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Course ***ISATEC***

M.Sc. Thesis in International Studies in Aquatic Tropical Ecology

Baseline Study for the restoration of a formerly oligotrophic, presently eutrophicated lake in northern Germany

Presented by

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Baseline Study for the restoration of a formerly oligotrophic, presently eutrophicated lake in northern Germany

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Place and Date	Signature

To my both sons

Samee and Fahmee

Abstract

Silver Lake (“Silbersee”) is situated in the sandy Saalian moraine landscape east of Bremerhaven (Northern Germany), is about 8.0 m deep, and covers approximately 6.5 hectares. The lake is a nature reserve but, a part is nevertheless used for bathing and angling. In order to understand the water and sediment chemistry of the lake water samples were collected monthly from three different sites, while sediment samples were collected once from three other sites in the central deep area of the lake. During the summer, surface water is warmer than the bottom water, thus a thermocline with steep temperature changes is created. Water analysis indicated that P and N concentrations are too high to classify the lake as “oligotrophic” as it was in former times. This is further supported by the oxygen depletion in the deep water body during summer. The pH of the lake water is weakly acidic (about 6.5). The source of the water is only precipitation, and almost no water comes from outside the lake. Even in shallow waters the brownish colorations of the water and its increased turbidity by phytoplankton provide light conditions that are disadvantageous to rare primary plants of the Littorelletea-community with the exclusive occurrence of *Isoetes lacustris* in Lower Saxonia (northwestern Germany). These plants are further endangered by the accelerated eutrophication process reflected in the increased competition of the emergent vegetation as well the coverage (overgrowth) by filamentous algae. Sediment analyses indicate that C, N and P contents are high in the near-the-surface layer but decline downwards in the sediment. The

sediments are to be regarded as potential sources especially of P for the water nutrient regime.

To evaluate the effect of filter-feeding bivalves on water quality, measurements were taken to estimate the respiration and ingestion rates of the swan mussel *Anodonta cygnea,* which is now abundant in Silver Lake. The result of the respiration rate experiment had a low, stable rate at about 3.07 mg O_2 d^{-1} per average individual at a temperature of 10°C and ingestion rates were calculated at 47.5 µg Chl-*a* $d^{-1.}$ They can ingest only 1.9% of the assumed total Chl-*a* present in Silver Lake, which is not significant amount. So, the study presumes that filter feeding effects have not the sufficient potential for reducing the Chl-*a* from the Silver Lake

Lake restorations are attempted to improve water quality and life conditions, aesthetic and recreational needs. This study advises i) to remove macrophytes, ii) taking out sediments, iii) to control of runoff from adjacent farm land, iv) to cut down the deciduous trees from the bank area and to remove live and dead material from the water edge v) some regulations for bathing and angling people as well as vi) mechanically ventilate the deep water of the lake during summer.

Future research should however be undertaken to get insights in the production, the fluxes of nutrients and practibality of production control by fish as well as the possible dystrophication influences from the adjacent raised bog and the emergent vegetation before a very strong effort is put into restoration measures.

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1 Introduction

1.1 Characteristics of lakes

On a larger scale, natural lakes are not only part of human's quality of life, but also increase the biodiversity and functional properties of the surrounding ecosystems. The environment and conservation value of lakes include biodiversity, heritage and visual values as well as values for water uses. In terms of nutrient concentration, lakes are generally classified into three categories: i) oligotrophic, ii) mesotrophic, and iii) eutrophic (Owens and Chiras 1990). Oligotrophic lakes are characterised by low nutrient concentrations often associated with low pH and low CO_2, reflected in low macrofloral abundances and meagre phytoplankton production. These lakes have phosphorus concentrations less than 1 microgram per litre (Klapper 1991). In contrast, eutrophic lakes are characterized by high nutrient levels (e.g. phosphorus concentrations can be up to 1 milligram per litre; Klapper 1991), turbid water, and abundant macrophyte populations (Owen and Chiras 1990), as well as strong pH variation and (deep water) oxygen depletion. Mesotrophic lakes form intermediate stages.

1.2 Plant communities of oligotrophic western and central European lakes

Western and central European lowland oligotrophic freshwater lakes are inhabited by a typical plant community characterised by Littorelletea (Schaminee et al. 1992, 1995). The Littorelletea-community is characterised by small limnophytic and amphiphytic plants, growing in the littoral zone of oligotrophic to slightly mesotrophic tarns, lakes and pools. These communities are relatively

poor in species. In addition, the characteristic species have a low competitive ability. These communities have disappeared in many parts of their range due to natural succession and/or human impact. Thus, the characteristic species are among the rarest plants of the native flora in Germany, and their communities are elements of the most endangered ecosystems (Dierssen 1981). The Littorelletea include “isoetid” plant species, such as *Littorella uniflora, Lobelia dortmanna* and *Isoetes* spp. (Den Hartog and Segal 1964, Schoof-Van Pelt 1973, Wittig 1982) (Fig. 1 a-c). These plant species can only survive in stagnant, extremely weakly buffered oligotrophic waters with carbon dioxide levels of generally below 40 pmol l^{-1}. Many other submersed species depending on CO_2 uptake through their leaves are unable to absorb enough CO_2 for net photosynthesis in such lakes, because the diffusion rate of CO_2 is very low, e.g. in stagnant water 10^4 times lower compared to the diffusion rate in air (Madsen et al. 1993). However, pore water of fresh water-body sediments may hold CO_2 levels 10-100 times higher compared to the water layer and can reach values up to 4,000 pmol l^{-1} (Roelofs 1983). Isoetid plant species have several physiological and morphological adaptations to survive under those conditions, such as root uptake of CO_2 (Wium-Anderson 1971, Sand-Jensen and Sondergaard 1979), recapture of photo respired CO_2 in their lacunal system (Sondergaard 1979), and high oxygen release by their roots (Sand-Jensen et al. 1982, Roelofs et al. 1984, 1994). Besides carbon dioxide, the availability of nutrients such as phosphorus and nitrogen, is very low in oligotrophic lake systems. Several isoetid plants have mycorrhiza symbionts, which support them in “nutrition”. As a result, a quite stable ecosystem, with low productivity, is sustained for decades or even

centuries. Through pollen extracted from sediments from a Danish lake, it is reported that there have been hardly any changes in the abundances of isoetid species between 6,000 and 100 years ago (Müller and Kleinmann 1998). The pollen record of Lake Wollingst, Northern Germany, also shows that this lake was oligotrophic since its origin at the end of the Pleniglacial. After medieval forest clearing the lake has changed its quality, and its sediments exhibit altered pollen composition (Müller and Kleinmann 1998). The numbers of isoetids decreased drastically and the abundances of species inhabiting eutrophic environments increased in the last century, (B. Van Geel, personal communication). Eutrophication and the decline of isoetid species of similar lake systems in Germany and the Netherlands were observed in the last century (Schoff-Van Pelt 1973, Westhoff 1979, Wittig 1982, Arts 1990). Roelofs (1983) revealed that in 12 out of 53 lake systems, from which isoetid species had disappeared since 1950, the water changed to more or less turbid conditions, reflected in the presence of more eutraphent species such as *Riccia fluitans* in combination with mesotraphent species such as *Myriophyllum atterniflorum* and *Ranunculus peltatus* (Roelofs 1996). As a result of the altered light condition, the occurrences of *Lobelia dortmanna, Isoetes lacustris* and *Litorella uniflora* became restricted to the very shallow shore waters, while they were found down to 5 m depths in cooler waters before eutrophication. Thus, these plants became more exposed to critical influences e.g. overgrowth and competition by other plants, disturbances by bathing people, ice and wave forces and the global and local warming (Rachor, lecture in Oldenburg, Feb. 2009, Vahle 1990).

a

b

c

Fig. 1: Typical Littorelletea community inhabiting oligotrophic lakes a: *Isoetes lacustris* (L.) b: *Littorella uniflora* (L.) c: *Lobelia dortmanna (L.)*

1.3 Freshwater bivalves

Benthic suspension feeder communities are considered among the most efficient assemblages in extracting and processing energy-rich organic matter from aquatic ecosystems (Gili and Coma 1998). Suspension feeding bivalves directly control phytoplankton biomass in lake ecosystems (Cahoon and Owen 1996, Strayer et al. 1999). They are capable of cycling a significant amount of nutrients (Lewandowski and Stanczykowska 1975, Stanczykowska and Planter 1985, Kasprzak 1986, Vanderploeg et al. 1995).

Bivalves of the family Unionidae are key components of freshwater ecosystems. Being primary consumers, they occupy an intermediate position in the food web, passing energy from the primary producer to other animals and to micro-organism. Thus, their filtering activity may contribute to maintain lake, river and stream ecosystems (Müller and Patzner 1996).

The size and composition of unionid communities may affect the primary producer community structure and indirectly other grazers as fresh water bivalves may filter phytoplankton, bacteria and particulate organic debris from the water column (Paterson 1986, Leff et al. 1990). Filtration rates vary with bivalve species and size, temperature, particle size, nutrition concentration, oxygen conditions, water turbulence and currents (Vaughn and Hakenkamp 1988). On the other side, the bivalves may modulate nutrient and organic matter dynamics through excretion as well as biodeposition of faeces and pseudofaeces. Excretion rates are both, size and species dependent, influenced by the reproductive stage, and vary largely with temperature and food availability. Bioturbation of sediments through bivalve movements increases sediment water

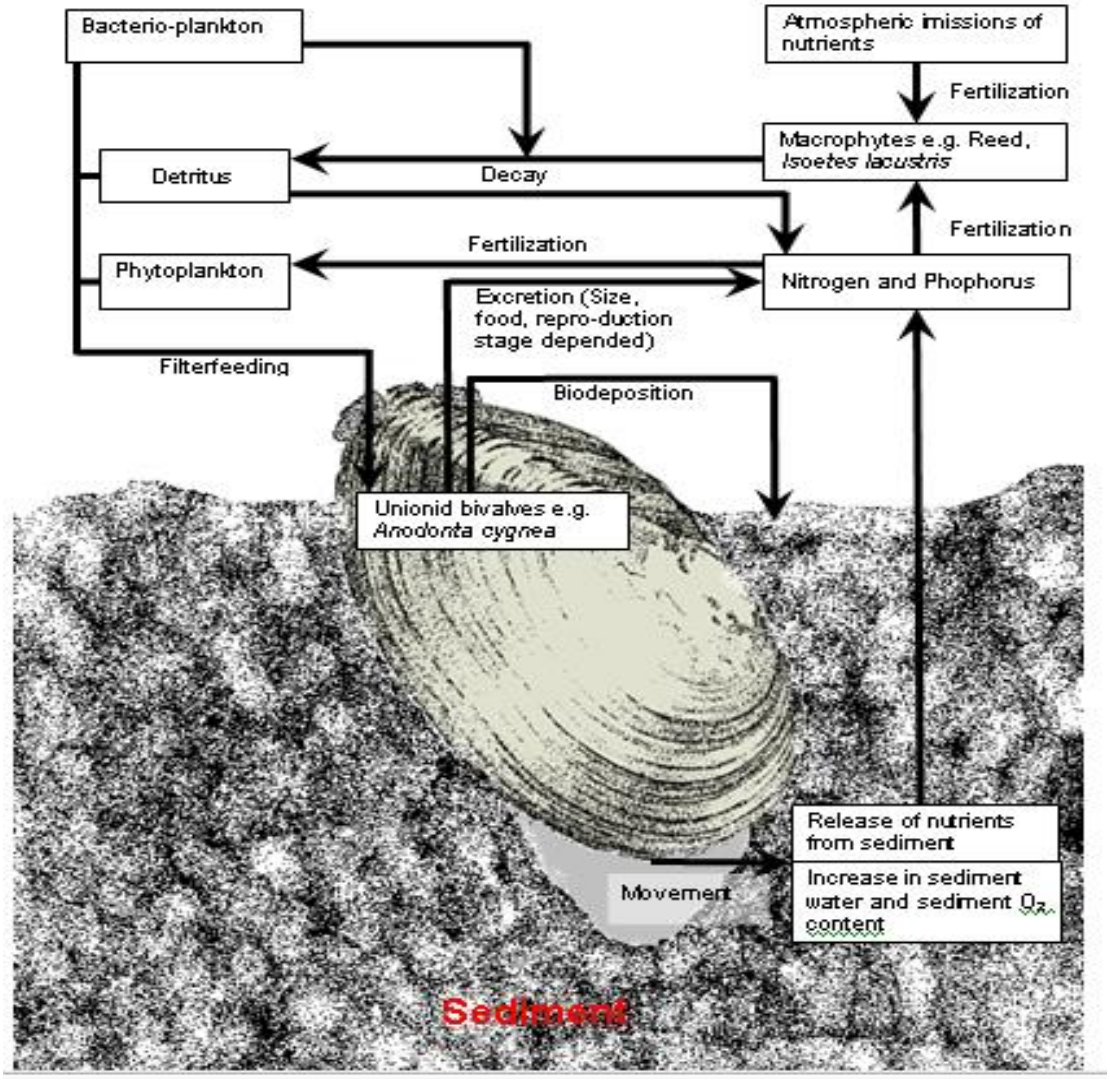

Fig. 2: Flow chart of nutrient and organic matter decomposition in relation of unionid bivalves in lakes (modified from Vaughn and Hakenkamp 1988)

and oxygen contents and releases nutrients from the sediment to the water column (Vaughn and Hakenkamp 1988, Fig. 2). The 'Swan mussel' ("Teichmuschel") *Anodonta cygnea* (L.,1758) inhabits large ponds, lakes and slow moving water, such as canals and (small) rivers with muddy bottoms.

