ASSESSMENT OF THE ECOLOGICAL INTEGRITY OF TRAUNSEE (AUSTRIA) VIA ANALYSIS OF SEDIMENTS AND BENTHIC MICROBIAL COMMUNITIES

CHRISTIAN GRIEBLER[1,2]*, BETTINA SONNTAG[3], BIRGIT MINDL[2,3],
THOMAS POSCH[3], SUSANNE KLAMMER[3] and ROLAND PSENNER[3]
[1] *Center for Applied Geoscience, Eberhard-Karls University of Tübingen, Tübingen, Germany;*
[2] *Institute for Limnology, Austrian Academy of Sciences, Mondsee, Austria;* [3] *Institute of Zoology and Limnology, University of Innsbruck, Innsbruck, Austria*
(author for correspondence, e-mail: christian.griebler@uni-tuebingen.de, fax: +49 7071 295139)*

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Abstract. Since nearly one hundred years Traunsee experiences the import of tons of liquid and solid waste originating from salt and soda production. Today, the lake exhibits chloride concentrations of up to 170 mg L^{-1} and 19% of the lake floor are directly or indirectly influenced by industrial deposits (ID). Based on the comparison of several microbial parameters in unaffected, directly affected and intermediate lake bottom sediments, the ecological integrity of the lake was evaluated. The highly alkaline ID, which were exclusively colonized by microorganisms, harbored a bacterial community reduced by a factor of 10 in abundance and biomass compared to undisturbed sediment areas within the lake. The bacterial community of ID was furthermore characterized by a reduced content of actively respiring cells (INT-formazan reduction), a lower frequency of dividing cells (FDC) and a significantly reduced cell and biomass production. A 80 to 90% reduction in carbon recycling is estimated for the area exclusively covered by ID. Protists, although occasionally absent from the industrial sediments, were in general found to be less sensitive to the contaminant stress. Differences in alkalinity and dissolved organic carbon (DOC) concentrations of sediment porewaters as well as the total organic content and C/N ratios of sediments partly explain the microbial pattern observed at the various sampling sites. Possible consequences of the continuous industrial tailings for the whole lake ecosystem and the validation of the ecological integrity are discussed.

Keywords: alkaline sediments, bacterial production, benthic microbial community, chloride, ciliates, C/N ratio, DOC, ecological integrity, Protozoa, sediment bacteria

1. Introduction

Traunsee, one of the largest (24.35 km^2) and deepest (191 m) lake of Austria, receives several hundred tons of waste per day from the soda (Solvay Austria AG) and salt industry (Saline Austria AG). The dissolved and solid industrial effluents have been introduced into the lake for more than 100 years (Müller *et al.*, 1986). Since 1928 industrial deposits (ID) have been directly discharged into the Ebensee Bay in the southern part of the lake (Figure 1). Meanwhile a 47 m high pile was formed from ID, consisting mainly of various forms of carbonate (calcite, aragonite, vaterite), gypsum ($CaSO_4 \cdot 2H_2O$) and brucite ($Mg(OH)_2$) (Müller and

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Schneider, 1984). These ID have highly alkaline porewaters (pH 8.5 to 12.7) and along with flood events of the main inflow, the Traun River, turbidity currents from the ID cone move towards the deepest basin of the lake (Schmidt, 1989). The settling material subsequently covers the natural sediments and thus part of the lake floor is turned into a hostile environment from time to time. Today, more than 19% of the lake floor are directly or indirectly affected by these alkaline deposits (Müller *et al.*, 2002). Additionally to the import of solid material, a high load of salts such as sodium chloride (NaCl) and calcium chloride ($CaCl_2$) enter the lake, resulting in high chloride concentrations in lake water (Pechlaner and Sossau, 1982). On basis of new national and international standards and directives in water laws (e.g. ÖNORM M 6231 and 6232; European Water Framework Directive), the province of Upper Austria ordered an assessment of the ecological integrity of Traunsee. This article summarizes the results from microbiological investigations of Traunsee sediments in relation to the industrial tailings.

Microbes are, without doubt, the most abundant organisms in the world and form the basis of most food webs. During the past two decades their importance in aquatic ecosystems has repeatedly been documented (Pomeroy, 1974; Williams, 1981; Azam *et al.*, 1983; Sherr and Sherr, 1988, 1994). Microorganisms may be characterized as the driving force for the cycle of elements (Meyer-Reil, 1994). In sediments they play a major role in the decomposition, production as well as the consumption of organic matter and the release of inorganic nutrients to the environment (Meyer-Reil, 1993). Recent studies proved a close relationship between the abundance and distribution pattern of bacteria and protists in sediments and several abiotic and biotic parameters, such as sediment grain size, oxygen concentration, organic matter content, perturbation and grazing (e.g. Jones *et al.*, 1979; Meyer-Reil, 1993; Berninger and Epstein, 1995; Lucchesi and Santangelo, 1997). The short generation times and physiological diversity allow microorganisms to react immediately on changing environmental conditions, what makes them valuable bioindicators. The successful application of microbes in risk assessment of anthropogenic impacts has already been demonstrated (Cairns *et al.*, 1992; Doelman *et al.*, 1994; Lehman *et al.*, 1997). Nevertheless, taxonomic difficulties in the study of bacteria and certain groups of protists still hamper the development of practical microbial indices. A first example for a water quality assessment in natural aquatic ecosystems using microbes was published by Berger *et al.* (1997), *i.e.* a microsaprobiological index (DIN 38410) based on the identification and ecology of ciliates, flagellates and bacteria. The present study, for the first time, evaluated the ecological integrity of an anthropogenically impacted lake based on investigations of the sediment microbial community.

The ecological integrity is assessed via the comparison of the actual status (‘*status quo*’) of an ecosystem with its status prior to the anthropogenic impact of concern (‘expected status’). This comparison can be done on basis of earlier data from the affected system or via comparison with unaffected so called ‘reference systems’ of similar character, and data from the literature. With respect to

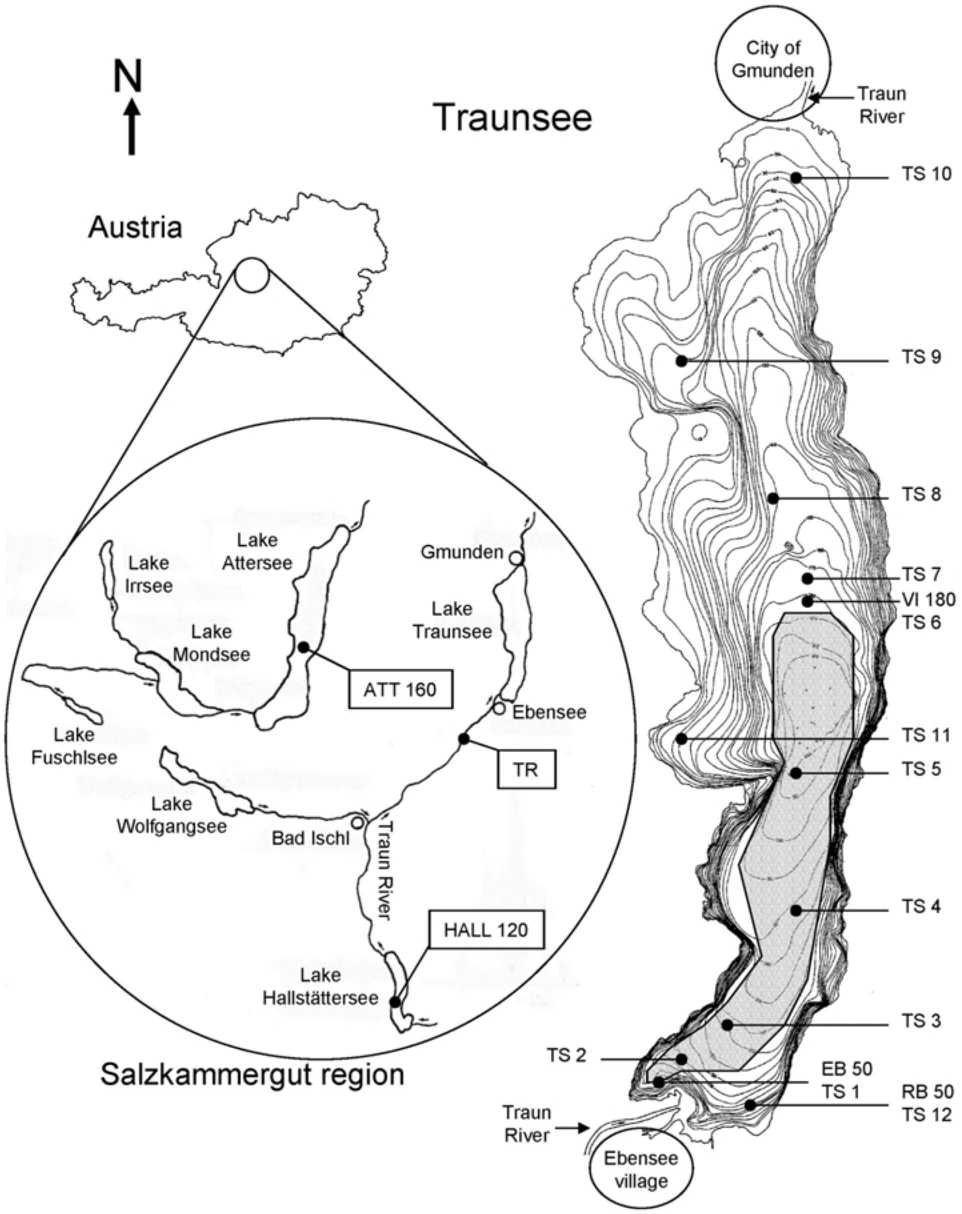

Figure 1. Sampling locations (bathymetric map from Müller and Schneider, 1984). The grey-shaded area indicates the total area of lake floor directly and indirectly influenced by industrial deposits (Müller *et al*., 2002).

