa. Earlier investigations by Kalff & Watson (1986) and Hubble & Harper (2002) recorded higher numbers of 143 and 173 taxa, respectively. One reason for different numbers of species between our and previous studies is a decrease in the number of diatom species. Hubble & Harper (2002) found 69 diatom taxa, whereas our study recorded only 15 species. Furthermore, the eutrophic condition of L. Naivasha can stimulate the growth of *Microcystis* species. In 2006, dense blooms of *M. aeruginosa* were observed near Elsamere in the southwestern lagoon (Krienitz, unpublished observations).

In L. Oloidien, we found 26 taxa, a considerably lower number than in L. Naivasha. This can be related to the increasing alkalinity and salinity. According to Hammer (1986), alkaline-saline environments are relatively poor in species but with high numbers of individuals. This is supported by Kalff & Watson (1986) who described 94 taxa in 1979/1980 when L. Oloidien was still a freshwater lake. *A. fusiformis* and *A. elenkinii*, which exhibited a progressive increase of biomass in L. Oloidien, are typical cyanobacteria of alkaline-saline lakes (Vareschi, 1982; Melack, 1988; Ballot et al., 2004). In 2004, we observed flocks of Lesser Flamingos (*Phoeniconaias minor*) feeding on the increasing biomass of *A. fusiformis* at L. Oloidien.

Changes in phytoplankton communities of lakes Naivasha and Oloidien can be contextualized to studies on equilibrium phases which reflect degradation-scenarios (Naselli-Flores et al., 2003; Padisák et al., 2003). According to the criterion that only one,

two, or three algal species contribute to more than 80% of total phytoplankton biomass to define a period of equilibrium (Sommer et al., 1993), we found several stages of equilibria in our study-sites. In L. Naivasha, in June 2001, *Cyanocatenella planktonica*, *Pediastrum simplex*, and *Aulacoseira granulata* together reached 75% of the total biomass and almost fulfilled the equilibrium criterion. In September 2002, *B. terribilis* reached a biomass of more than 90%. In L. Oloidien, equilibrium was indicated by the dominance of unidentified coccoid green algae in June 2001. From March 2002 until 2005 very long lasting steady state phases were established by the cyanobacteria *C. minutus*, *A. elenkinii*, and *A. fusiformis*. Under tropical conditions such equilibria can be longer lasting than in temperate climate (Komárkova & Tavera, 2003; Becker et al., 2008).

The comparison of our results to former studies shows a clear shift in dominating species, in L. Naivasha from cyanobacteria to chlorophyte-dominated periods and in L. Oloidien from freshwater to salt-tolerant taxa. Our study showed that both lakes have deteriorated considerably. Although L. Naivasha has maintained freshwater conditions, it has developed towards a eutrophic lake. The presence of the potential toxic cyanobacterium *M. aeruginosa* is a health risk to the local population and their livestock. Haande et al. (2007) have isolated a toxic *Microcystis*-strain from L. Naivasha. Lake Oloidien is progressing towards a hypereutrophic alkaline-saline lake. The phytoplankton community in L. Oloidien has changed dramatically and is now dominated by cyanobacteria typical for alkaline-saline lakes.

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Table S1: Geographical position, altitude, surface area, catchment area depth and total rainfall at Lakes Naivasha and Oloidien (Verschuren, 1999; Verschuren et al., 2000^a; Bergner et al., 2003^b).

	Lake Naivasha	Lake Oloidien
Geographical position of sampling points	00°48'51.90" S, 036°18'43.93" E	00°49'00.88" S, 036°15'52.15" E
Altitude above sea level (m)	1885	1885
Surface area (km²)	135 ^a – 180 ^b	5.1
Depth (m)	6	4
Catchment area (km²)	3400	-
Rainfall (mm)	500-700	500-700

Table S2: Physico-chemical conditions of L. Naivasha and L. Oloidien (June 2001 – February 2005).

Parameters	Lake Naivasha			Lake Oloidien		
	2001 - 2005			2001 - 2005		
	Min.	Median	Max.	Min.	Median	Max.
Water temperature (C°)	20.9	22.65	25.9	15.8	25.4	33.4
Secchi depth (m)	0.26	0.50	0.62	0.17	0.22	0.40
pH	8.0	8.5	9.4	9.3	9.7	9.9
Conductivity ($\mu\text{S cm}^{-1}$)	282	330	374	3890	4000	5270
Alkalinity (meq L^{-1})	2.6	3.8	5.0	39.4	54.8	65.0
TP (mg L^{-1})	0.07	0.09	0.2	0.4	0.5	1.0
TN (mg L^{-1})	< 0.5	1.5	2.4	0.9	3.4	6.3

Conductivity, pH and salinity were measured directly in the lakes with WTW Multiline P4 (Wissenschaftlich Technische Werkstätten Weilheim, Germany). Water transparency was measured with a Secchi disc ($\text{\O} 20 \text{ cm}$). Samples for the analyses of total nitrogen (TN) and total phosphorus (TP) were taken few centimeters below water surface. Laboratory analyses were carried out within three hours from the time of collection. For TN and TP, Nanocolor tube tests (two replicates each) and a field photometer (Nanocolor 300 D; Macherey-Nagel GmbH Düren, Germany) were used. The detection limits were 0.5 mg N L^{-1} (TN) and 0.01 mg P L^{-1} (TP).