Fig.3: Picture of a Swan mussel *Anodonta cygnea*

Its distribution is limited down to 10 m depth. Highest abundances (> 10 ind./m^2) are common between 2.5 and 6 m depth (Patzner et al. 1993). *A. cygnea* prefers nutrient rich waters and is one of the most common freshwater bivalve species widespread across central Europe and the United Kingdom. They burrow into the substrate normally with just the siphon tips exposed to filter particles from the water, pumping each up to 30 litres of water a day (Müller and Patzner 1996).

1.4 Lake Restoration

A lake is seen as part of an interdependent system of surface and subsurface water and of plant and animal habitats. These components are related to, and interact with each other. Thus, lake restoration requires general and special knowledge of the specific lake ecology, the causes of changes in water quality and species composition, as well as the techniques for restoring and protecting such lakes. Additionally, the legal and financial realities are to be considered, and

the administrative and technical resources available. Lake restoration begins with ecological awareness. Ecosystem-based restoration efforts typically involve the establishment of restoration targets. Ideally, these targets should be reflective of historical conditions (Lichatowich et al. 1995, Shuter and Mason 2001), although in reality, the relevant information on historical states is rarely directly available or obtainable, leaving managers often to speculate as to the historical state of ecosystems. The lack of baseline information on physical, chemical and biological interactions is a major obstacle to efforts to characterize the ecological changes. Such information may be a critical element in the evaluation of the restoration potential. However, old historical records, comparative studies (of similar systems) and lake sediments can help to understand the lake history. New approaches based on the reconstruction of historical ecosystems may thus make a substantial contribution to ecosystem-based restoration efforts.

However, ecosystem-based restoration can be limited by a number of constraints, especially drastic changes in the surrounding landscape and in land use and drainage, and, nowadays, by drastic climatic alterations, and the presence of exotic species in freshwater lake systems (e.g. Coblentz 1990, Lodge 1993, Mills et al. 1994, Ricciardi and MacIsaac 2000). In many cases, limnic ecosystems have lost part of their native species assemblage and may host a variety of introduced and invasive species, many of which dramatically alter the structure and function of these systems (Ludyanskiy et al. 1993, Mills et al. 1994, MacIsaac 1996).

1.5 Actual state of Silver Lake

The morphology and hydrology of Silver Lake with its slow water renewal and an unfavourable relation of the epi- and hypolimnion, make the lake ecosystem very sensitive, especially to nutrient burdening (Rachor 1998). Eutrophication is the natural aging process for most lakes, which involves an increase in nutrient concentrations in the water body, as well as rising sedimentation. The actual trophic stage of Silver Lake is indicated by oxygen depletion and H_2S formation in the deep-water body during each summer and the lack of any profundal fauna. It is now eutrophicated mainly by P- and N-compounds. Atmospheric imission of nutrients into the lake is almost sufficient today, to keep it in critical trophic stage, with a total phosphate concentration between 0.06 and 0.08 mg P per litre in 1996 and 1998 (Rachor 1998, in Lake Wollingst). According to near-by imission measurements, 11.5 kg of ammonium- and nitrate-N and 0.25 kg of phosphate-P per hectare are annually deposited from the atmosphere (Rachor 1998). Accordingly, and considering the poor water renewal rates of Silver Lake, the amount of dissolved inorganic N may be renewed within about 3-5 years, while P may be replenished within a few more years, not considering temporary sinks in the sediments.

Additional causes for nutrient richness may be:

- remainders of uncontrolled bathing activities in the 1950s to 60s, especially P-compounds,
- introduction of new nutrients by bathing and angling
- the (P and N rich) runoff/emissions from the adjacent farming and holiday lodging areas,

- the surrounding dominating emergent and terrestrial plant species and their leave litter,

- influences from the adjacent raised bogs nutrients

The resulting brownish colouration of the water and its increased turbidity by phytoplankton provide even in the shallow waters light conditions that are disadvantageous to the rare Lobelion-association (Rachor 1998, Vahle 1990). Additionally, the mentioned plants are covered by fouling organisms (algae, fungi, etc.) especially in spring, which is also a light inhibiting and even a burdening obstacle to sensitive plants. But the lake condition in terms of the physical, chemical and biological parameters are not fully understood and relevant scientific studies and reports are lacking yet.

Therefore the objectives of the present research for restoration measures are:

a) to describe the recent physico-chemical and biological properties of Silver Lake (oxygen, temperature, pH, nutrients i.e. P, N) in order to determine the actual status

b) to monitor the surviving primary plants

c) to investigate the metabolic rate and feeding of the Swan mussel *Anodonta cygnea* and estimate its possible influence on the nutrient regime.

d) to describe the restoration proposal for future actions.

2 Materials and Methods

2.1 Study site

Silver Lake (Silbersee, Fig. 4) is located approximately 14 km east of Bremerhaven (northern Germany) near the little village Wehdel in the community of Schiffdorf. It is situated at an altitude of approximately 10 meters above the sea level of the Beverstedt Moorgeest (Pleistocene Saalian old moraine landscape with bogs in depressions). The lake was recorded to be 11 meters deep in the past; in recent years just 8 meters were measured; and it covers approximately 6.5 hectares. Silver Lake was originally oligotrophic, but the feature on its exact origin is still unclear and the origin of the lake is under discussion. According to Merkt and Kleinmann (1998), a Pingo genesis (or transformation) during the last glaciation period as suggested for the near-by Lake Wollingst may be most plausible. The lake is situated in the sandy to sometimes loamy Saalian moraine landscape. The slope of Silver Lake shore is about 2 meter higher in the North, while a degenerated raised bog in the West is not much elevated from the landscape.

Fig. 4: Location (upper picture) and aerial view of Silver Lake (Silbersee), Source of upper picture: (http://cuxland-gis.landkreis-cuxhaven.de/gis/schutz-nature/viewer.htm) Source of aerial view DLRG Wehdel e.V.

There are no visible inflows and only poor groundwater supplies to the lake, which is partly adjacent to degenerated raised bogs. According to Vahle (1990), a relict oligotraphent vascular plant association was still existent in the shallows in 1990: *Isoetes lacustris* (Fig. 1a) and *Littorella uniflora* (Fig. 1b). Mainly to protect these rare, in Germany almost extinct assemblage and associated organisms, the lake and its direct surroundings (32.7 ha) is a nature reserve since 1932. Nevertheless, recreational activities such as swimming and angling are tolerated. The history of the vegetation in the near-by Lake Wollingst indicates that in former times most of the shallow lake bottom was covered by an Isoeto-Lobelietum community; but in the last century, especially in the seventies, a dramatic decline of this assemblage has been observed (extinction of *Lobelia dortmanna* and reduction of the growing belt of *Isoetes lacustris* and *Littorella uniflora* lo less than 0,7 m water depth). By the accelerated eutrophication process the emergent vegetation has rapidly increased since the fifties, with *Sphagnum* and other paludal plants as well as *Phragmites australis* and others dominating (Rachor 1998, for Lake Wollingst). Similarly, in Silver Lake, species of *Typha angustifolia, Nuphar leatum, Nymphaea alba, Potamogeton* spp*,* reed, mosses and others have taken over. This indicates an acceleration of the dystrophication process, which might be part of a natural succession together with anthropogenic impact in such types of lakes (Rachor 1998).

2.2 Water analyses

2.2.1 Sites

Water samples were collected from three different sites namely, “DLRG-station”, “Deep” and “Angling” (Fig. 9). Water samples were analysed for NH_4^+, NO_3^-, NO_2^-, total N, PO_4^+, total P, pH, *in situ* temperature, and electrical conductivity (EC). The water level and Secchi disc visibility depths were additionally measured.

2.2.2 Sampling

Samples were collected monthly from August 2007 to March 2009. At “DLRG-station” and “Angling” replicated water samples were taken by filling two 100ml polyethylene bottles at 0.2-0.5 m depth, while the deep area was sampled at about 8 m depth using a Ruttner sampler (Hydro-Bios, Germany). All samples were transported to the laboratory immediately and stored at -80°C prior to analyses of nutrients and electrical conductivity (EC).

Fig. 5: Water sampler (Ruttner sampler, Hydro-Bios, Germany) used to sample water from 8 m depth of Silver Lake, in this case from the ice in January 2009.

2.2.3 Physico-chemical analyses

Water samples were analysed in the laboratory of the section vegetation and nature conservation of the Institute of Biology and environmental science, Carl von Ossietzky University of Oldenburg to quantify reactive orthophosphate using the molybdenum blue method (Grasshoff et al. 1983). Ammoniacal nitrogen (N-NH_3 + N-NH_4^+, hereafter referred to as ammonia) was determined by indophenol (Parsons et al. 1992). Nitrite was quantified by the diazotation method (Grasshoff et al. 1983), and Nitrate was determined by the reduction in a Cd-Cu column followed by diazotation (Grasshoff et al. 1983). Dissolved oxygen and temperature were measured by a diffusion O_2 meter (YSI Model-57, EQUIPO, USA); pH was measured by a pH meter (Multi 340i, WTW, Germany) from at least three different depths (1, 5 and 8 m) in the water column of the deep station.

2.3 Sediment analysis

2.3.1 Sites and sampling

Sediment samples were collected from three selected sites (P1, P2 and P3, Fig. 7) using a KB (Kajak - Brinkhurst) core sampler (Model: 603 – 034, Rickly hydrological company, USA). Cores were sliced into 3 horizons where possible: 0-10 cm, >10-20 and >20-30 cm, respectively. After collection, samples were air dried; roots and gravel were eliminated prior to analysis.

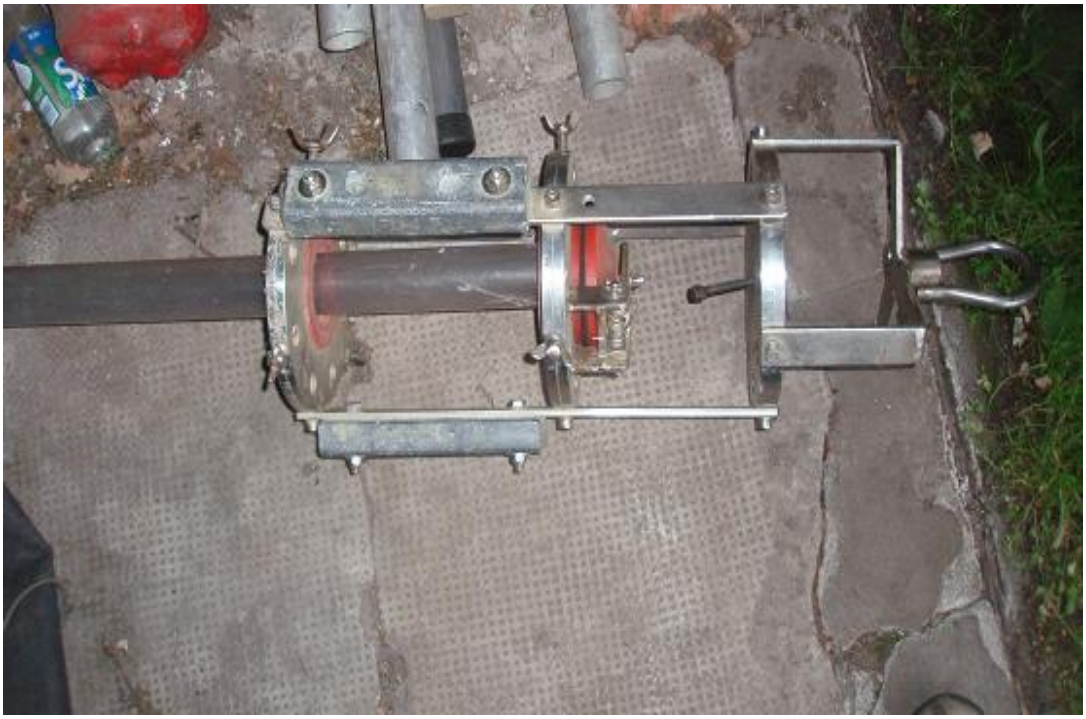

Fig. 6: KB (Kajak - Brinkhurst) core sampler (Model: 603 – 034, Rickly hydrological company, USA).