the microorganisms, the term ‘ecological integrity’ still waits for its definition. Hardly any data are available on microorganisms, which date back more than two decades. A comparison with ‘microbial’ conditions prior to the anthropogenic

TABLE I

Annual mean chloride concentrations as observed at various depths in the water column and in the sediment porewater of three sampling sites in Traunsee, compared to the reference lakes Hallstättersee and Attersee

	Water column Cl^- concentration ($mg\ L^{-1}$)			Sediment porewater Cl^- concentration ($mg\ L^{-1}$)		
Traunsee	EB 0–40	(n = 32)	93.43 (39.27)	EB 50	(n = 8)	124.25 (6.28)
	RB 0–40	(n = 35)	81.16 (30.60)	RB 50	(n = 8)	115.03 (17.58)
	VI 0–160	(n = 60)	101.98 (28.95)	VI 180	(n = 8)	101.10 (28.13)
Hallstättersee[a]	HALL 0–80	(n = 4)	6.09 (0.61)	HALL 120	(n = 1)	6.73
Attersee[a]	ATT 0–80	(n = 4)	3.55 (0.05)	ATT 160	(n = 1)	3.8

n = number of measurements, values ± S.D. in parentheses.

[a] Concentrations determined only once in May 1999.

impact to an ecosystem is therefore impossible in most cases. What leaves is the comparison with ecologically intact reference systems. Nevertheless, a traditional evaluation based on species lists is, with respect to most microbes (bacteria and flagellates), hampered by taxonomical and methodological difficulties. To our opinion one should focus on functional changes within the microbial community – what means the outfall or replacement of functional groups – and its consequences for the cycling of matter. The present study investigated biomass and activity pattern of the benthic bacterial community in a quantitative sense for sediments directly impacted by industrial tailings and compared these with undisturbed sites within Traunsee. Additionally, as far as possible, the protozoan community was analysed qualitatively. A further comparison with two lakes of similar morphometrical, trophic and physico-chemical pattern from the same region, i.e. Attersee and Hallstättersee, completed our study.

2. Materials and Methods

2.1. SITE DESCRIPTION

Traunsee is located in the southern part of Upper Austria (Figure 1). Details on the morphology and hydrology of the lake are summarized in Jagsch *et al.* (2002). The major tributary to the lake is the Traun River (80% of inflow), which drains an area of 1417 km^2. The high discharge of the river results in a short lake water residence time (1.04 yr) and a lack of a regular ice cover in winter. A monthly sampling of sediments took place at three sites in Traunsee from November 1997 till October 1998. Sampling stations were chosen according to the discharge of industrial wastes, with one site located directly in the zone of industrial tailings

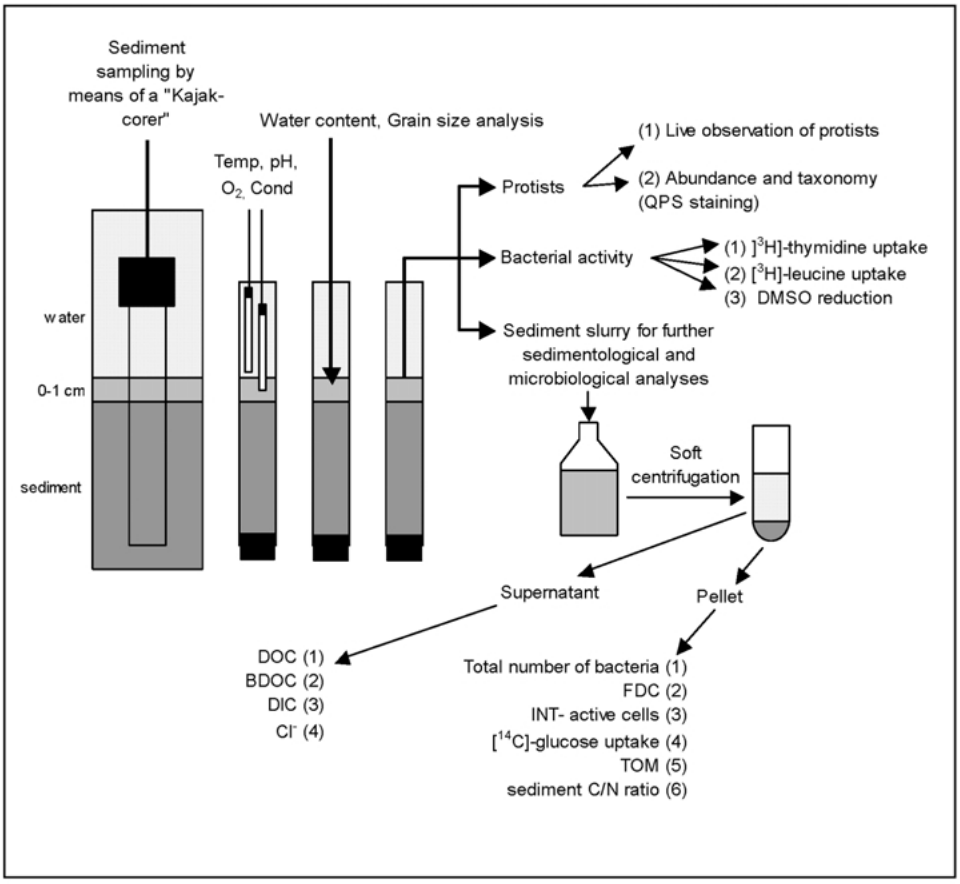

Figure 2. Flow chart showing the successive steps in physico-chemical and microbiological sediment analysis. For a detailed explanation see ‘Materials and Methods’ section.

(Ebensee Bay, 50 m depth; [EB 50]), and two sites unaffected by ID (Rindbach Bay, 50 m depth; [RB 50] and ‘Viechtau’ near the deepest point of the lake, at 180 m depth; [VI 180]) (Figure 1). Location of the identical sampling sites was managed using a geographic positioning system (GPS, Trimble Corp.). In May 1999 sediment samples from Traunsee were compared with samples from two ‘reference lakes’, *i.e.* Attersee and Hallstättersee (Figure 1, Table I). Sediment samples, in this comparison, were collected near the deepest point at a depth of 180, 160 and 120 m in Traunsee ([TR 180] = [VI 180]), Attersee [ATT 160] and Hallstättersee [HALL 120], respectively (Figure 1). An additional sampling of 12 sediment sites [TS 1–12] along a South to North transect in Traunsee took place in July 1999 (Figure 1).

2.2. SAMPLE COLLECTION AND HANDLING

Sediments were collected by means of a ‘multi-Kajak corer’ with plastic core liner (Danielopol and Niederreiter, 1990). Physical and chemical variables, such as temperature, oxygen, conductivity and pH were measured immediately after withdrawal of the samples in the uppermost centimetre of the sediment by using WTW field sensors (Wissenschaftlich Technische Werkstätten, Weilheim). One representative and undisturbed sediment core was taken to the lab for water content measurements and once for sediment grain size analysis (Figure 2).

For further sedimentological and microbiological analysis the upper first centimetre of sediment from 2–3 cores was carefully subsampled with a sterile 10 mL one-way pipette and combined in a sterile 100 mL glass flask (combusted at 450 °C for 4 hr). Subsequently, part of the sediment slurry was either processed immediately on board (e.g. microbial activity measurements), or conserved with appropriate fixatives (e.g. for abundance and biomass analysis) or transported to the laboratory in a cooling box and processed there within 3–7 hr (e.g. for live observations, and other sediment properties) (Figure 2). Those analyses which required a distinction between the solid sediment matrix and the sediment porewater, were performed after centrifugation of the sediment (at $250 \times g$ for 10 min). The pellet and the supernatant were used for sediment and porewater analysis, respectively. If not stated otherwise, all analyses were carried out in triplicates. In addition, a killed control was used for activity measurements.

2.3. SEDIMENT AND POREWATER ANALYSIS

Samples for sediment water content measurements were weighted and dried to a constant weight at 100 °C. Total organic matter (TOM) content was estimated from dried sediments by loss of ignition (450 °C, 4 hr). Carbon/Nitrogen (C/N) ratios were measured with a CHN element-analyser (Carlo Erba, Model 1106).

Sediment porewater was analysed for the concentration of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and chloride (Cl^-). Samples for DOC and DIC were initially filtered through precombusted glass fiber filters (GF/F, Whatman). DOC and DIC concentrations were determined as reported by Mindl *et al.* (2000). The easily biodegradable part of the DOC (BDOC) in the porewater was determined following a batch culture approach described by Servais *et al.* (1987). Cl^- concentrations were determined by automated titration of water samples with silver nitrate ($AgNO_3$) using an ion-selective electrode (716 DMS Ditrino, Metrohm).

2.4. MICROBIOLOGICAL ANALYSIS

Total numbers of sediment bacteria were determined in duplicates with subsamples from the sediment pellet (Figure 2). After removal of the cells from the sediment particles, following the protocol of Griebler *et al.* (2001), cells were stained with

4′, 6-diamidino-2-phenylindole (DAPI, Sigma, 5 μg L^{-1} final conc.). The counting was performed on a Zeiss Axioplan epifluorescence microscope (UV excitation: BP 360 nm, FT 395 nm, LP 395 nm). For the calculation of total bacterial carbon, a conversion factor of 50 fg C cell^{-1} was applied based on single bacterial biovolume measurements and values reported by Kirschner and Velimirov (1999) and a conversion factor of 300 fg C μm^{-3} for cells 0.1 to 0.2 μm^3 in size (Posch *et al.*, 2001).