Table S3: Phytoplankton composition in Lakes Naivasha and Olodien.

Legend + = sporadic ++ frequent +++ = dominant.

Species	Lake Naivasha	Lake Olodien
Domain Eubacteria		
Division Cyanobacteria (Cyanoprokaryota)		
<i>Anabaena</i> sp.	+	
<i>Anabaenopsis elenkinii</i> Miller		+++
<i>Anabaenopsis</i> sp.	++	
<i>Aphanizomenon</i> sp.	++	
<i>Aphanocapsa</i> spp. (3)	+++	++
<i>Aphanocapsa delicatissima</i> West et West	++	
<i>Aphanocapsa elachista</i> West et West	+++	
<i>Aphanocapsa holsatica</i> (Lemmermann) Cronberg et Komárek	++	
<i>Aphanothece</i> sp.	++	
<i>Arthrospira fusiformis</i> (Voronichin) Komárek et Lund	+	+++
<i>Borzia</i> sp.	+	++
<i>Chroococcus catenatus</i> Komárek et Novelo	++	
<i>Chroococcus cronbergae</i> Komárek et Novelo	++	
<i>Chroococcus limneticus</i> Lemmermann	+++	
<i>Chroococcus minutus</i> (Kützing) Nägeli		+++
<i>Chroococcus</i> spp. (2)	++	
<i>Cyanocatena planctonica</i> Hindák	+++	
<i>Gloeothece</i> sp.	++	
<i>Lemmermanniella</i> sp.	++	
<i>Limnothrix guttulata</i> (Van Goor) Umezaki et Watanabe	+	+++
<i>Merismopedia punctata</i> Meyen	++	
<i>Merismopedia tenuissima</i> Lemmermann	++	
<i>Microcystis aeruginosa</i> (Kützing) Kützing	+++	++
<i>Microcystis</i> spp. (2)	+	
<i>Oscillatoria</i> sp.	++	
Oscillatoriales		+++
<i>Phormidium</i> cf. <i>tenuis</i> (Agardh ex Gomont) Anagnostidis et Komárek	++	
<i>Phormidium</i> sp.		+
<i>Planktolyngbya tallingii</i> Komárek et Kling	++	
<i>Pseudanabaena</i> sp.	+	++
<i>Spirulina subtilissima</i> Kützing ex Gomont	+	+
<i>Synechococcus</i> sp.		+
<i>Synechocystis salina</i> Wislouch	++	
<i>Synechocystis</i> sp.		++
Domain Eukarya		
Division Ochrophyta, Class Xanthophyceae		
<i>Goniochloris</i> sp.	+	
<i>Pseudostaurastrum hastatum</i> (Reinsch) Chodat	+	
<i>Pseudostaurastrum</i> cf. <i>lobulatum</i> (Nägeli) Chodat	+	
<i>Tetraedriella</i> cf. <i>regularis</i> (Kützing) Fott	++	
<i>Tetraedriella</i> cf. <i>spinigera</i> Skuja	+	
<i>Tetraplektron</i> cf. <i>torsum</i> (Skuja) Dedushenko Shchegoleva	++	
<i>Pseudogoniochloris</i> sp.	+	

Table S3 (cont.): Frequent phytoplankton species in Lakes Naivasha and Olodien.