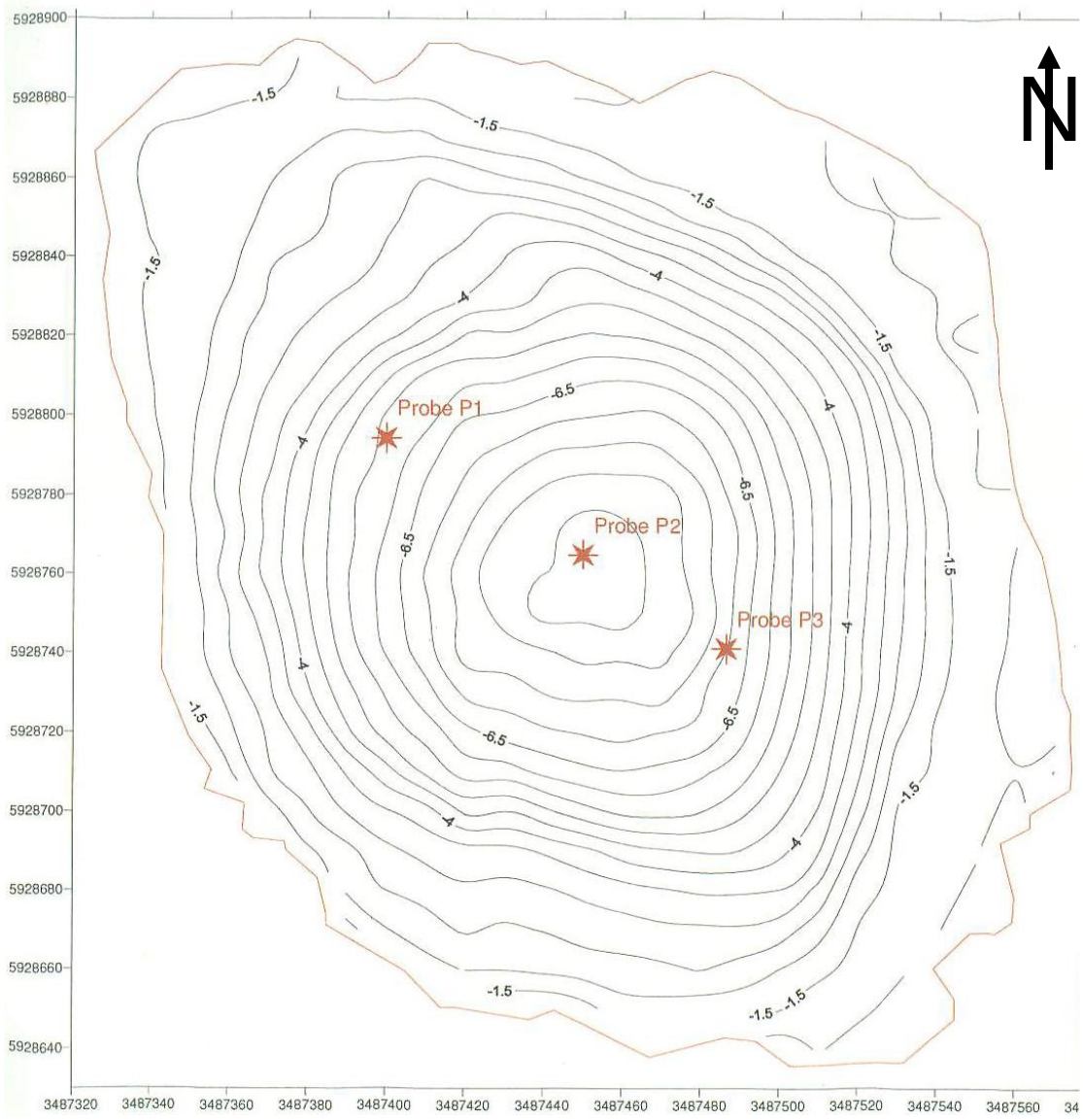

Fig. 7: Bathymetric map from 21.02.2008 (1:1000) showing the three sediment sampling sites (P1, P2 and P3). Source: Hydrographic Service GmbH, Schessel.

2.3.2 Chemical sediment analyses

Sediment samples were analysed in the laboratories of the sections of Geology and Geochemistry, Alfred Wegner Institute for Polar and Marine Research (AWI). Before the chemical analyses started, sediment samples were air dried, ground and passed through sieves (2mm mesh size) to get rid of larger particles and

stones. The samples were then analysed for total nitrogen, total phosphate, total sulphur, total carbon, total calcium (%$CaCO_3$) and total minerals as explained in the following paragraphs.

2.3.2.1 Total nitrogen

Total nitrogen content of sediments was determined by the Kjeldahl digestion method (Kjeldahl 1883). A catalyst mixture (K_2SO_4: $CuSO_{4*}$ $5H_2O$: Se = 10: 1: 0.1), 30% H_2O_2 and concentrated H_2SO_4 were used to digest the soil samples. Nitrogen was estimated by distillation with 40% NaOH followed by titration of the distillate, trapped in H_3BO_3 with 0.01 N H_2SO_4 (Page et al. 1982).

2.3.2.2 Total phosphate

100 mg soil samples (from the three sites × three horizons) were placed in a 50 ml boiling flask before 3 ml of sodium hypobromite (NaOBr) solution was added, and the flask was swirled for a few seconds to mix the contents. The flask was allowed to stand for 5 min., before it was swirled again and placed in a sand bath adjusted to 260 to 280°C. The sand bath was situated in a hood. The flask was heated until the contents evaporated to dryness (10 to 15 min). After evaporation, the flask was continuously heated for additional 30 min. Thereafter the flask was removed from the sand bath, and allowed to cool down for 5 min, 4 ml of distilled water and 1 ml of formic acid were added. The flask was shaken and 25 ml of 0.5 *M* H_2SO_4 was added. The mixture was transferred to a 50 ml plastic centrifuge tube and centrifuged at 12,000 rpm for 1 min. For analyzing total P, 2 ml of centrifuge sample was transferred into a 25 ml volumetric flask. Thereafter 4 ml of ascorbic acid reagent was added and field up to volume with

distilled water. The solution was mixed and placed for 30 min for color development. Optical density of sample was measured at a wavelength of 720 nm (Dick and Tabatabai 1977).

2.3.2.3 Total carbon

Equipments used in sample processing were combusted at 400°C for at least 4 hours to get rid of all combustable organic matter. The soil samples of Silver Lake remained frozen at -20°C until processing. Sediment samples are thawed, homogenized and dried in an oven at 40°C. 10g of the sample was removed, ground and homogenized. Dried and homogenized samples were placed in an aluminum-weighing pan and dried at 105°C. The LECO CR-412 Carbon Analyzer was calibrated prior to the analyses of samples. Different amounts of high purity calcium carbonate standard (99.95% purity, carbon content of 12.0%) were used to calibrate the instrument. The approximate amounts of calcium carbonate used for the six-point calibration were 0.01 g, 0.05 g, 0.10 g, 0.25 g and 0.50 g. An empty carbon-free combustion boat was analyzed as a blank for the calibration curve. Total carbon was analyzed by placing approximately 0.350 g of the dried, ground and homogenized sample into a clean, carbon-free combustion boat. The sample boat was placed on the autosampler rack assembly and loaded onto the LECO Carbon Analyzer. Each sample boat was treated with phosphoric acid drop by drop until the sample stopped “bubbling” and the sample was completely moist with acid to remove the calcium carbonate from the sample. The sample was placed into an oven set at 40°C for 24 hours and then transferred to an oven set at 105°C.

Calculations:

Carbon content:

$$Carbon\ [\ g\ ] = (b) * (A) + a \quad (1)$$

Where:

b = the slope of the linear calibration curve (g per unit area)

A = the area under the sample curve

a = the intercept of the calibration curve (g)

Percent total Carbon

$$\%TC = \frac{Carbon\ [\ \ g\ ]}{W[\ \ g\ ]} \quad (2)$$

Where W (g) = dry sediment analysis mass (g)

Percent Total Organic Carbon content (TOC)

$$(\%)TOC = \frac{Organic\ \ Carbon\ [\ \ g\ ]}{W[\ \ g\ ]} \quad (3)$$

Note: When sample had been acidified, organic carbon (g) replaces carbon (g) in the above equation.

Percent Total Inorganic Carbon Content (TIC)

$$(\%)TIC = \cdot(\%)TC - (\%)TOC \quad (4)$$

2.3.2.4 Total calcium

Percentage of calcium carbonate, $CaCO_3$ [%], is defined as the total calcium. Percent calcium carbonate [%$CaCO_3$] was determined by mass of total inorganic carbon (TIC) [%] multiplied by 8.33 (mass of $CaCO_3$/mass of carbon =100/8).

To express TIC as a percent calcium carbonate ($CaCO_3$), use the following equation.

$$CaCO_3\ [\%] = (TC - TOC) * 8.33 \quad (5)$$

2.3.2.5 Total minerals

Empty crucibles were weighed by digital balance (AC211S, Sartorious, Germany), and labeled by a pencil. Then the sample (crucible +sediment) was dried at 60°C (Memmert, Germany) for 24 hours. Thereafter the dried sample is combusted in a Muffle Kiln (Heraeus, Germany) at 600°C for 10 hours. Total minerals were calculated in the following equations:

$$Total\ minerals = \frac{(N - T)}{(B - T)} * 100 \quad (6)$$

Where,

N = mass of crucible with sample after burning at 600°C

T = mass of empty crucible

B = mass of crucible with dried sample before burning.

2.4 Metabolic rate and feeding of the swan mussel *Anodonta cygnea*

In September 2007, 15 Swan mussels (*Anodonta cygnea*) were transported alive to the Alfred Wegener Institute for Polar and Marine Research (AWI, Germany) and were kept for 4 - 6 weeks in aerated aquaria with natural freshwater and sediments from Silver Lake (about 8cm thick layer) before starting the experiments. Bivalves were fed once a week with a live algal suspension maintained in the laboratory.

2.4.1 Respiration

Respiration was measured in a multi-channel modified intermittent flow system as described by Heilmayer and Brey (2003). Prior to respiration measurements, *A. cygnea* were maintained without food for three days, in order to eliminate the impact of specific dynamic action (SDA) on respiration (Bayne et al. 1976). Bivalves were allowed to accommodate to the respiration chambers

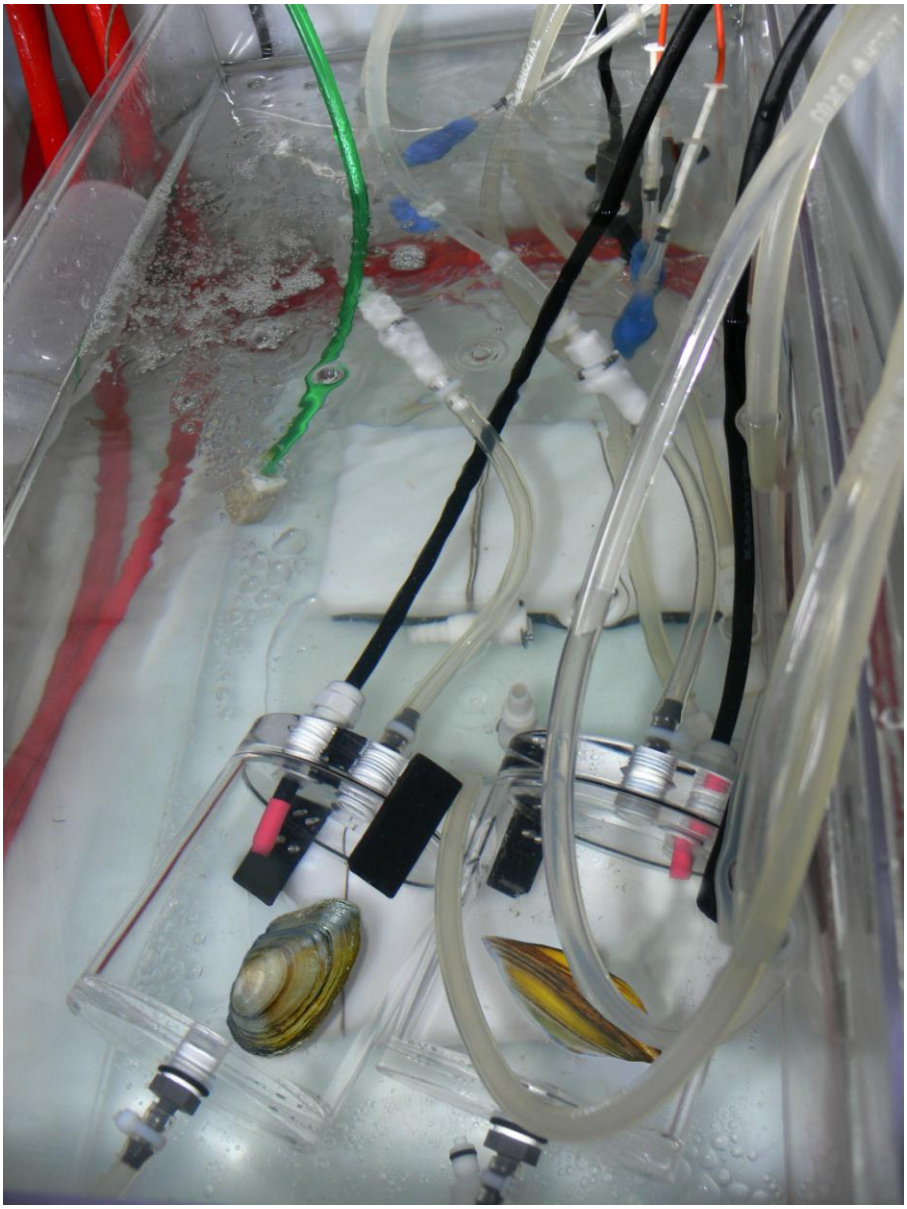

Fig 8: Picture of the Swan mussel *Anodonta cygnea* in the chamber

overnight; and oxygen consumption of only actively respiring animals that had their siphons open to the surrounding water were measured. Respiration chambers consisted of small Perspex cylinders with a movable lid to adjust chamber volume between 600 ml and 1450 ml to animal size (Heilmayer and Brey 2003). Experimental temperature was maintained stable (10°C) by placing the chambers in a water bath set in a within jacketed container, that was connected to a thermo circulator (Julabo FP 40, USA). Three respiration chambers with one animal each (of similar size) and a control chamber (without animal) were measured simultaneously per experimental run. Total two runs were taken for each animal. Oxygen content in the chambers was monitored continuously with oxygen microoptodes connected to a MICROX TX3 array (PreSens, Neuweiler, Germany). Optodes were calibrated to 100% oxygen solubility in saturated air and to 0% in N_2-saturated freshwater (technical gas with 99.996% N_2) at experimental temperatures. All measured data were stored in a PC (Program Excel, Microsoft office, 2003, USA). After the measurements, animals were dissected immediately. Soft tissue wet mass (WM) was determined to 0.001g precision after careful blotting with blotting paper. The soft tissue was dried at 60°C for at least 48h to get a dry mass value (DM). Thereafter dried tissues were combusted at 500°C for 24h and ash free dry mass (AFDM = DM - ash) was calculated.