The content of actively respiring cells of the sediment bacterial community was determined via the enumeration of 2-(4-iodophenyl)-3-(4-nitrophenyl)-5-phenyltetrazolium chloride (INT) reducing cells in relation to the total number of DAPI stained cells, by a modification of the technique described by Alfreider *et al.* (1997). 0.5 g of sediment were placed in a centrifuge tube (15 mL), suspended in 2 mL of bacteria-free porewater (0.2 μm filtered, Millipore) and shaken on a vortex test tube mixer for 30 sec. After settling of the sediment, 1 mL of the supernatant was incubated with INT for 1 hr at 20 °C in darkness. Counting of INT-active cells followed the protocol of Posch *et al.* (1997). FDC, expressed as percentage of dividing cells, were obtained by computing the fraction of the total bacterial population with clear invaginations of the cell wall following a protocol of Hagström *et al.* (1979).

The electron transport system (ETS) activity of benthic microbial communities was determined via the dimethyl sulfoxide (DMSO) reduction method (Griebler and Slezak, 2001). One mL of sediment slurry was placed into a 25 mL glass vial which was immediately filled with 0.2 μm filtered sample water. After amendment of 198 μL of DMSO (99%, Merck) vials were closed bubble-free with teflon-coated silicon septa, briefly mixed and incubated for 2–3 hr in darkness at ambient environmental temperatures. Incubation was stopped by addition of 500 μL of 6 N NaOH. Samples were stored at 4 °C in the dark. Dimethylsulfide (DMS) measurements were performed as described by Griebler and Slezak (2001).

Bacterial cell and biomass production of sediment bacterial communities were estimated via the incorporation of radiolabeled thymidine and leucine into bacterial DNA and protein, respectively. A volume of 0.9 mL of sediment slurry was placed in 1.5 mL Eppendorf tubes with screw caps. Samples were amended either with [methyl-^{3}H]thymidine (specific activity, 75 Ci mmol^{-1}, Amersham) or [methyl-^{3}H]leucine (specific activity, 52 Ci mmol^{-1}, Amersham). After mixing hot and cold substrates at a ratio of about 1:100, final concentrations of thymidine and leucine in the samples were 10 and 50 μM, respectively. These substrate concentrations showed saturation in preliminary experiments. Controls were treated by the addition of cold tracer (100 μL, 40 mM methyl-thymidine or L-leucine, Merck) and trichloroacetic acid (TCA, 130 μL, 50% [w/v]) 10 min prior to sample incubation. Samples were briefly mixed and incubated for 30 min at ambient environmental temperatures in darkness. Incubation was stopped by addition of cold tracer and TCA (see treatment for controls). Extraction of samples containing thymidine followed the protocol of Kirschner and Velimirov (1999). Leucine containing samples were extracted at 95 °C for 60 min with a brief mixing after 30 and 60 min. After cooling for 5 min in the fridge, samples were centrifuged for 5 min at 15 000 rpm (Biofuge pico, Heraeus). The supernatant was discarded and the pellet was resuspended in 1 mL TCA (5% [w/v]). This procedure was repeated once. For extraction of proteins, the pellet was resuspended in 500 μL of 0.5 N NaOH, mixed briefly and extracted at 95 °C for 15 min. The protein-containing supernatant was collected in a scintillation vial. Extraction of the pellet was repeated and supernatants subsequently combined. After the addition of scintillation cocktail (5 mL, Ultima Gold, Packard) samples were counted in a liquid scintillation counter (Tri-Carb 2000, Packard). Measured [^{3}H]-thymidine and [^{3}H]-leucine incorporation rates were normalized to 1 L or 1 dm^3 of wet sediment, corresponding to the upper centimetre of sediment of an area of 0.1 m^2 [^{3}H]-thymidine incorporation was converted into cell production applying a factor of 2.15×10^{18} cells mol^{-1} thymidine (Smits and Riemann, 1988). Bacterial carbon production was calculated by assuming a mean cell carbon content of 50 fg. [^{3}H]-leucine incorporation was converted into bacterial carbon production according to Kirchman (1993).

Bacterial uptake, incorporation and respiration of glucose in sediment samples were determined as follows: 10 mL of sediment slurry were placed into 100 mL Winkler flasks and amended with D-[U-^{14}C]glucose (specific activity, 310 mCi mmol^{-1}, Amersham) to a final concentration of 100 nM. After one hour at ambient environmental temperatures in darkness, incubation was stopped by the addition of 2 mL of 6 N H_2SO_4. The subsequently released $^{14}CO_2$ was trapped overnight on β-phenethylamine (Riedel de Haen) soaked filter paper (Whatman), placed in plastic wells attached to the rubber stoppers (Hobbie and Crawford, 1969). One mL aliquotes of the remaining sediment fraction were subsampled and treated to remove the non-incorporated and unspecifically bound radiotracer by the addition of non-labeled glucose (final conc. 10 μM) and brief mixing, followed by 3 times centrifugation (5 min, 15 000 rpm) and washing (MQ water, Millipore) in 1.5 mL Eppendorf tubes. Remaining sediment pellets as well as filters containing $^{14}CO_2$ were resuspended in 5 mL scintillation cocktail (Ultima Gold, Packard) and counted in a liquid scintillation counter (Tri-Carb 2000, Packard).

For live observations of benthic Protozoa, 10–20 mL of fresh sediment slurry were put into clean, HCl rinsed (30% technical grade) 1-L plastic bottles. Bottles were transported to the lab in a cooling box and examined within 24 hr. For further qualitative analysis, 2.45 mL of sediment slurry were fixed immediately after sampling with 0.37 mL Bouin's solution, diluted in 4.63 mL of filtered lake or tap water. As recommended by Montagnes and Lynn (1987) the Bouin's solution consisted of 15:5:1 of saturated picric acid, borax buffered formaldehyde (36%) and glacial acetic acid, respectively. Prior to further analysis fixed samples were centrifuged over a density gradient to separate the microbes from interfering sediment particles following a protocol of Starink *et al.* (1994), *i.e.* 2 mL of sample were placed on top of 8 mL Percoll (Amersham Pharmacia Biotech, U.K.) in a centrifuge tube and spun for 15 min at 5000 × *g* in a swing-arm rotor (Heraeus centrifuge). Ciliates in the supernatant were filtered onto 1.2 μm cellulose nitrate filters (Sartorius) and protists were prepared following the quantitative protargol staining (QPS) procedure as described in Pfister *et al.* (1999). As no density gradient could be established during the Percoll centrifugation, filters were analysed only qualitatively. Identification of stained protists was carried out on a microscope equipped with differential interference contrast (DIC) and brightfield (Axiophot II, Zeiss). Live observations were done by scanning single drops of sediment slurry at low magnification (50–100×) in dark field. Single cells were picked out of the drop with a micropipette and determined morphologically based on the keys of Foissner *et al.* (1991, 1992, 1994, 1995) and Patterson and Larsen (1991). No comprehensive key is yet available for the appropriate identification of flagellates (for further comments see Arndt *et al.*, 2000).

3. Results

3.1. CHLORIDE CONCENTRATIONS

Chloride concentrations in Traunsee, as measured in samples from the water column and the sediment porewater at the three sampling sites during the time of our study, covered a range of 45 to 156 mg L^{-1}. Sediment porewaters, in all cases, contained Cl^- concentrations similar to the values found in the hypolimnion (Table I). No significant difference could be found between porewaters of the ID and natural sediments (Table I). Hallstättersee, a lake which experienced the discharge of effluents from a local salt mining company and elevated Cl^- concentrations of up to 30 mg L^{-1} in the past (Schwarz and Jagsch, 1998), contained about 6 mg L^{-1} Cl^- in water and sediment porewater samples in May 1999. Even lower values of less than 4 mg L^{-1} were measured in samples from Attersee (Table I), which is suggested to represent the geogenic Cl^- background of the region.

3.2. CHARACTERISTICS OF TRAUNSEE SEDIMENTS

Sediment grain size analysis at EB 50, RB 50 and VI 180, which were performed once in the beginning of our study, resulted in no significant differences between our sampling sites, with 70–90% of sediment particles found in the silt fraction (5–63 μm), 5–25% in the fine sand fraction (63–200 μm) and 3–4% in the middle sand fraction (200–600 μm). Sediments from EB 50 and RB 50 contained larger amounts of fine sand, along with a reduced amount of silt (data not shown). RB 50 sediments occasionally contained a high amount of coarse particulate organic matter (CPOM), imported by the Traun River along with leave-fall and/or flood events, which was not detected at the time of our grain size analysis. The uppermost centimetre of sediment was typically flocculent at all investigation sites with a water content of 80 to 97%. The ID showed pronounced differences in stratification patterns from natural sediments. While natural sediments always showed

TABLE II

Physico-chemical parameters determined along a South to North transect in Traunsee in June 1999. All measurements were carried out at the sediment surface, except pH[a]

Location	Sampling site	Depth (m)	Spec. cond. (μS cm^{-1})	Temp. (°C)	O_2 (mg L^{-1})	pH A. sed.	pH Sed.	pH Inlays
Ebensee Bay I	TS 1	52	614	8.6	8.5	8.68	9.42	
Ebensee Bay II	TS 2	90	725	8.1	8.4	8.72	10.03	
Bartelkreuz	TS 3	133	434	n.b.	8.9	8.83	8.98	
Löwendenkmal	TS 4	161	558	8.6	8.6	8.71	8.70	9.29
Traunkirchen	TS 5	182	613	5.8	8.3	8.69	8.58	9.36
Viechtau	TS 6	183	612	6.8	8.1	8.74	8.32	
Viechtau	TS 7	175	719	6.5	9.0	8.38	7.85	
Hoisn	TS 8	116	718	5.6	8.6	8.51	7.79	
Hollereck	TS 9	56	713	5.8	9.0	8.49	7.94	
Gmunden Bay	TS 10	52	663	7.1	9.1	8.42	7.91	
Traunkirchen Bay	TS 11	52	691	6.3	9.1	8.45	7.93	
Rindbach Bay	TS 12	42	654	9.6	8.2	8.22	n.d.	