Species	Lake Naivasha	Lake Olodien
Class Bacillariophyceae		
<i>Amphora copulata</i> (Kützing) Schoeman et Archibald	+++	
<i>Amphora veneta</i> Kützing	+	
<i>Anomoeoneis</i> cf. <i>sphaerophora</i> (Ehrenberg) Pfitzer		+++
<i>Aulacoseira granulata</i> (Ehrenberg) Simonsen	+++	
<i>Cymbella</i> sp.	+	
<i>Gomphonema parvulum</i> Kützing	+	
<i>Nitzschia frustulum</i> (Kützing) Grunow	++	+++
<i>Navicula</i> sp.	+	+++
<i>Planothidium lanceolatum</i> (Brébisson) Round et Bukhtiyarova	+	
<i>Psammodictyon constrictum</i> (Gregory) Mann	+	
<i>Surirella linearis</i> W. Smith	+++	
<i>Surirella</i> sp.	+++	
<i>Thalassiosira weissflogii</i> (Grunow) Frixel et Hasle	+	
<i>Ulnaria acus</i> (Kützing) Aboal	+	
<i>Ulnaria ulna</i> (Nitzsch) Compère	+	
Division Cryptophyta, Class Cryptophyceae		
<i>Cryptomonas</i> spp.	+++	
Division Dinophyta, Class Dinophyceae		
<i>Ceratium hirundinella</i> (Müller) Dujardin	+++	
<i>Peridinium gatunense</i> Nygaard	+	
Division Euglenophyta, Class Euglenophyceae		
<i>Euglena</i> spp. (2)	++	++
<i>Euglena oxyuris</i> Schmarda	+++	
<i>Euglena</i> cf. <i>texta</i> (Dujardin) Hübner	++	
<i>Lepocinclis ovum</i> (Ehrenberg) Lemmermann	+	
<i>Phacus acuminatus</i> Stokes	++	
<i>Phacus meson</i> Pochman	++	
<i>Phacus tortus</i> (Lemmermann) Skvortsov	++	
<i>Strombomonas acuminata</i> (Schmarda) Deflandre	+	
<i>Trachelomonas bernardinensis</i> Vischer emend. Deflandre	++	
<i>Trachelomonas hispida</i> (Perty) Stein emend Deflandre	+++	
<i>Trachelomonas raciborskii</i> Woloszyńska	++	
Division Chlorophyta, Class Chlorophyceae		
<i>Botryococcus terribilis</i> Komárek et Marvan	+++	
<i>Chlamydomonas</i> sp.	+	
<i>Chlorolobium</i> sp.	++	
<i>Chlorophyceae</i> (coccolid)		+++
<i>Coelastrum indicum</i> Turner	+	
<i>Coelastrum pseudomicroporum</i> Korshikov	++	
<i>Coelastrum reticulatum</i> (Dangeard) Senn	+	
<i>Coenococcus planctonicus</i> Korshikov	++	
<i>Crucigeniella pulchra</i> (West et West) Komárek	+	
<i>Crucigenia tetrapedia</i> (Kirchner) West et West	+	
<i>Desmodesmus armatus</i> (Chodat) Hegewald	++	
<i>Desmodesmus communis</i> (Hegewald) Hegewald	+++	+++
<i>Desmodesmus opoliensis</i> (Richter) Hegewald	+	
<i>Desmodesmus subspicatus</i> (Chodat) Hegewald et Schmidt	+	
<i>Dictyosphaerium pulchellum</i> var. <i>minimum</i> Deflandre	+	
<i>Dispora cuneiformis</i> (Schmidle) Printz	+	
<i>Eudorina elegans</i> Ehrenberg	+	
<i>Fusola viridis</i> Snow	++	

Table S3 (cont.): Frequent phytoplankton species in Lakes Naivasha and Olodien.

Species	Lake Naivasha	Lake Olodien
Division Chlorophyta, Class Chlorophyceae		
<i>Granulocystis</i> sp.	+	
<i>Hindakochloris nygaardii</i> (Fott) Comas	++	
<i>Kirchneriella contorta</i> (Schmidle) Bohlin	+	
<i>Kirchneriella diana</i> e (Bohlin) Comas	++	
<i>Kirchneriella irregularis</i> var. <i>spiralis</i> Korshikov	++	
<i>Kirchneriella obtusa</i> (Korshikov) Komárek		+++
<i>Kirchneriella</i> sp.	+	+++
<i>Lagerheimia subsalsa</i> Lemmermann	+++	
<i>Monoraphidium contortum</i> (Thuret) Komárková-Legnerová	+++	
<i>Monoraphidium</i> sp.	+	+
<i>Nephrochlamys subsolitaria</i> (West) Korshikov	+	
<i>Nephrochytium agardhianum</i> Nägeli	++	
<i>Oocystis lacustris</i> Chodat	+++	
<i>Oocystis marssonii</i> Lemmermann	++	
<i>Oocystis</i> sp.	+++	
<i>Pandorina minodi</i> Chodat	++	
<i>Pediastrum boryanum</i> (Turpin) Meneghini	++	
<i>Pediastrum duplex</i> var. <i>duplex</i> Meyen	+	
<i>Pediastrum duplex</i> var. <i>gracillimum</i> West et West	+	
<i>Pediastrum simplex</i> Meyen	+++	
<i>Pediastrum tetras</i> (Ehrenberg) Ralfs	+	
<i>Phacotus lenticularis</i> (Ehrenberg) Stein	+	
<i>Scenedesmus acuminatus</i> (Lagerheim) Chodat	+	
<i>Scenedesmus acutus</i> Meyen	+	
<i>Scenedesmus dimorphus</i> (Turpin) Kützing	+++	
<i>Scenedesmus disciformis</i> (Chodat) Fott et Komárek	+	
<i>Scenedesmus linearis</i> Komárek	+++	+
<i>Scenedesmus obtusus</i> Meyen		+
<i>Scenedesmus</i> sp.		+++
<i>Tetraedron caudatum</i> (Corda) Hansgirg	++	
<i>Tetraedron minimum</i> (Braun) Hansgirg	++	+
Division Streptophyta, Class Charophyceae		
<i>Closterium aciculare</i> T. West	++	
<i>Closterium acutum</i> var. <i>variabile</i> (Lemmermann) Krieger	++	
<i>Closterium gracile</i> Brébisson ex Ralfs	++	
<i>Closterium parvulum</i> Nägeli	++	
<i>Cosmarium</i> spp. (2)	+	
<i>Gonatozygon</i> sp.	+++	
<i>Pleurotaenium trabecula</i> (Ehrenberg) Nägeli	+	
<i>Staurastrum anatum</i> Cooke ex Wills	++	