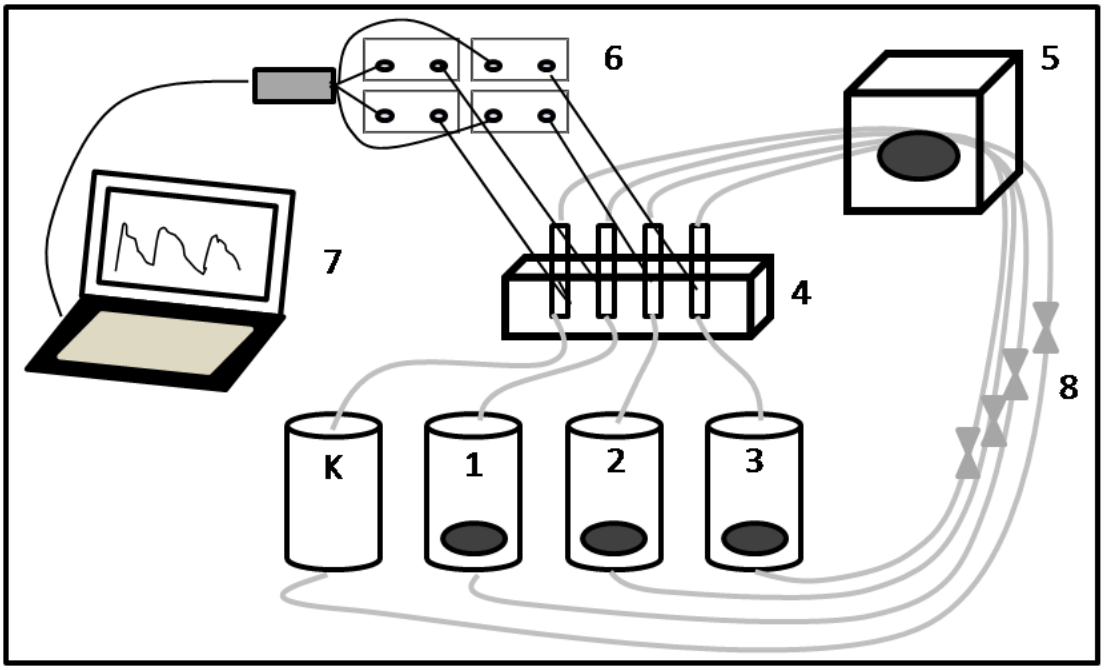

Fig. 9: Multi-channel modified intermittent flow system, K) control, 1-3) Chambers with animals, 4) Optodes, 5) Peristaltic pump, 6) TX-3 Boxes, 7) Recording PC, 8) Opening structure

2.4.2 Metabolic rate

Standard metabolic rate (SMR, μmol O_2 ind^{-1} h^{-1}) was calculated from the slope of the oxygen saturation curve after subtraction of the microbial oxygen demand, determined as post-measurement blank. Percent O_2 saturation was transformed to VO_2 (i.e. micromoles of dissolved oxygen) using known values of oxygen solubility (α_{O_2}, μmol dm^{-3}, Benson and Krause 1984) by:

$$VO_2 = \frac{satt_o}{satt_{60}} \cdot \alpha_{O_2} \cdot V_{chamber} \qquad (7)$$

where α_{O_2} is the oxygen solubility in freshwater (μmol* dm^{-3}), $V_{Chamber}$ is the volume of the respiration chamber and tubing (dm^3), *sat* t_0 is the oxygen saturation (%) at the beginning of the experiment and *sat* t_{60} is the oxygen saturation (%) after 60 min as calculated from linear regression. Individual metabolic rates were corrected (SMR= Standard metabolic rates) with the

oxygen consumption of control chambers (no animal) and converted to milligram O_2 by 44.66 µmol O_2 = 1 mg O_2 (Brey 2001).

2.4.3 Quantification of *A. cygnea* filter feeding

Swan mussels *A. cygnea* were placed in the above described chambers and the chamber volume (600-1450 ml) adjusted to animal size. Three chambers with one test bivalve each (of similar size) and a control chamber (without animal) were used simultaneously per experimental run (one run for each animal). Oxygen content in the chambers was monitored continuously with oxygen microoptodes as described above. After 30 minutes acclimatization time a fresh algal suspension was added to the chambers. After two hours the chambers were disconnected without losing water. The water of each chamber was drained into separate plastic bottles and homogenized by shaking three times. Three replicate 100 ml water samples per chamber were filtered through a pre-combusted Whatman GF/F filter, and the filters stored at -80°C in 2 ml cryo vials. Thereafter, filters were ground in the dark after 4 ml of aqueous acetone solution had been added and kept at 4°C for 12 hours before the filter slurry was centrifuged at 675 g for 15 min to clarify the solution. An aliquot of the supernatant was transferred to a glass cuvette, and florescence was measured before and after acidification by adding 0.1N HCl. Then the solution was transferred to a glass cuvette, and concentration of Chlorophyll *a* (Chl-*a*) was determined by fluorometry (TD-700, Turner Designs Inc., USA). After that 2 drop of 0.1N HCl were added into the glass cuvette to determine Pheophytin *a* by fluorometery (TD 700). Sensitivity calibration factors, which have been previously

determined on solutions of pure Chl-*a* of known concentration were used to calculate the concentration of Chl-*a* and Pheophytin *a* in the sample extract as

$$Chl\ a = K(\frac{Fm}{Fm-1}) * (Fb - Fa) * (\frac{v}{V}) \quad (10)$$

$$Pheo\ a = K(\frac{Fm}{Fm-1}) * [F_m * (F_a - F_b)] * (\frac{v}{V}) \quad (11)$$

Where K is the sensitivity coefficient, Fm is the maximum acid ratio Fb/Fa of pure Chl *a* standard, Fb is the fluorescence before acidification, Fa is the fluorescence after acidification, v is the extract volume and V is the filtered water volume.

Thereafter corrected Chl-*a* concentrations were calculated according to the equation:

$$Corrected\ Chl\ a = \frac{C}{V1} * 1000 \quad (12)$$

the Ingestion coefficient was estimated as:

$$I = Ce - Cc \quad (13)$$

Where, Ce and Cc is the concentration of corrected Chl *a* with test animal and without animal (blank).

Finally the clearance rate CR (volume cleared per biomass and time) was computed as:

$$CR = \frac{I}{b} \quad (14)$$

Where b is the biomass of the tested bivalve within the chamber.

2.5 Assessment of the lake vegetation

2.5.1 Sites

In order to assess the vegetation inhabiting the shallow water of Silver Lake, different observation plots (from north-east of the DLRG-station to south-east of the angling pier) were employed in water depths down to 75 cm (Fig. 22).

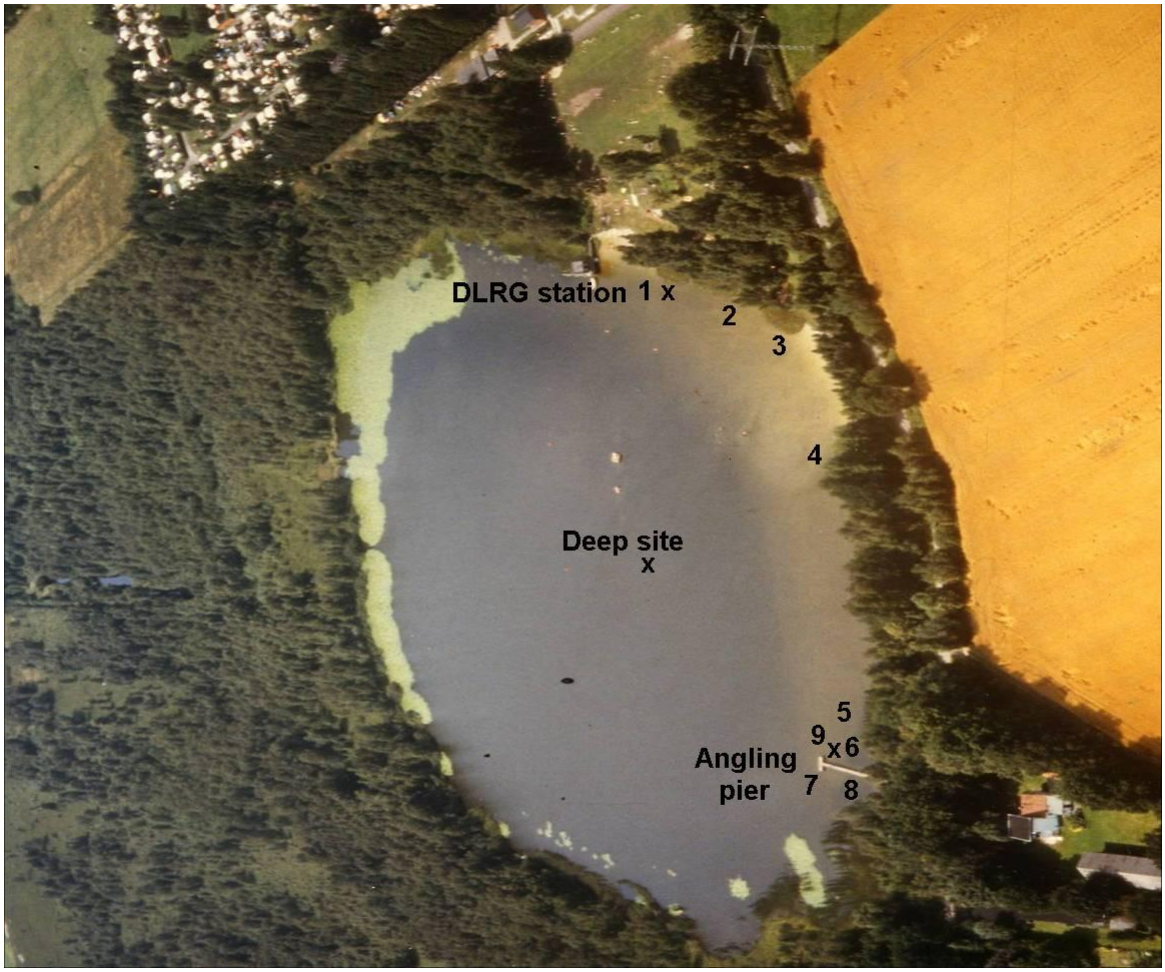

Fig. 10: Map showing the three water sampling sites (X) and nine (1-9) vegetation observation plots. (Modified from DLRG Wehdel e.V.).

2.5.2 Monitoring of the plant assemblage

Plant assemblage monitoring as well as quantification of the submerged vegetation was carried out from March to May (spring to summer) at each plot.

Species identification followed books (Cordes et al. 2006, Vahle 1990) and the personal communication with experts. For *Littorella uniflora* the size of the covered area was additionally measured by hand scale (Zollstock) .

3 Results

This chapter presents the results of the study of different aspects of Silver Lake.

3.1 Description of water body

3.1.1 Water chemistry

3.1.1.1 Variability of phosphorus

The chemistry of the three sampling sites showed considerable similarities in their seasonal changes (Fig. 11 and 12). Maximum total phosphate (TP) concentration was measured in the two winter seasons, the highest value amounted 0.0412 mgl^{-1} at the deep site in January 2009. Total phosphorus concentrations were lowest (0.0233 – 0.0231 mgl^{-1}) at “Angling pier” in spring and throughout most of the summer. Phosphate phosphorus showed a maximum (0.0151 – 0.0153 mgl^{-1}) at the deep site in winter and a minimum (0.0091 – 0.0093 mgl^{-1}) at “Angling pier” in summer (Fig. 12). Highest concentrations of total phosphorus (0.0233 mgl^{-1}) and phosphate phosphorus (0.0153 mgl^{-1}) were recorded at the deep site compared to “Angling pier” and “DLRG station”. Whereas total phosphorus and phosphate phosphorus concentrations were similar at the two latter sites.