[a] A. sed. = Above sediment; Sed. = measurement in the upper first centimeter of sediment; Inlays = pH measurement in a layer of industrial deposits (white band) embedded in the natural sediment.
[b] Spec. cond. = specific conductivity.
[c] Temp. = temperature.

TABLE III

Organic and inorganic carbon concentrations and C:N ratios of Traunsee sediments at three sampling sites

Sampling site	TOM (% dw^{-1}) n = 12	TC (% dw^{-1}) n = 12	TN (% dw^{-1}) n = 12	C/N ratio n = 12	DOC (mg L^{-1}) n = 8	BDOC (%) n = 1
EB 50	5.7 (1.9)	10.02 (0.68)	0.21 (0.03)	47.7 (6.7)	16.1 (10.6)	13.3
RB 50	8.3 (1.2)	11.04 (0.30)	0.38 (0.05)	29.1 (3.7)	6.9 (2.8)	32.7
VI 180	6.7 (1.1)	8.64 (0.19)	0.32 (0.03)	27.0 (2.3)	4.3 (0.9)	14.3

n = Number of measurements, values are annual means ± S.D.
TOM = total organic matter, TC = total carbon, TN = total nitrogen, C/N = carbon/nitrogen ratio, DOC = dissolved organic carbon of sediment porewater, BDOC = biodegradable DOC.

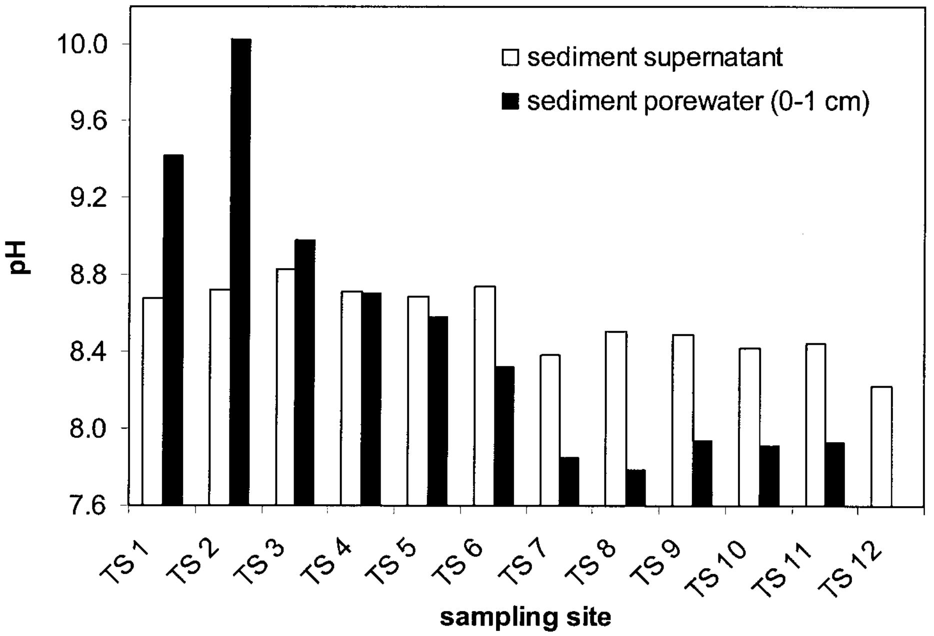

Figure 3. pH conditions above (sediment supernatant) and in the upper first centimetre of Traunsee sediments along a South to North transect; for position of sampling stations see Figure 1 (values are means of duplicate measurements).

a clear stratification with a light brownish to ochre surface followed by layers of varying brownish, greyish and black shades, the homogeneous whitish ID at EB 50 exhibited no stratification at all. The high carbonate content of ID and their distinct mineral composition of the ID resulted in highly alkaline porewaters. The highest pH values were detected in the Ebensee Bay at the dumping site. Sediment sampling along a South-North transect in Traunsee (Figure 1, Table II) clearly showed the dependence of the alkalinity from the distance of the ID source (Figure 3). ID layers, which already have been covered by natural sediments, for instance at TS 4 and TS 5, still contained pH values >9 (Table II). Differences between ID and natural sediments in Traunsee were observed also concerning various carbon parameters. The amount of TOM was significantly lower in ID compared to RB 50 ($p = < 0.001$, *t*-test) and VI 180 ($p = 0.041$, *t*-test). Highest TOM values were determined at RB 50 (Table III). Carbon/nitrogen (C/N) ratios were found to decrease with distance from the source of industrial discharge along the North-South transect (Figure 4A). The hydrologically separated Rindbach Bay (RB 50), in the south of the lake, showed low C/N ratios as well. Summarizing the monthly data from EB 50, RB 50 and VI 180, a significant difference in C/N ratios was observed between the ID (EB 50) and the natural sediments at RB 50 ($p = <0.001$, *t*-test) and VI 180 ($p = < 0.001$, *t*-test) (Table III, Figure 5). No significant difference was observed for RB 50 and VI 180. The reference lakes, Attersee and

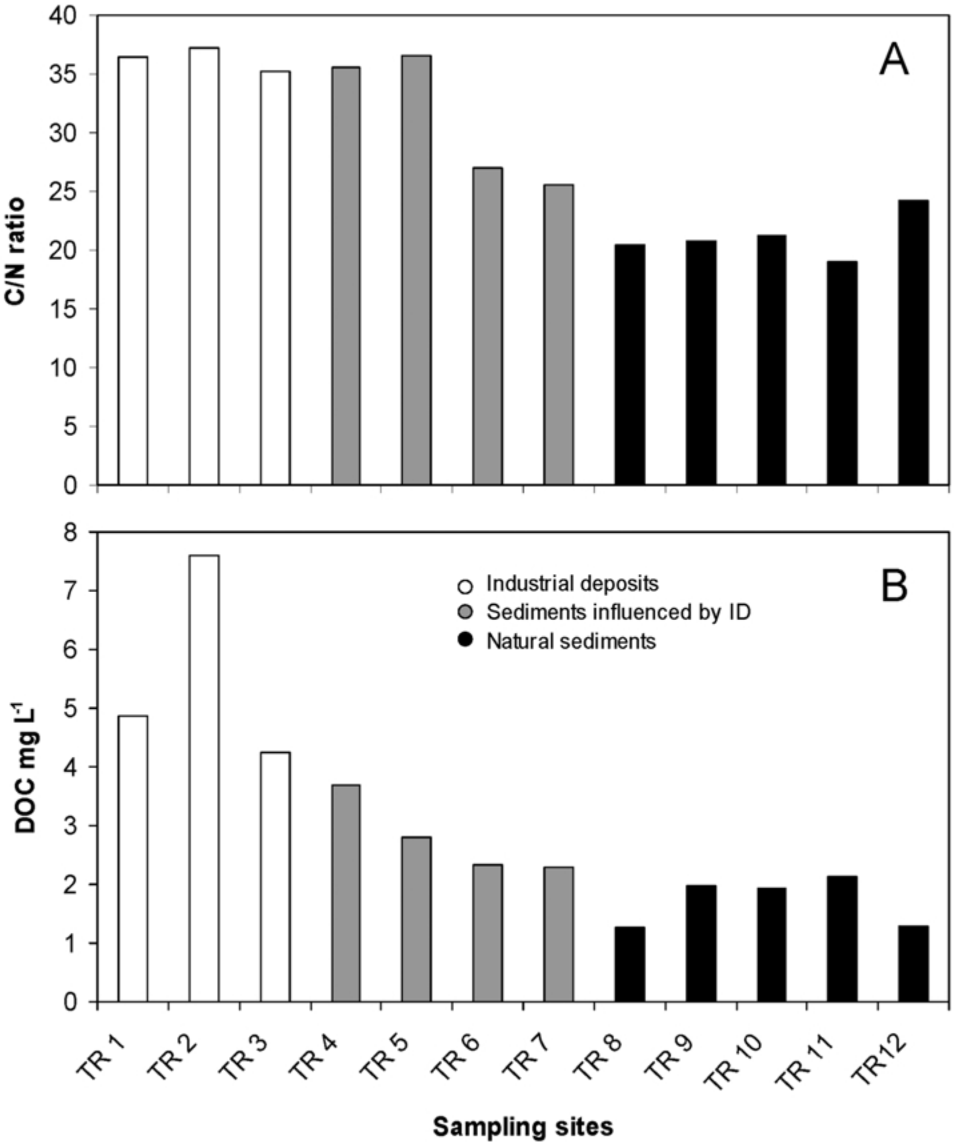

Figure 4. (A) C/N ratios and (B) DOC concentrations along a south–north transect in Traunsee; for position of sampling sites see Figure 1 (values are means of duplicate measurements).

Hallstättersee, exhibited C/N ratios of 25:1 and 15:1, respectively, and therefore matched with the natural sediments of Traunsee or were even smaller (Figure 5).