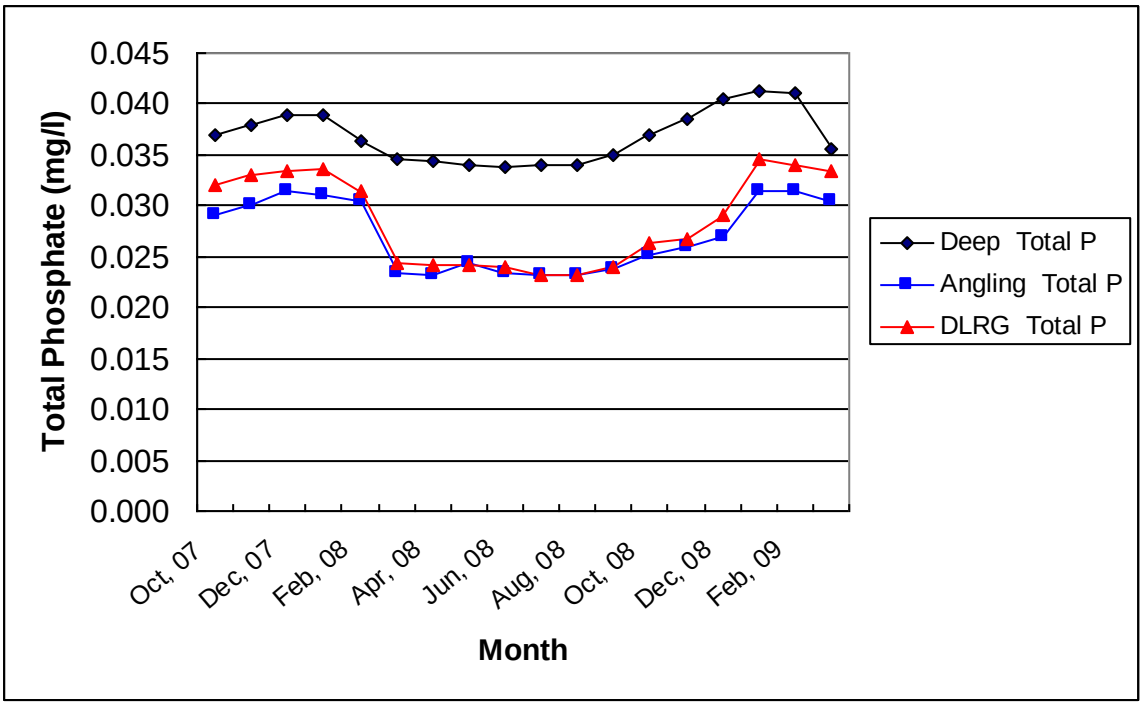

Fig. 11: Variability of Total Phosphate (mg/l) at three different locations (Deep, Angling and DLRG) of Silver Lake from October 2007 to March 2009.

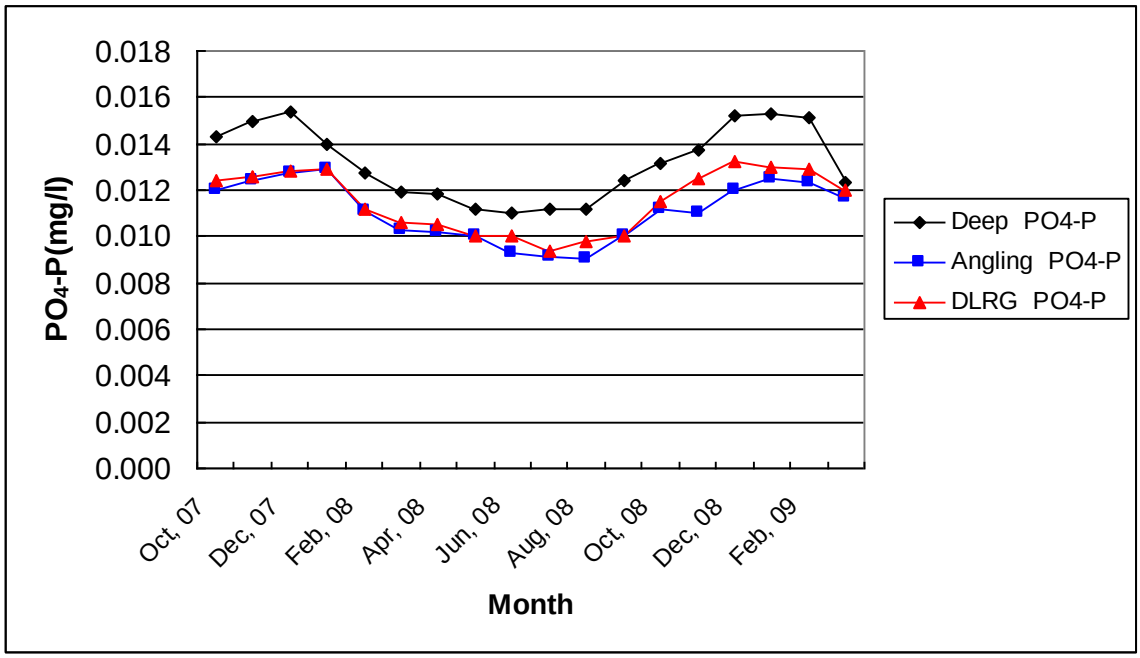

Fig. 12: Variability of PO_4-P (mg/l) at three different locations (Deep, Angling and DLRG) of Silver Lake from October 2007 to March 2009.

3.1.1.2 Variability of nitrogen

Figure 13 shows that the total nitrogen concentration was maximum in fall and winter at all three sites. The highest concentration was recorded 1.43 mg l^{-1} in January 2009 at the deep site. Total nitrogen concentrations were relatively low in spring and in summer at all three stations, total nitrogen concentrations were observed highest at the deep site (1.1500 – 1.4285 mg l^{-1}) compared to the other two stations (Angling: 1.0530 – 1.3475 mg l^{-1} and DLRG: 1.1100 – 1.3215 mg l^{-1}) (Fig. 14). Total nitrogen concentrations were similar at the angling pier and the DLRG station. Overall, NH_4-N was more important than NO_3-N (Fig. 14 and 15). In summer, NH_4-N concentration was much higher (0.197 mg l^{-1}, June 2009) with a very strong smell of H_2S at the deep site compared to the angling pier and DLRG station. At the same time NH_4-N concentrations at the angling pier and DLRG station were very low (<0.030 mg l^{-1}); without any smell of H_2S in the shallow water of these two sites.

Figure 15 shows, that NO_3-N was absent at the deep site in summer, but NO_3-N was present at the angling pier and DLRG station at that time. NO_3-N was higher in late fall to summer at the angling pier and DLRG station compared to the deep site.

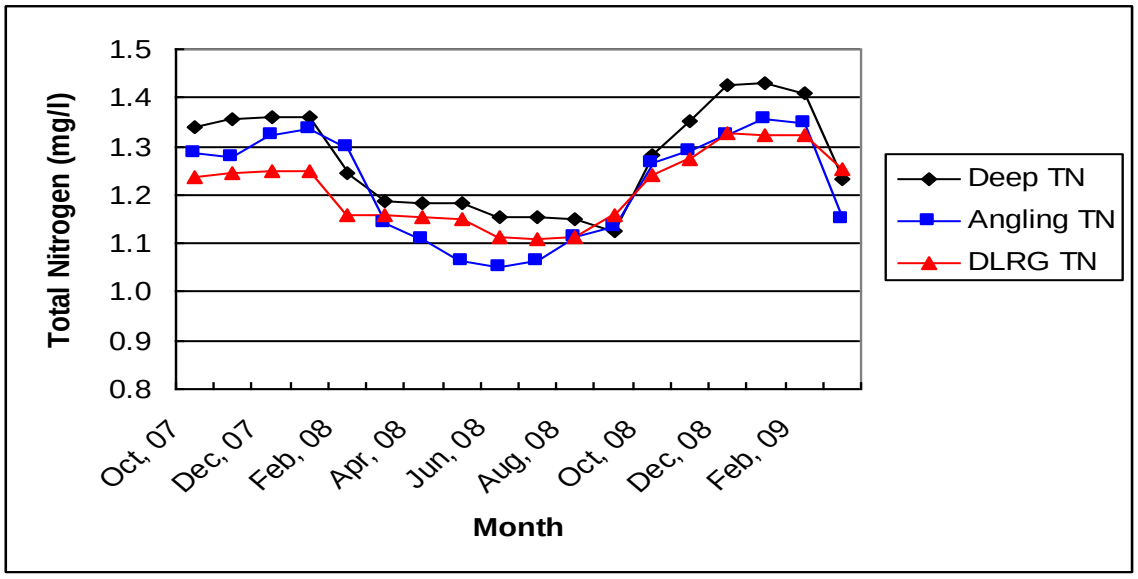

Fig. 13: Variability of total Nitrogen (mg/l) at three different locations (Deep, Angling and DLRG) of Silver Lake from October 2007 to March 2009.

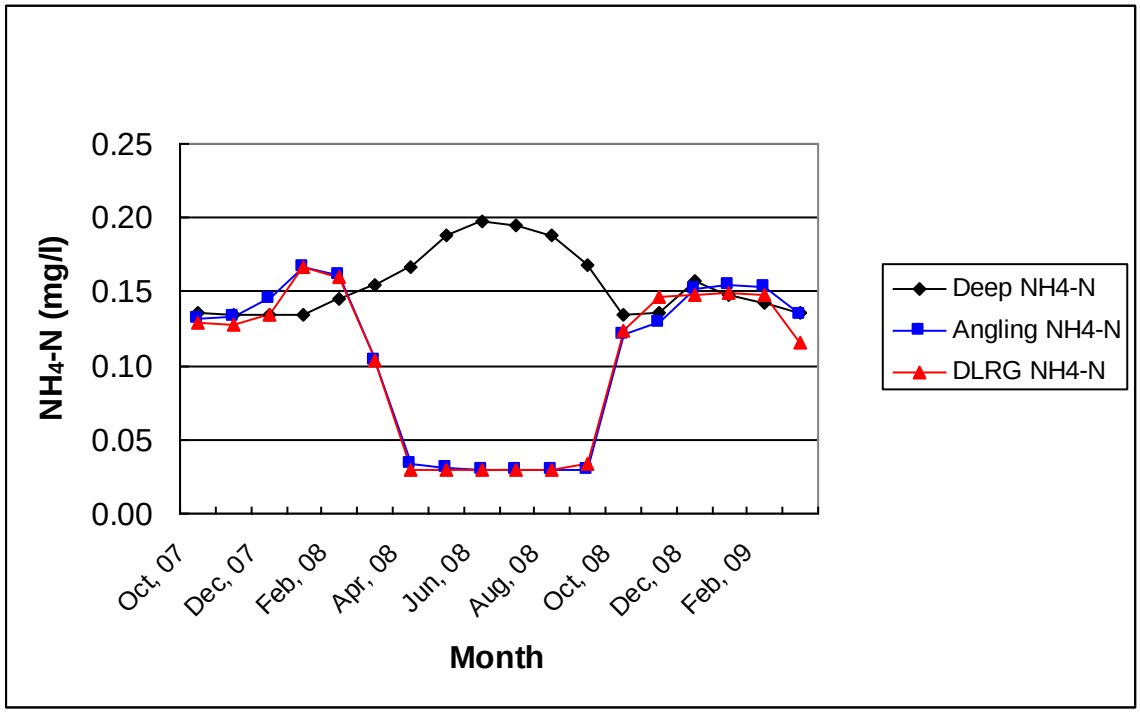

Fig.14: Variability of NH_4-N (mg/l) at three different locations (Deep, Angling and DLRG) of Silver Lake from October 2007 to March 2009.

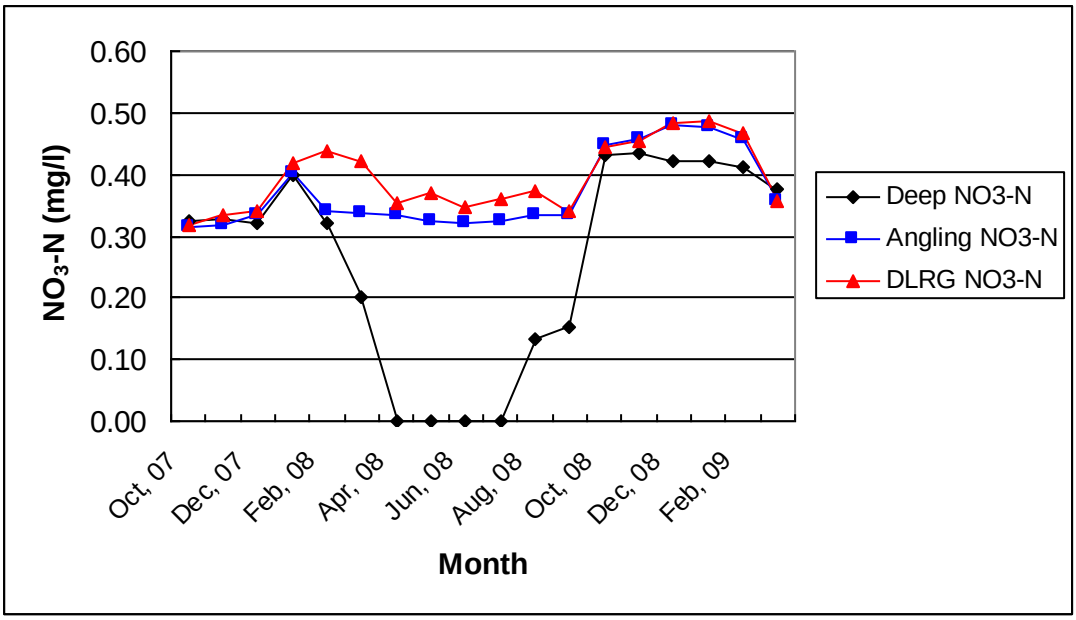

Fig. 15: Variability of NO_3-N (mg/l) at three different locations (Deep, Angling and DLRG) of Silver Lake from October 2007 to March 2009.

3.1.1.3 Variability of electrical conductivity

Electrical conductivity (EC) ranged between 67.0 – 77.1 μScm^{-1} at the DLRG station, 67.0 - 76.6 μScm^{-1} at the angling pier and 63.7 - 77.0 μScm^{-1} at the deep site (Fig. 16) with highest values in winter and lowest in summer. Figure 16 also shows that EC starts to increase from mid fall to winter and decreases from spring to summer and shows almost identical values at all three sites throughout the study period.

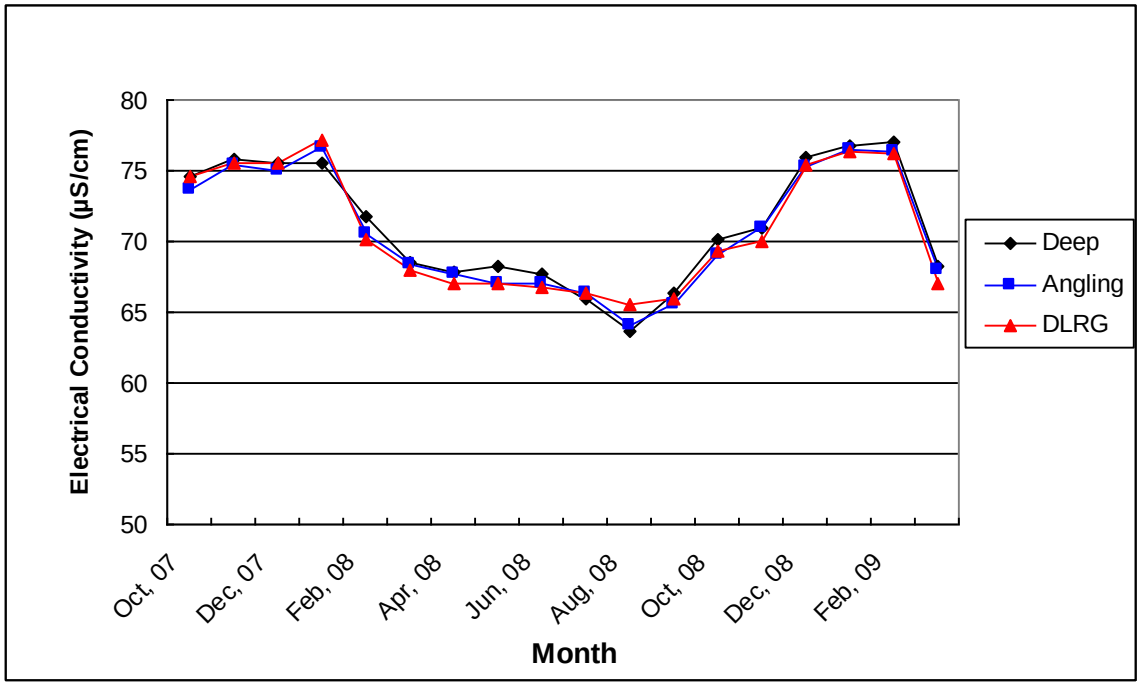

Fig. 16: Variability of Electrical Conductivity of water from three different locations (Deep, Angling and DLRG) of Silver Lake from October 2007 to March 2009

3.1.2 Physical parameters

3.1.2.1 pH-value

The pH-value of Silver Lake water ranged from 6.3 to 6.7 (Figure 17). Figure 17 shows that highest pH was measured during winter (6.7) at all three stations. While lowest pH values were recorded in summer at all three stations.

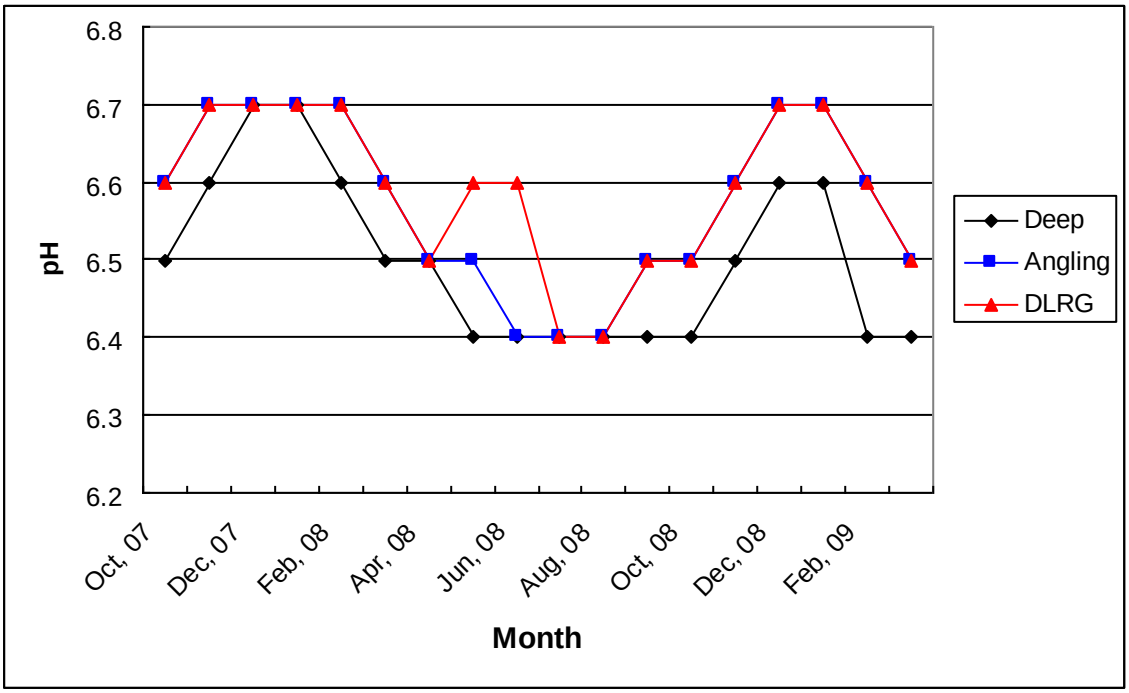

Fig. 17: Variability of the pH at three different locations (Deep, Angling and DLRG) of Silver Lake from October 2007 to March 2009.

3.1.2.2 Variability of oxygen

The upper water layer (about 1m depth) of Silver Lake was well saturated (101 to 104%) with dissolved oxygen around the year. A considerable depletion (0%) was observed at the deep water body (5 and 8 m) in summer (Fig. 18).

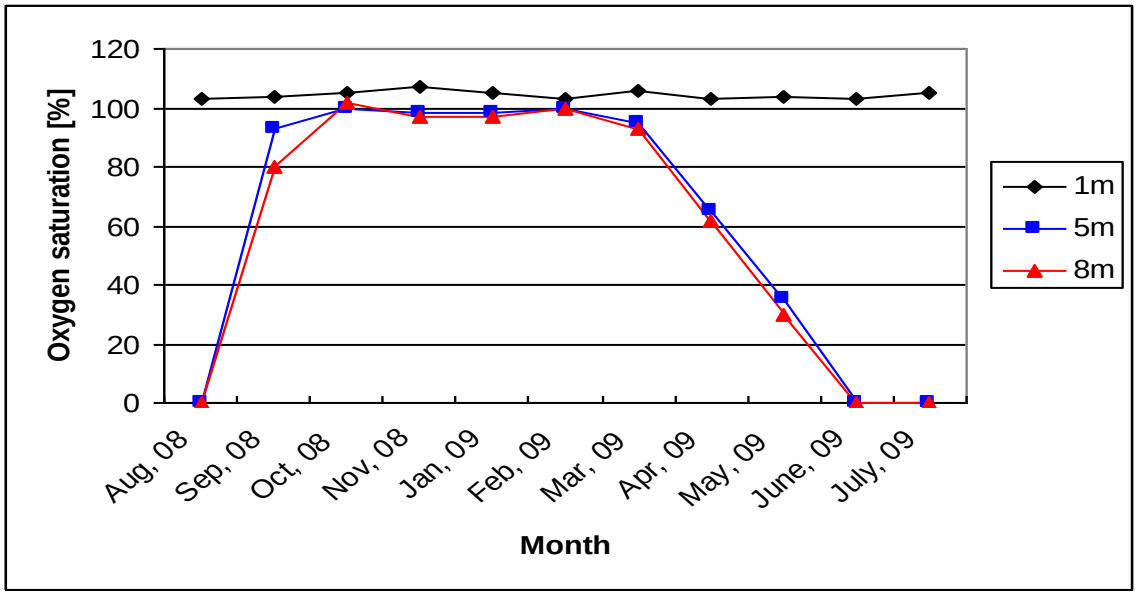

Fig. 18: Oxygen saturation [%] at three different depths of the water column (1, 5 and 8 m) of Silver Lake from August 2008 to July 2009.

3.1.2.3 Variability of temperature

Result on temperature variability show that water temperature was more or less stable (about 3°C) during the winter at all three depths (1, 5 and 8 m) of the water column (Fig. 19). During summer, temperature was ≥20°C in the epilimnion (measured at 1m depth, June 2009), the temperature of the hypolimnion (8m depth) varied between 7.5°C (June 2009) and 7.9°C (July 2009), respectively.

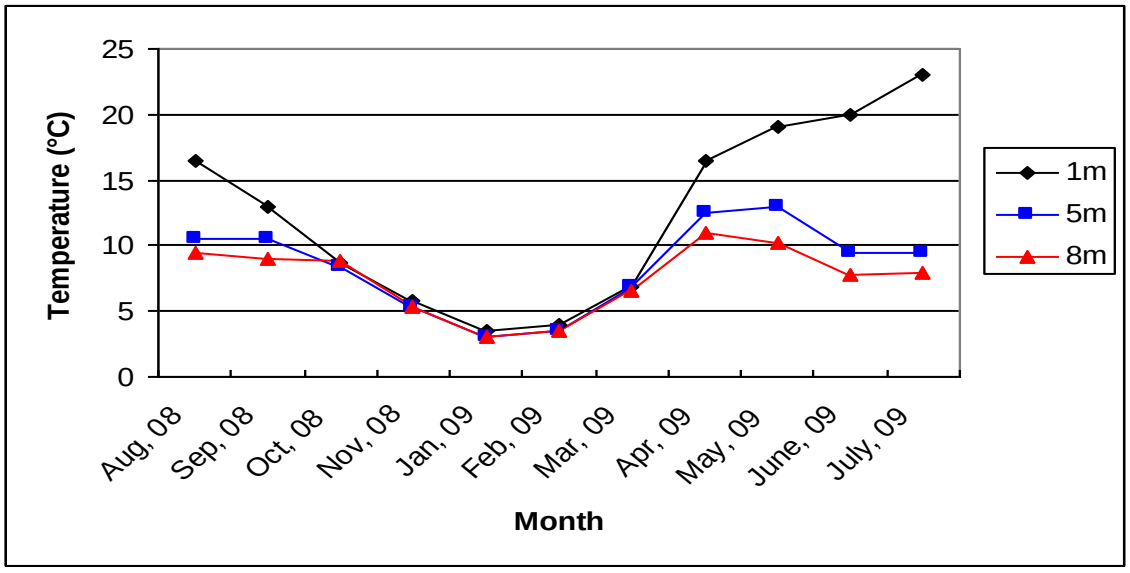

Fig. 19: Variability of water temperature at three different depths of the water column (1, 5 and 8 m) of Silver Lake from August 2008 to July 2009.

3.1.2.4 Water transparency

Secchi disk visibility depth ranged between 1.62 – 1.75 m in Silver Lake from September 2008 to July 2009 (Fig. 20). The maximum depth was measured in November 2008, while the minimum depth was recorded in June 2009. This indicates that water turbidity is higher in summer compared to winter months.