Surprisingly high concentrations of dissolved organic carbon (DOC) were found at EB 50 throughout the year with maximum values of 26 mg L^{-1} (Table III), whereas the concentration of dissolved inorganic carbon (DIC) was comparably low in April 1998 with 3.3 mg L^{-1}. In contrast, the natural sediment porewaters

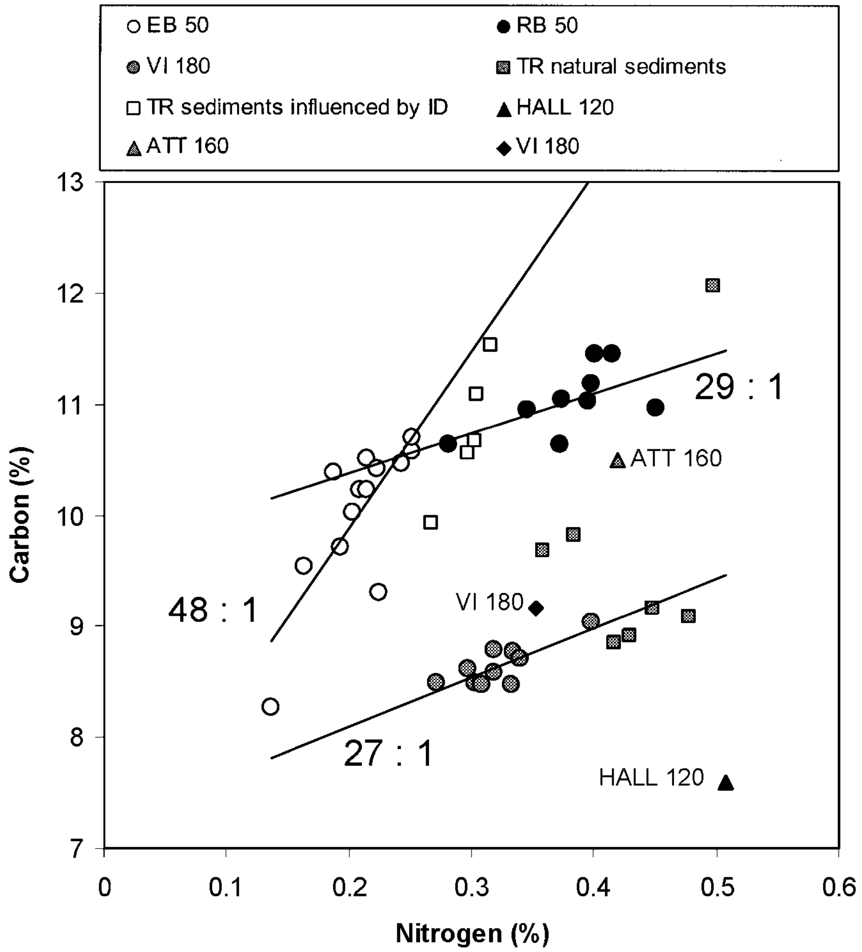

Figure 5. Linear regression analysis of pooled C/N ratios from the three sampling sites. Additionally, single values of a inter-lake comparison in May 1999 (VI 180, Traunsee; ATT 160, Attersee, HALL 120, Hallstättersee) and a sampling of a South to North transect in June 1999 (□) are included.

contained significantly lower DOC concentrations of 2.7 to 9.6 mg L^{-1} and 2.8 to 5.3 mg L^{-1} at RB 50 ($p = 0.038$) and VI 180 ($p = 0.01$), respectively (Table III). DIC values were significantly higher in RB 50 ($p = <0.001$) and VI 180 ($p = 0.001$) compared to EB 50, with values of 51.5 and 31.4 mg L^{-1}, respectively. Similar to the pH values and C/N ratios, a clear gradient of DOC concentrations was found in the uppermost centimetre of sediments along a south-north transect (Figure 4B). The content of readily biodegradable DOC (BDOC) and refractory DOC (RDOC) showed similar values for EB 50 and VI 180 samples, but a two-fold content at RB 50 (Table III). In absolute concentrations, EB 50 sediment porewater contained about 3.5 mg L^{-1} of readily biodegradable DOC, whereas RB 50 and VI 180 contained 1 and 0.8 mg L^{-1}, respectively.

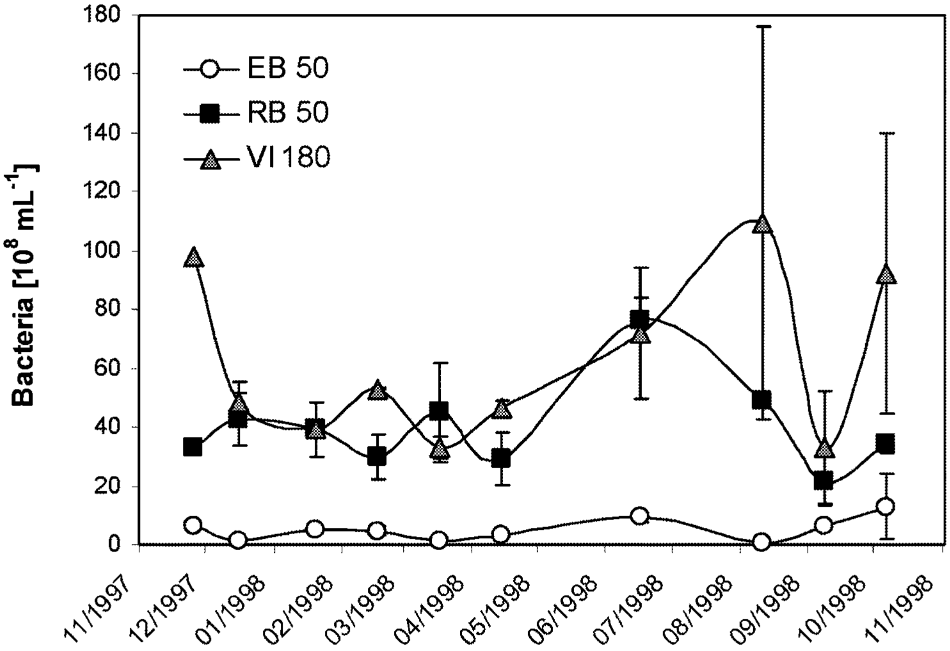

Figure 6. Total number of bacteria in the sediments at the three sampling sites.

TABLE IV

Bacterial parameters at the three sampling sites

Site	BA (cells 10^{11} L^{-1}) n = 12	INT-AC (%) n = 6	FDC (%) n = 6	BP (10^7 cells L^{-1} hr^{-1}) n = 6	BCP (μg C L^{-1} hr^{-1}) n = 6	BDT (d) n = 6
EB 50	5.15 (3.83)	23.7 (10.6)	2.4 (1.5)	5.7 (5.0)	2.9 (2.5)	530 (280)
RB 50	40.00 (15.20)	30.4 (12.7)	4.3 (1.7)	26.1 (15.5)	13.1 (7.8)	1158 (1403)
VI 180	62.45 (28.47)	41.2 (17.3)	4.1 (2.0)	92.7 (43.1)	46.4 (21.5)	284 (112)

n = Number of measurements, values are annual means ± S.D.

BA = Bacterial abundance, INT-AC = respiratory active cells, FDC = frequency of dividing cells, BP = bacterial cell production, BCP = bacterial carbon production, BDT = doubling time of the bacterial community.

3.3. THE BACTERIAL COMMUNITY

The bacterial abundance in the upper first centimetre of the industrial deposits at EB 50 was significantly reduced (p = <0.001) throughout the year (Figure 6). On average, EB 50 sediments contained about 8 and 12 times less bacteria than RB 50 and VI 180 sediments, respectively (Table IV). Beside this, no clear seasonal trend was observed at the three sampling sites. Analysis of bacterial morphotypes in

TABLE V

Distribution of bacterial morphotypes at the three sampling sites. Classification of morphotypes was carried out according to Kirschner and Velimirov (1999)

Sampling site	Cocci (%) n = 7	Rods (%) n = 7	Filaments (%) n = 7
EB 50	39.5 (14.9)	56.5 (16.8)	4.1 (3.4)
RB 50	39.6 (10.6)	53.8 (8.8)	6.6 (2.9)
VI 180	39.3 (6.8)	49.7 (6.8)	11.0 (3.4)

n = Number of measurements, values are annual means ± S.D.

Traunsee sediments did not result in any significant differences for the 3 sampling sites (Table V).

The content of INT-active bacteria was lowest in EB 50, followed by RB 50 and VI 180 sediments (Table IV). A significant difference could only be observed between EB 50 and VI 180 ($p = 0.041$). The frequency of dividing cells (FDC), as a further community activity parameter, was almost two-times higher on average at the sites of no ID influence (Table IV).

Bacterial cell production (BP), as estimated from [^{3}H]-thymidine uptake, was 4.5 to 16 times reduced at EB 50 compared to samples from RB 50 and VI 180, respectively (Table IV). Calculated doubling times for the bacterial communities (BDT) revealed lowest values at VI 180, followed by EB 50 and longest turn over times at RB 50 (Table IV). Bacterial production, estimated from the uptake of [^{3}H]-leucine, which was measured in sediment samples along a North-South transect in Traunsee, revealed highest BP values in the Bay of Gmunden (TS 10) and Traunkirchen (TS 11) (Figure 7). No clear trend and no significant difference between ID and natural sediments was observed in May 1999. A multiple assay comparison of various activity parameters was carried out with sediments from the three sampling sites in Sept 1998. The activity of the different bacterial communities was determined via the uptake of [^{3}H]-thymidine as well as [^{3}H]-leucine and the bacterial reduction of dimethyl sulfoxide (DMSO). Each microbial process showed significantly lower rates for samples from EB 50 (Figure 8). No statistical difference was found in BP between the undisturbed, natural sediment site VI 180 in Traunsee and reference sites in Attersee and Hallstättersee in May 1999 (Figure 9). The bacterial carbon conversion efficiency, which was determined using [^{14}C]-glucose as a model substrate, was lowest at EB 50 with a growth efficiency of about 30%. RB 50 and VI 180 samples revealed growth efficiencies of about 50%. Concerning bacterial biomass, the percentage of bacterial carbon was lowest in ID samples, followed by sediments from RB 50. Highest content of bacterial carbon was calculated for VI 180 sediments (Table VII).