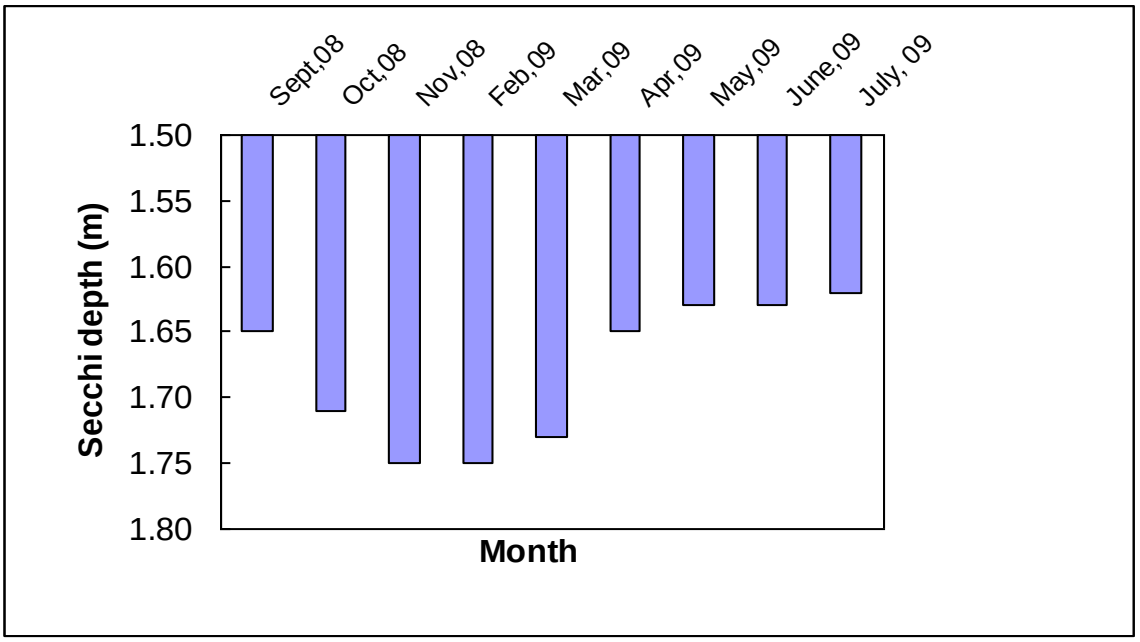

Fig. 20: Secchi disk depth and water transparency indicating the degradation of the light conditions in the Silver Lake from September 2008 to July 2009.

3.1.3 Hydrology

3.1.3.1 Fluctuations in water level

The water level increased by 14.5 cm from October 2008 to January 2009 (Fig. 21) and was highest from January (maximum) to March. It decreased from April 2009 to June 2009, and thus the lowest water level was recorded for the latter month (Fig. 21).

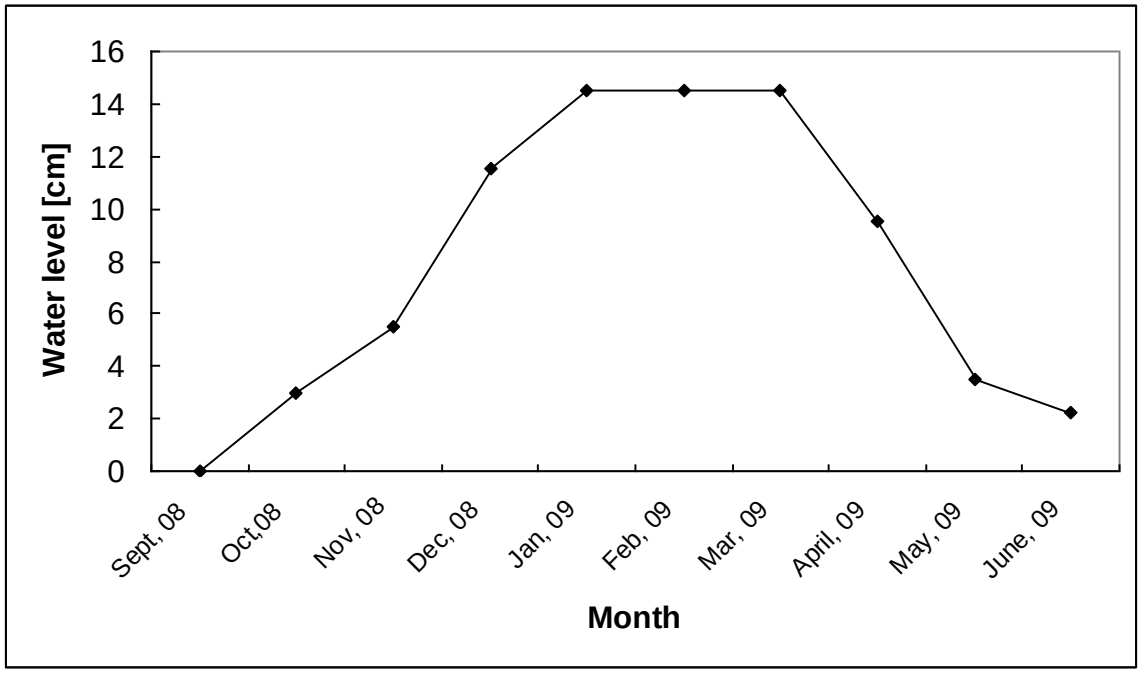

Fig. 21: Water level fluctuations in Silver Lake from October 2008 to June 2009.

3.2 Sediment chemistry

3.2.1 Carbon : nitrogen and nitrogen : phosphorus ratio

The highest C (20.442 – 26.599%), N (1.518 – 1.856%) and P (0.111 – 0.183%) contents of the lake sediment were observed at the bottom surface, which declined towards deeper horizons of the sediment (Table 1). For the sediment surface (0-10 cm) a C:N of 13.47 and a N:P ratio of 9.03 were measured, respectively. Both ratios increased gradually (≥15) to deeper horizons of the sediment (10-30 cm).

Table 1 Status of C:N, N:P ratio, $CaCO_3$ and % total minerals (burning) of Silver Lake collected from three different sites (P1, P2 and P3) and depths (A: 0-10, B: >10-20 and C >20-30 cm), for site locations refer to Figure 7. (note that the core of site P2 was only 20 cm, thus horizon C could not be taken).

Sampling site	%N	%C	%P	C:N ratio	N:P ratio	%$CaCO_3$	Total minerals (burned) [%]
P1A	1.616	24.342	0.111	15.06	14.56	12.847	47.338
P1B	0.857	14.219	0.055	16.59	15.58	6.820	71.362
P1C	0.309	06.535	0.017	21.17	18.16	2.573	82.961
P2A	1.856	26.599	0.183	14.33	10.14	9.407	44.235
P2B	0.977	16.893	0.076	17.28	12.86	6.522	66.055
P3A	1.518	20.442	0.168	13.47	9.03	11.513	55.261
P3B	1.111	17.072	0.121	15.37	9.17	7.183	64.185
P3C	0.207	03.188	0.019	15.39	10.90	2.142	91.083

3.2.2 Status of calcium carbonate

$CaCO_3$ concentrations of Silver Lake (Table 1) were highest (12.847, 9.407 and 11.513%) in the upper sediment horizon (0 -10 cm), values declined with depth to 6.802, 6.522 and 7.183% (>10-20 cm), and 2.142 – 2.573% (>20-30 cm), respectively.

3.2.3 Status of percentage of total minerals

Table 1 show that the percentage of total minerals was lowest in the upper sediment layer and increased with depth. The percentage of total minerals ranged from 44.24 to 55.26 in the surface sediment of the three sites. In the middle horizon and the lower horizon percentage of total minerals ranged between 64.19 and 71.36, and 82.96 to 91.08, respectively.

3.3 Primary plants

The shoreline vegetation was divided into nine plots from north-east near the DLRG station to the south-east of the angling pier. Except for plot no. nine, *Littorella uniflora* dominated at all plots across the shoreline. The area covered by *Littorella uniflora* was estimated to be approximately 262 m^2 (Table 2). This primary plant grew in water depths down to 40 cm. *Isoetes lacustris* was found in plot 7 and 9, on both sides of the angling pier; and counted a total 420 of individuals. This plant grows individually and was found at a depth range between 25 to 50 cm (Fig. 22). *Lobelia dortmanna* was completely absent from the observed area with presence of some other species e.g. *Carex rostrata, Eleocharis palustris, Hydrocotyle vulgaris* and *Lysimachia thyrsiflora* also *Menyanthes trifoliata*, *Potentilla palustris*, *Typha angustifolia.* This indicates a presence of other invasive plants and no longer a mere occurrence of *Littorella uniflora.* However, the boundary between the occurrences of *Littorella uniflora* and *Isoetes lacustris* is quite sharp; there is only a very narrow strip, in which both species occur together (Fig. 22). On the other side, *Littorella unifloria* and *Eleocharis paulistris*, *Isoetes lacustris* occur together with *Typha angustifolia*, the latter stock is sometimes very dense with no presence of *Isoetes lacustris*. The substrate of *Isoetes lacustris* is sandy-gravelly with single larger stones, in contrast to the more (silty-) sandy areas, where *Littorella unifloria* occurs (Fig. 22). There are many other plant species present in this lake, e.g. *Phragmites australis, Nuphar luteaum. Nymphaea alba, and Potamogeton* species. *Nymphaea alba* are very densely found in the north-west part of the lake.

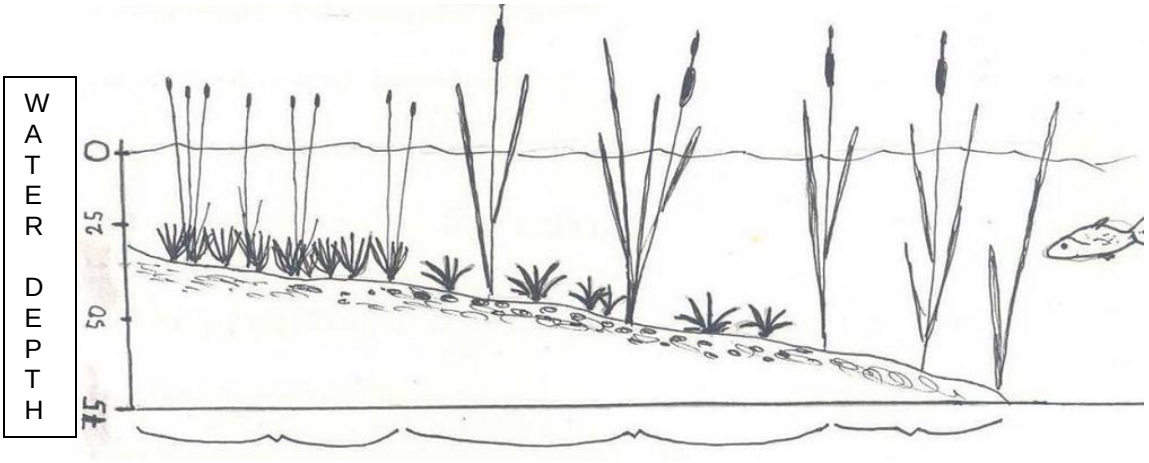

Fig. 22: Distribution pattern of vascular plants in Silver Lake (Buchwald and Hilbich 2008).

Table 2 List of vascular plants and mosses in Silver Lake (Buchwald and Hilbich 2008).

Experimental plot	1	2	3	4	5	6	7	8	9
Name of species									
Isoetes lacustris							x		X
Littorella uniflora	X	X	X	X	X	X	X	X	X
(area covered in m^2)	1	1	4.5	0.9	128	24	84	18	1
Agrostis canina	X								
Carex rostrata	X	X	X	X	X	X	X	X	X
Eleocharis palustris	X	X	X	X	X	X		X	X
Hydrocotyle vulgaris	X	X	X	X	X	X		X	
Juncus articulatus	X			X					
Juncus bulbosuss	X	X							
Juncus effusus	X			X					
Lycopus europaeus	X								
Lysimachia thyrsiflora	X	X	X		X	X		X	
Menyanthes trifoliata					X				
Myrica gale		X							
Potentila palustris	X			X	X			X	
Ranunculus flammula	X								
Sphagnum spp.			X						
Typha angustifolia				X	X		X		

Others, mainly outside the plots: *Phragmites australis, Nuphar luteaum. Nymphaea alba, Potamogeton* spp. and several mosses

3.4 Metabolic rate of *Anodonta cygnea*

3.4.1 Measurements of test bivalves

The size range of the measured test bivalves varied from 73 - 160 mm (Table 3). All animals were dissected after the respiration and ingestion experiments, respectively. Accordingly, shell length, shell height, shell dry mass, shell free dry mass (DM) and ash free dry mass (AFDM) were measured.

Table 3 Size and mass parameters of the animals for the respiration and ingestion measurements: N =15,

Animal ID	Shell length [mm]	Shell height [mm]	Shell dry mass [g]	Shell free dry mass [g]	Ash free dry mass [g]
1	96.	57	18.798	1.690	1.3589
2	98	59	21.978	1.470	1.1946
3	126	74	51.774	8.717	7.2230
4	147	80	71.318	6.443	5.8638
5	90	54	17.306	1.148	0.9208
6	149	92	92.80	14.626	13.3070
7	160	90	103.787	7.333	5.8472
8	145	83	81.213	8.736	7.9016
9	149	96	89.892	8.278	7.0844
10	95	59	24.943	2.124	1.8034
11	155	98	83.524	10.654	9.0865
12	124	73	61.285	7.599	6.2518
13	73	45	15.127	1.447	1.1843
14	88.5	56	21.306	2.046	1.7284
15	153	95	103.340	9.344	8.4632
Mean	123.233	74.067	52.226	6.110	5.2810

3.4.2 Size- mass relationship

Figure 23 indicates the logarithmic relationship of ash free dry mass against shell height of *Anodonta cygnea*. The regression line describes the following relationship: AFDM = -12.934*height$^{3.338}$, R^2 = 0.8594, indicating that AFDM is linearly related with height.