TABLE VI

List of the benthic Protozoa which could be identified at the three sampling sites. The preferred salinity range of single species is noted: he = holo-euryhaline (0–>30‰), oe = oligo-euryhaline (0-$^{-1}$0‰), ome = oligo- to meso-euryhaline (0–30‰), oms = oligo- to meso-stenohaline (0–4‰), os = oligo-stenohaline (0-$^{-1}$‰)

	EB	RB	VI
Ciliates observed at each sampling event			
Aspidisca cicada (Mueller, 1786) Claparède and Lachmann, 1858 (he?)		X	X
Aspidisca lynceus (Mueller, 1773) Ehrenberg, 1830 (ome?)		X	
Cinetochilum margaritaceum (Ehrenberg, 1831) Perty, 1849 (ome, he?)		X	
Cyclidium sp.	X	X	X
Cyrtophorida		X	X
Euplotes moebiusi Kahl, 1932 (he)	X		
Euplotes spp.		X	
Holophrya sp.		X	
Hymenostomata	X		
Hypotrichia		X	X
Lacrymaria sp.		X	
Paramecium spp.		X	X
Placus luciae (Kahl, 1926), Kahl, 1930 (ome)			X
Pleuronema spp.		X	X
Scuticociliata		X	
Spathidium spp.	X		
Spirostomum teres Claparède and Lachmann, 1858 (oe, he?)		X	
Stylonychia sp.		X	
Tachysoma pellionellum (Mueller, 1773) Borror, 1972 (ome, he?)		X	
Tetrahymena sp.	X		
Uroleptus sp.		X	
Ciliates detected occasionally			
A. cicada	X		
A. lynceus	X		
Coleps hirtus (Mueller, 1786) Nitzsch, 1827 (oms, he?)			X
Coleps nolandi Kahl, 1930 (he)			X
Coleps sp.		X	
Cyclidium glaucoma Mueller, 1773 (he)	X		
Euplotes affinis (Dujardin, 1841) Kahl, 1932 (he?)	X		X
E. cf *moebiusi*			X
Frontonia leucas (Ehrenberg, 1833) Ehrenberg, 1838 (oe)		X	X
Frontonia sp.	X		
Glaucoma reniforme Schewiakoff, 1892 (os)	X		

TABLE VI

(continued)

	EB	RB	VI
Ciliates detected occasionally (continued)			
Glaucoma scintillans Ehrenberg, 1830 (oe)	X		
Holophrya sp.			X
Holosticha monilata Kahl, 1928 (ome)		X	
Odontochlamys alpestris Foissner, 1981 (os)		X	
Paramecium putrinum Claparède and Lachmann, 1859 (ome)	X		
P. luciae		X	
Pleuronema sp.	X		
Uronema sp.	X		
Urotricha sp.		X	
Other protists			
Diverse flagellates	X	X	X
Bodonidae	X		
Euglenidae		X	X
Rhizopoda	X	X	X
Ciliate resting-cysts	X	X	X

TABLE VII

Bacterial production patterns at the three sampling sites

Site	BA (10^{11} cells kg dw^{-1}) n = 12	BC (mg C kg dw^{-1}) n = 12	OC (gC kg dw^{-1})	BC/TOC (%) n = 12
EB 50	14.3 (10.6)	71.5 (53.0)	0–5	0.0 –1.4 (1.1)
RB 50	95.6 (36.3)	478.0 (181.0)	15–20	2.4 (0.9)–3.2 (1.2)
VI 180	177.3 (80.9)	886.5 (404.5)	10–15	5.9 (2.7)–8.9 (4.0)

n = number of measurements, values are annual means ± S.D.

BA = bacterial abundance, BC = bacterial carbon, OC = organic carbon (values from Claes and Kersting, 1981), BC/TOC = bacterial carbon versus total organic carbon.

Factors for conversion from sediment volume (L) to dry weight (kg) were 2.77, 2.39 and 2.84 for EB 50, RB 50 and VI 180, respectively.

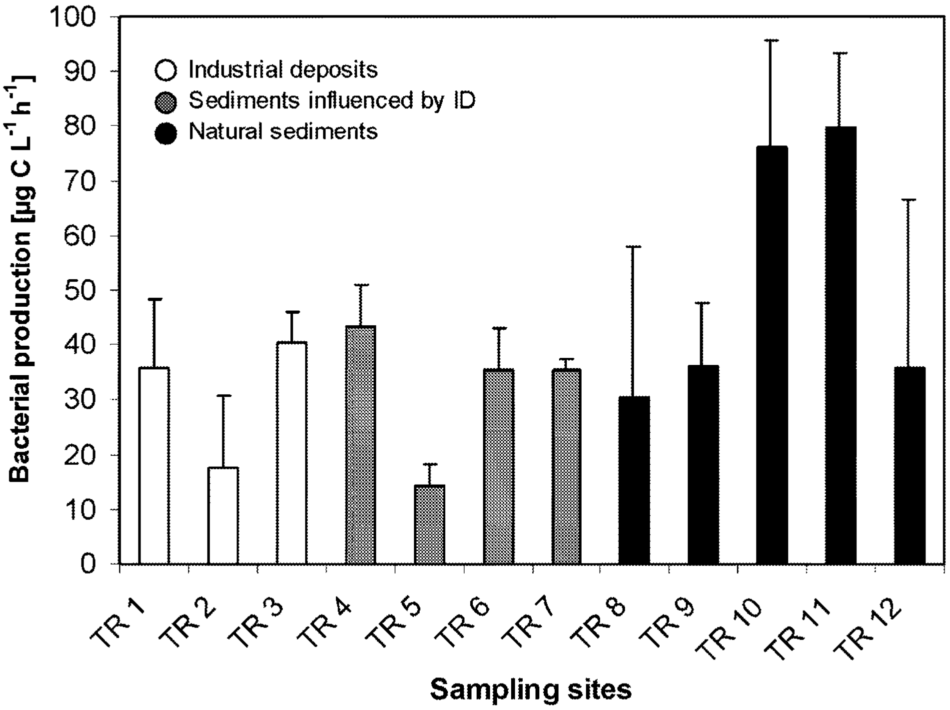

Figure 7. Bacterial production pattern along a South to North transect as determined in June 1999; for location of sampling sites see Figure 1 (values are means of triplicates ± S.D.).

3.4. THE BENTHIC PROTOZOAN COMMUNITY

Based on live observations (LO) and quantitative protargol staining (QPS), 35 different ciliate taxa consisting of 22 genera could be identified in sediments from Traunsee (Table VI). Additionally, several heterotrophic and autotrophic flagellates, Testacea and ciliate resting cysts of *Pelagostrombidium fallax*, a pelagic species, have been observed. Only two species, *i.e. Cyclidium* sp. and *Euplotes affinis* were found at all sampling sites (EB 50, RB 50 and VI 180). Six species were detected at more than one site. Samples from RB 50 revealed most ciliate taxa with 19 species, followed by EB 50 with 14 species and VI 180 with 11 taxa.

At VI 180 and RB 50 a persisting composition of the protistan community was observed. The highest species diversity was found at RB 50, maybe due to the regular import of allochthonous material by the Traun River. *Spirostomum teres*, *Tachysoma pellionellum*, *Aspidisca cicada*, *A. lynceus* and *Cinetochilum margaritaceum* were present throughout the whole investigation period and seemed to be a regular component of RB sediment. A reduced species number was found at VI 180, possibly a fact of the great depth (ca. 190 m depth) and the lower input of fresh allochthonous and autochthonous organic matter. Nevertheless, *A. cicada* and *Placus luciae* formed – beside others – a constant part of the ciliate community

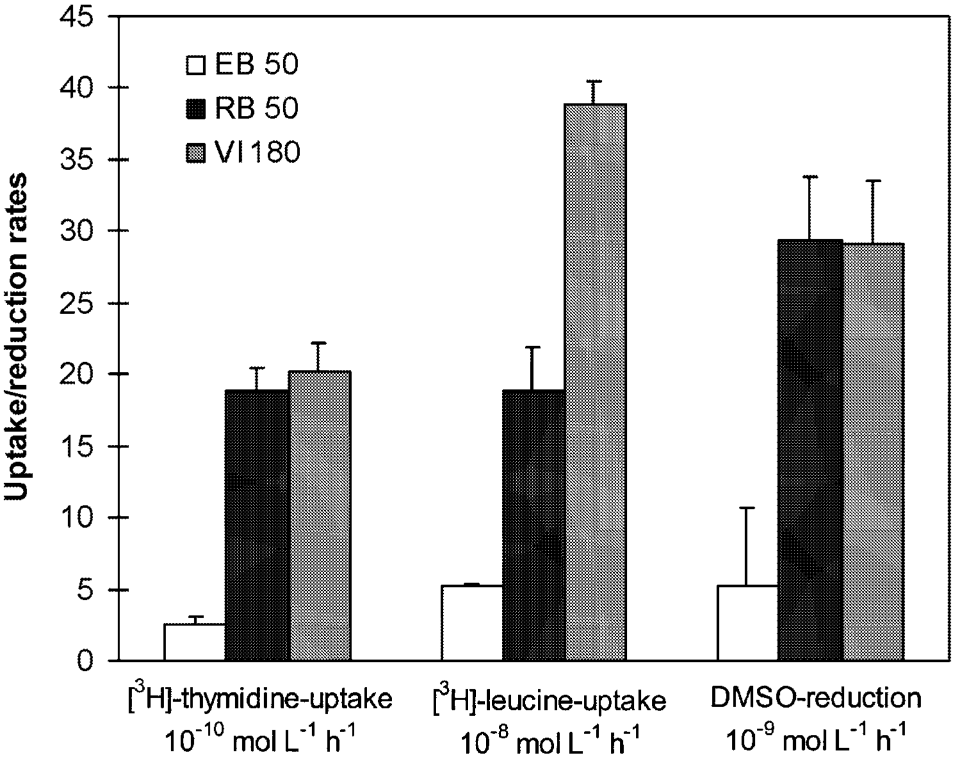

Figure 8. Multiple method comparison of bacterial activity with sediments from the three sampling sites in September 1998 (values are means of triplicates ± S.D.).

at VI180 throughout the year. A problem in investigating fixed sediment samples was that especially one obviously dominant species at location RB50, *Spirostomum teres*, could not withstand fixation and/or the staining procedure. We never detected this species in our QPS preparations.

Cysts of the ciliate *Pelagostrombidium fallax* (identified by Müller H., personal communication and according to Müller and Wünsch 1999; see also taxonomic discussion therein) could be found in the sediment at all 3 sampling sites in October 1998 from QPS preparations. Additionally, in September 1998 cysts were present in the sediment at RB 50.

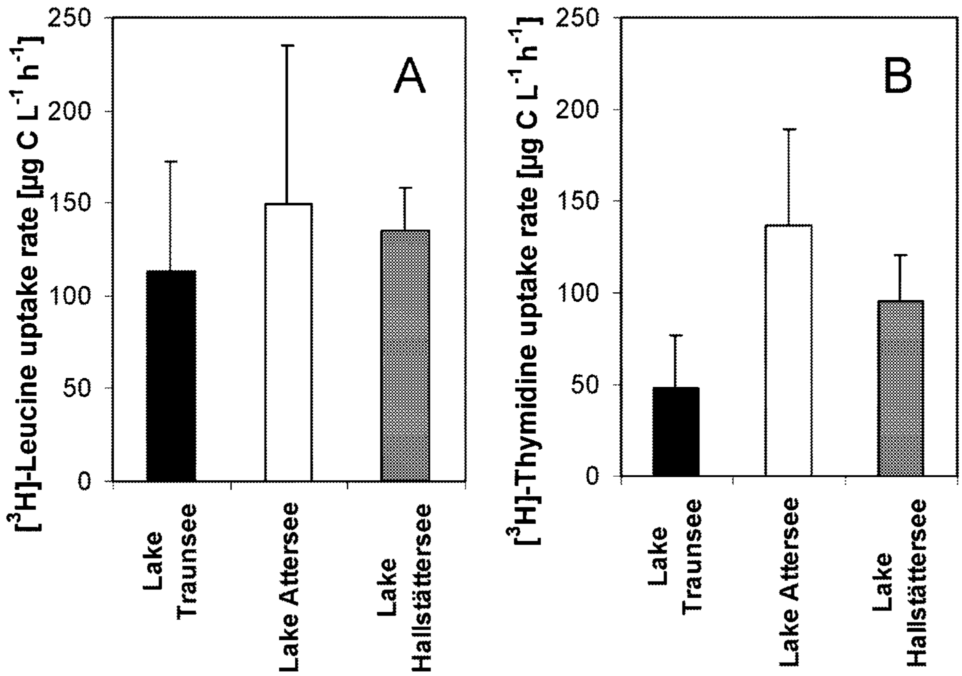

Figure 9. Bacterial carbon production pattern of Traunsee and the two reference lakes as obtained via (A) [^{3}H]-leucine and (B) [^{3}H]-thymidine uptake measurements in May 1999 (values are means of triplicates ± S.D.).

4. Discussion

4.1. CHARACTERISTICS OF TRAUNSEE SEDIMENTS

Natural sediments of Traunsee are of various origin and therefore of different character. Most particulate matter is supplied by the Traun River with about 36 000 t a^{-1} (Baumgartner, 1984). A minor part originates from several small brooks located in the western and eastern part of the lake and from autochthonous biogenic decalcification (Claes and Kersting, 1981). Beside the import and formation of natural sediments, Traunsee is supplied with about 90 000 m^3 or 135 000 t a^{-1} (Müller *et al.*, 2002) of solid material from the soda and salt industry, which is almost exclusively composed of carbonates (>80%, Claes and Kersting, 1981). This deposition already formed a 47 m high cone of industrial deposits (ID), which continuously broadens into all directions but mainly moves along a depth gradient to the north (Müller *et al.*, 2002; Figure 1). Along with flood events of the Traun River, avalanches of ID (= turbidity currents) are resuspended in the water column and tons of solid material are transported to the deepest part in the middle of the lake (Schmidt, 1989). A first turbidity current was mentioned for the year 1929 (Ruttner, 1949), and till today their number steadily increased (Schmidt, 1989).

With a further extension of the ID in the Ebensee Bay eastwards, they would come into a direct and permanent influence of the Traun River followed by a continuous distribution of industrial waste within the lake. In the 1970 a lake bottom area of 4% was suggested to be exclusively covered by ID (Jagsch, 1975). A five-year study in the early 1980 revealed that 15% of the lake floor were impacted by ID (Müller and Schneider, 1984). Today, this area has increased to 19% (Müller *et al.*, 2002).

4.2. DISTRIBUTION OF MICROBES

The number of microorganisms in the sediments of lakes varies with its trophic status and the depth of the water body. Their distribution is closely related to several abiotic (e.g. grain size, redox conditions, carbon and nutrient concentration) and biotic (e.g. perturbation, grazing) parameters (Jones *et al.*, 1979; Meyer-Reil, 1993; Berninger and Epstein, 1995; Lucchesi and Santangelo, 1997). In general, the microbial abundance, biomass and activity tends to decrease with sediment depth (Goulder, 1971; Jones *et al.*, 1979; Meyer-Reil, 1993; Rothfuss *et al.*, 1997). One reason for this distribution pattern lies in the decreasing nutrient and energy availability. Another factor, especially important for protists, is the availability of space. Whereas lake sediments are typically flocculent at the surface they tend to be densely packed with less pore space and decreased permeability a few centimetres below the sediment surface, thus also the exchange of redox couples (solutes, gases) is strongly reduced. Our investigation therefore focused on the upper first centimetre of sediment, where pore space was not limiting and redox measurements indicated oxygenated conditions (G. Wolfram, personal communication).

All investigated sediments were inhabited by bacteria, flagellates and ciliates. However, the industrial deposits (ID) were exclusively colonised by microorganisms, whereas the natural sediments contained a fairly abundant meio- und macrofauna (Wolfram *et al.*, 2002). The bacterial abundances at all sampling sites showed values typical for oligotrophic deep lakes (Griebler and Posch, 2001). Nevertheless, the total number of bacteria at EB 50 was one order of magnitude lower compared to the sites not affected by ID.

The highest diversity within the protozoa was found at RB 50, a site frequently fuelled by fresh CPOM imported by the Traun River (Table VI). The lower number of species found at VI 180 is suggested to be related to the great depth (180 m) and the reduced availability of high-quality organic material. However, both ID unaffected sites showed persisting community patterns throughout the year. At EB 50 the composition of the ciliate community differed at each sampling event depending on the age of the industrial sediment. Protists in these upper layers of industrial deposits were very sparse or sometimes even absent.

4.3. HIGH ALKALINITY AND CHLORIDE CONCENTRATIONS

Former studies already observed pH values ranging from pH 8.5–12.7 in the ID (Müller and Schneider, 1984; Müller *et al.*, 2002). Free CO_2 is suggested to be bound by hydroxides such as $Mg(OH)_2$ and $Ca(OH)_2$ in the ID, which causes a shift to alkaline conditions (Ruttner, 1937). Higher organisms cannot stand pH conditions of <2 and >10 (Fenchel *et al.*, 1998), whereas several representatives of the bacteria, cyanobacteria and protozoa are known for their adaptation to extreme saline and alkaline conditions (Grant and Tindall, 1986; Reed, 1986). Nevertheless, these extreme environmental conditions are suggested to be responsible for the loss of about 90% of bacterial biomass at sites covered by ID. High alkalinity seems to be also a key factor for the distribution of the benthic protists. Some obviously pH – tolerant protists like *Protospathidium* sp., *Tetrahymena* sp., *Glaucoma reniforme*, *Glaucoma scintillans*, *Uronema* sp. and bodonid flagellates were detected exclusively at EB 50. In fact, besides one species of *Protospathidium* sp., Hypotrichia and Hymenostomata were the only ciliate groups detected in the ID. At EB 50 no ‘community’ and no recurring pattern in ciliate succession could be observed.

High salt concentrations may also have pronounced effects on microbial communities, including growth inhibition, increase in generation times, change in morphology, increased osmotic stress and related physiological effects, and shifts in the community composition (Ziemann, 1973; Valdes and Albright, 1981; Prieur *et al.*, 1987; Painchaud *et al.*, 1995; Rheinheimer, 1997). Traunsee is characterized by comparably high chloride concentrations which originate almost exclusively (90–95%) from industrial effluents. A chloride budget, calculated on basis of the monthly reports from the Solvay Austria AG (1950–1998), revealed a net gain of 380 000 t of chloride to the lake since the 1950s (data not shown). Nevertheless, threshold levels of chloride concentrations, which were shown to have negative effects onto heterotrophic nanoflagellates and bacteria (>1 and 15 g Cl L^{-1}, respectively Schulz *et al.*, 1997; Schulz and Baumgart, 1999) have not been detected in Traunsee. Most ciliates detected at the three sampling sites are described as ubiquitous species, tolerant against chloride and salinity conditions as observed in Traunsee. Wilbert (1995) investigated salt lakes in Canada, Egypt and Australia. Based on his results he referred to Thienemann (1913) and his second biocoenotic principle: ‘*Extreme living conditions drastically reduce the number of species*’. This principle can be also confirmed for the ID sites in Traunsee. Wilbert (1995) described that the ion composition of the salt is important to the ciliates resulting in different communities. He found species in thalassic lake sediments (*i.e.*, dominated by Na^+, Cl^-), which we could also detect in Traunsee, i.e. *Cinetochilum margaritaceum*, *Cyclidium glaucoma*, *Pleuronema coronatum*, *Uronema nigricans*, *Aspidisca cicada*, *Stylonychia mytilus*, *Tachysoma pellionellum*, *Frontonia leucas*. Some of them are recorded as freshwater species, too. These were *Coleps nolandi*, *Cyclidium glaucoma*, *Aspidisca lynceus* and *Euplotes moebiusi* – amongst a great variety of ciliates and bodonid and euglenid flagellates (Patterson *et al.*, 1989). According to the classification of Albrecht (1984) most species identified are oligostenohaline tolerant to chloride ranges of 0–400 mg L^{-1}, corresponding to a salinity of 0–1‰ (Table VI). Hence, in relation to the actual concentrations in Traunsee, only minor effects to the microbial communities are expected to occur from chloride.

4.4. SEDIMENT CARBON PATTERNS

Concentrations of dissolved and particulate organic as well as inorganic carbon in ID clearly showed the impact of industrial waste discharge and these may partly explain observed differences in microbial densities. TOM contents of ID, which mainly consists of carbonates, gypsum and brucite, were low. Similar results were already mentioned by Claes and Kersting (1981). Together with the significantly increased C/N ratios – the C/N ratio is an indicator of the quality of organic material (Schallenberg and Kalff, 1993) – which are a sign of a high content of refractory humic substances (Wetzel, 2001), the ID exhibited less favourable nutrient conditions than the natural sediments did. Surprisingly, the ID contained high DOC concentrations, which may have originated from the application of organic precipitators in salt purification. However, the high labile DOC (BDOC) fraction of 3 mg L^{-1} in June went not along with high bacterial activities, indicating, in comparison to natural sediment sites, an inhibition of carbon degradation. This compares well with the general observation of reduced microbial numbers, biomasses and activities in sediments influenced by or consisting of ID.

The ratio of bacterial carbon to total organic carbon (BC/TOC) in sediments is another indicator for the actual nutrient conditions (Meyer-Reil, 1993). A lake-internal comparison resulted in lowest values in EB 50 sediments (Table VII). However, a wide range of sediment BC/TOC ratios, covering three orders of magnitude (0.005 to 20%) can be found in the literature (e.g. Dale, 1974; Meyer-Reil, 1987; Schallenberg and Kalff, 1993; Sorokin, 1999). BC/TOC values of Traunsee are close to other freshwater sediment systems. Schallenberg and Kalff (1993) reported a range from 0.9–20.3% for various freshwater sediments and a range of 0.6 to 2.6% were calculated for the sediment of an eutrophic backwater (Kirschner and Velimirov, 1999). A range of 2.5 to 14.3% were found in sediment of mesotrophic Lake Erken (Goedkoop and Törnblom, 1996) and 8% in profundal sediment of a eutrophic Swedish lake (Boström, 1991).

4.5. BACTERIAL ACTIVITY AND THE CARBON CYCLE

By all activity parameters tested in sediments of Traunsee, the bacterial community at EB 50 showed slight to pronounced reductions. This was found for the content of actively respiring cells. However, in total, the content of INT active cells was found fairly high with 24 to 41% when compared to the bacterioplankton community which never exceeded 10% (Klammer *et al.*, this issue). Other studies reported the majority of benthic bacteria (90 to 95%) to be inactive or non-growing (Novitsky, 1983, 1987; Törnblom and Boström, 1995).

Bacterial production patterns at natural sediment sites in Traunsee matched well with data from the two reference lakes, Attersee and Hallstättersee. A comparison with literature data underlines the oligotrophic status of the lake (Table VIII). No clear differentiation between ID affected and unaffected sites can be drawn from calculated doubling times of the different bacterial communities. In general doubling times observed for Traunsee are in the upper range known from other aquatic sediment sites (Table VIII).

Experiments with radiolabelled glucose indicated that bacterial communities in ID had a much lower carbon conversion efficiency. However, a carbon assimilation of 50%, as observed with the ID undisturbed sites, seems rather high. Growth efficiency values in the literature for sediment bacteria range from 10 to 40%. Carbon conversion efficiencies (CCE) of 10–30%, for example, were found for benthic microbial communities in the highly eutrophic Lake Vallentunasjön (Bell and Ahlgren, 1987; Törnblom, 1996) and 17–40% in Baltic Sea samples (Boström and Törnblom, 1990). The CCE of 30% in EB 50 samples were therefore still considerably high, but showed a significant difference in the direct comparison with ID unaffected sediments of the lake.

Bacterial carbon production showed a 78 to 93% reduction at EB 50, compared to RB 50 and VI 180, respectively. Assuming that 19% of the Lake bottom are affected by ID, we can infer a significant biogenic loss which may affect the cycling of matter and the release of nutrients. The quantity of this effect is difficult to establish because short-term turbidity currents are interrupted by long period of natural sedimentation.

5. Conclusions

According to our results the lake floor of Traunsee can be separated into 3 categories: (1) Lake bottom areas which are covered exclusively by ID. These can be regarded as hostile to life. Beside the complete absence of meio- and macroorganisms, all microbiological parameters investigated in the ID were significantly different (by up to an order of magnitude) from other sediment sites less affected or unaffected by industrial tailings. The structure and functioning of food webs and the recycling of matter are strongly impaired. (2) Lake bottom areas which are indirectly influenced by the dumping of industrial waste. Along with floods of the Traun River and other hydrological events, natural sediments are occasionally covered by solid material from industrial discharge. Microbial parameters, in this area, showed minor to pronounced deviations from natural conditions. (3) Areas of the lake floor not affected by ID. These natural sediments in Traunsee showed no significant differences form sediments of comparable lakes. If we assume that the area exclusively covered by ID does not exceed 10% of the lake floor and that the

TABLE VIII

Comparison of bacterial production values from Traunsee and reference lakes with data from the literature (for abbreviations see legends of Tables V and VIII)

Location		BA (10^{11} cells L^{-1})	BC (mg C L^{-1})	BP (thymidine) (μg C L^{-1} hr^{-1})	BP (leucine) (μg C L^{-1} hr^{-1})	BDT (d)	Ref
Traunsee seasonal sampling							
EB 50	Oligotrophic	0.8–12.9	4–64	0.8–7.7		127–911	
RB 50	Oligotrophic	29.1–76.6	145–383	4.0–23.5		193–3953	
VI 180	Oligotrophic	32.8–109.6	164–548	21.3–79.6		134–420	
Three lakes comparison							
Traunsee	Oligotrophic			48.6 (±28.0)	113.2 (±59.3)		
Attersee	Oligotrophic			136.4 (±52.6)	149.4 (±85.6)		
Hallstättersee	Oligotrophic			93.8 (±25.1)	135.5 (±22.4)		
Various marine and freshwater aquatic sediments							
Marine sediments, Pacific	Oligotrophic	0.07–0.4	0.10–0.7	0.125–62.5[a]		5.0–8000	[1]
Lake George	Oligotrophic	0.17–9.5	0.85–48	24–390		0.1–83	[2]
Lake Erken	Mesotrophic	30.00–150	56–284	70–1000		74.0–458[a]	[3]
Kühwörther Wasser	Eutrophic	24.90–85.1	63.6–288	42–2350	67–2490	2.0–108	[4]
Lake Vallentunasjön	Hypereutrophic	100–500	275–1633	83–8000		2.3–250	[5]

[1] Sorokin, 1999; [2] Fallon and Boylen, 1990; [3] Goedkoop and Törnblom, 1996; [4] Kirschner and Velimirov, 1999; [5] Bell and Ahlgren, 1987. The following conversion factors have been applied: 1 mol thymidine = 2.15×10^{18} cells (Smits and Riemann, 1988), BCP (gC L^{-1}) Leu (mol $L^{-1}h^{-1}$ × 131.2 × 0.073 (% leu) × 0.86 (C/P ratio) × 2 (isotope dilution) (Kirchmann, 1993); where necessary, literature values were converted from mass kg^{-1} dw into mass L^{-1} using mean values of the sediment bulk density or water content values stated with the individual papers; where no bacterial carbon data were available, a value of 50 fg carbon $cell^{-1}$ was applied to convert bacterial numbers into bacterial carbon.

[a] Method unknown.

whole area influenced by ID from time to time accounts for about 20%, the actual ecological integrity may be impaired only to a minor but measurable extent. Taking into account, however, that there is a continuous destruction of habitats along with a permanent risk of a sudden mobilisation of the industrial solids deposited in the Ebensee Bay, a scenario already stressed by Müller *et al.* (1984, 2002), the ecological integrity of Traunsee must be regarded as considerably affected.

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