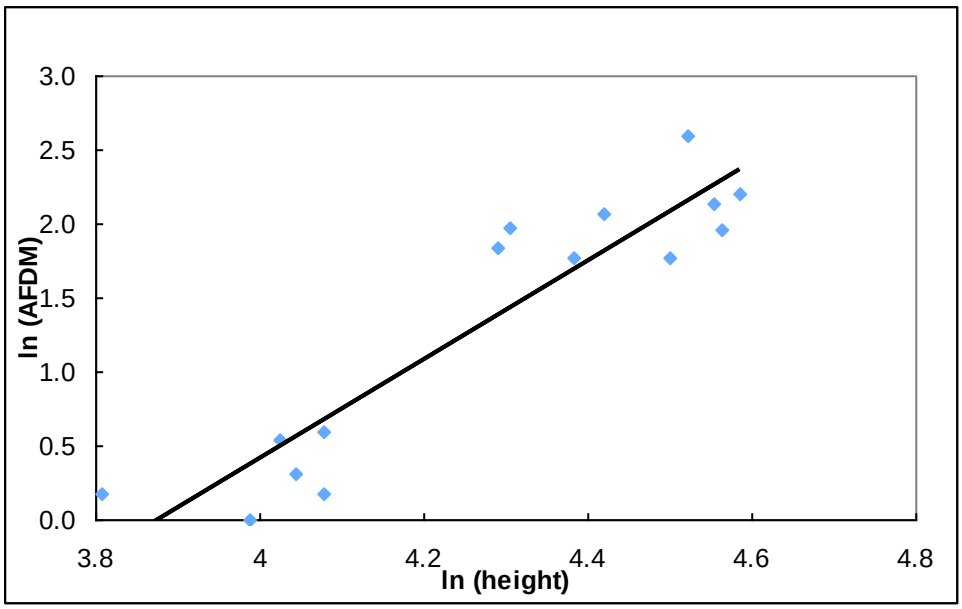

Fig. 23: Logarithmic relationship between the ash free dry mass (AFDM [g]) of the soft body and height [mm] of the Swan mussel *Anodonta cygnea*.

3.4.3 Whole animal metabolic (oxygen consumption) rate

Whole animals (N = 15) standard respiration rate was measured at 10°C. Figure 24 shows that oxygen consumption was 9.19 mg O_2 d^{-1} by animal no. 6 and shell free dry mass was 14.63 g. (Table 3). The lowest oxygen consumption was 3.03 mg O_2 d^{-1} by animal no. 13 and its shell free dry mass was 1.45 g. The average oxygen consumption was 3.07 mg O_2 d^{-1} (Fig. 24).

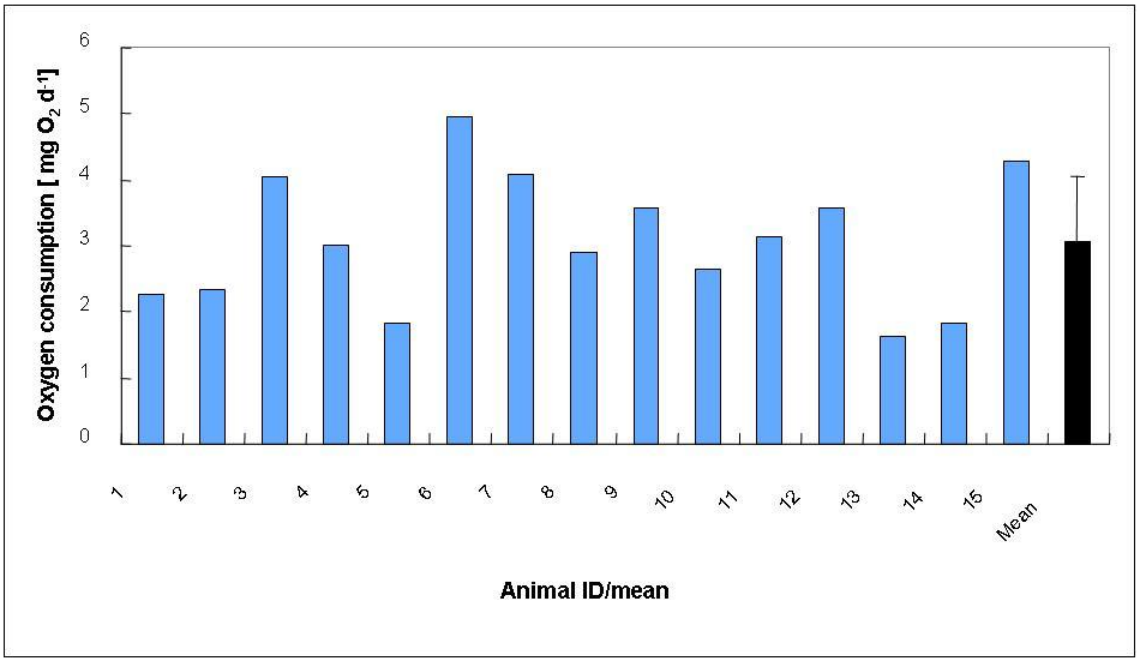

Fig. 24: Oxygen consumption rate (mg O_2 d^{-1}) of 15 *Anodonta cygnea* and their mean value at a temperature of 10°C. Bar is showing the standard deviation of the mean value.

3.5 Ingestion rates of *A. cygnea*

Ingestion rates of *Anodonta cygnea* were measured as an estimation of bivalve feeding. The bivalves clearly depressed phytoplankton concentrations in the experimental chambers compared to the control chamber (Fig. 25). Maximum and minimum ingestion rates of the Swan mussels were recorded as 0.0067 and 0.0046 µg Chl-*a* g $DM^{-1}min^{-1}$, respectively; and average ingestion rate was 0.0054 µg Chl-*a* g $DM^{-1}min^{-1}$. Average dry mass (N = 15) of *Anodonta cygnea* was recorded as 6.11 g (Table 3). So, mean individual ingestion rate of a standard individual was estimated to be 47.5 µg Chl-*a* $ind^{-1}d^{-1}$.

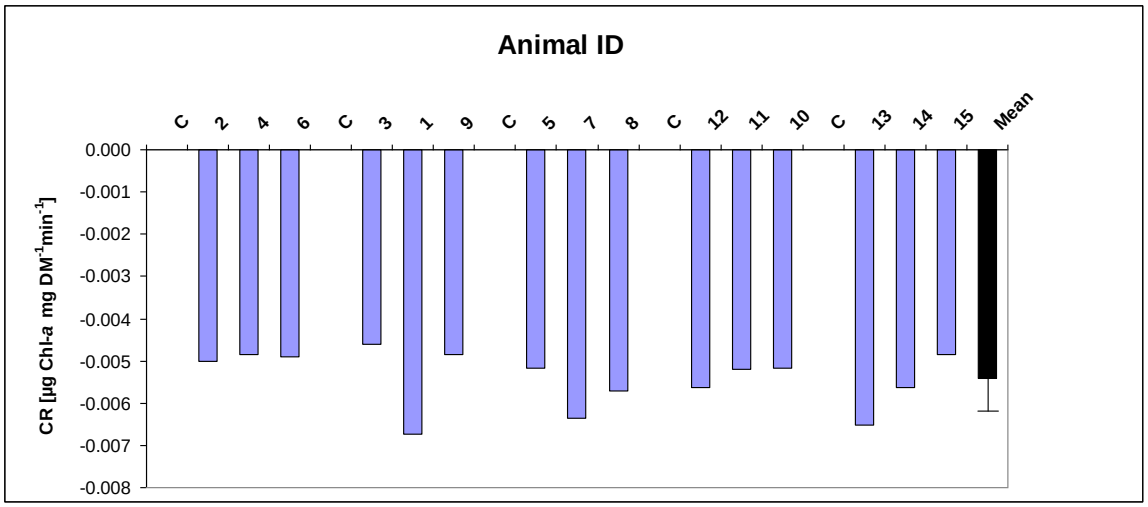

Fig. 25: Clearance rate (CR) (µg Chl-*a* mg $DM^{-1}min^{-1}$) of *Anodonta cygnea* at a temperature of 10°C (N = 15). Bar is showing the standard deviation of the mean value.

4 Discussions

The present research assessed physic-chemical and biological conditions of a typical central to western European, originally oligotropic lake, namely Silver Lake east of Bremerhaven. Based on existing data, this study clearly points that Silver Lake has changed its typical characteristics from an almost steady oligotrophic state towards an eutropicated phase. However, long term detailed investigations concerning the typical lake water regime are scarce (Herbichowa 1979, Dierssen 1981). First, for a better understanding of the lake processes, it is recommended to measure also the surface water qualities from the deep site to find out, whether there are influences of the shore plant belts on the local values (which sometimes seem to indicate low water nutrient conditions). The results of this study can be further helpful to restore the typical northern Germany lake

ecosystems. In the following I will discuss the feasibility of the restoration of Silver Lake with respect to specific questions.

4.1 What is the present feature of the physico-chemical factors of Silver Lake?

Taking into account the depth range up to 8 m, a considerable variation in temperature as well as oxygen content was observed for Silver Lake due to the summer stratification from June to August (Fig. 18 and 19, see also Buchwald and Hilbich. 2008). Only the warm top layer circulates, and it does not mix with the more viscous colder water, creating a transition zone called thermocline (Odum 1971). Hence, in depths downward from 4 m the lake becomes anoxic (Fig. 18) during summer, which supports also the results obtained by Buchwald and Hilbich 2008 and Rachor in earlier years (pers. comm.). During winter low water temperature and reduced light result in low photosynthesis; and the accumulated and regenerated nutrients remain unused (e.g. Odum 1971, Gupta and Gupta 2006). Therefore electrical conductivity tended to increase in winter (Fig. 16) compared with summer (Buchwald and Rath 2007). Increased conductivity is a result of high ionic concentrations, and decreased conductivity is mainly a result of low ionic concentrations in the water. In summer, a considerably higher amount of turbidity recorded in the lake water body may be allocated to a certain extent to the phytoplankton abundance. Accordingly, in this study, Secchi depth visibility (Fig. 20) showed a considerable decrease on a yearly cycle, which is in good agreement with the result obtained by Rachor (1998) in the nearby Lake Wollingst. The author found a gradual degradation of

the light condition from 1932 (about 4.5 m) to 1998 (1.5 m) Secchi depth for the similar lake type.

4.2 What are the major factors influencing eutrophication of Silver Lake?

Dissolved nitrogen and phosphorous levels frequently exceed the reported limiting values for an oligotrophic lake type (Fig. 12 and 13). The concentration of these nutrients tends to be higher in winter resulting from the eutrophication processes in summer and a general weak pH (e.g. Dierssen 1981). The relative concentrations of nutrients (N and P) in aquatic systems have been suggested to control primary producer community structure and biomass (e.g., Smith 1986, McCauley et al. 1989, Elser et al. 1990, Downing and McCauley 1992, Urabe 1993). Algae typically grow well at N : P-rates near 16 : 1 (Redfield 1958). N and P values of harvested algal biomass are within the range of 6–9% and 1–2%, respectively, of nutrient-rich freshwater (Adey and Loveland 1998). Absence of NO_3-N in the deep station in summer (Fig. 15) is well explained by the fact that during the summer, surface water becomes warmer than the bottom water. As a result a thermocline with a steep temperature gradient is created; and O_2 cannot enter into the deep water. Therefore, O_2 is depleted and denitrification starts; and NO_3-N is converted to N_2O, NO and finally N_2 gas or NH_4. But; in winter NO_3-N is higher than in summer because stratification is eroded in the late autumn time by cooling, strong wind and rainfall. On the other hand, in shallow areas such as at the angling pier or the DLRG station, NO_3-N concentration is much higher in summer than at the deep station due to the presence of O_2.

The C:N and N:P ratios found increasing with increasing sediment depths (Table 1) can be an outcome of nutrient load from the dead phytoplankton. Fresh

organic matter always deposits in the upper layer of the sediment, decomposes and mineralization of organic matter with organic nitrogen takes place; the soil microorganisms consume the mineralized nitrogen for their sustenance (Sharma and Biswas 2006). So, the share of nitrogen is higher in the upper layer and as a result C:N and N:P rations are low in the upper layer of the sediment. On the other hand humus materials with increased C shares increase with sediment depth, and the percentage of nitrogen is relatively low in deeper sediment layers. The increase in the C:N ratio with increasing depth is expected because of bacterial preference for degradation of N-rich compounds (Fenchel et al. 1998). In line, newly deposited sediment contains easily degradable material from algae and has a C:N ratio of 6–8 (Meyers and Ishiwatari 1993, Meyers and Teranes 2001, Talbot 2001), and when this material is degraded, the relative influence of more resistant terrestrial and decomposed material with a higher ratio becomes larger, leading to a higher C:N ratio of the sediment with depth.

4.3 What is the current status of the plants of Silver Lake?

Concerning the nutrient level, the originally oligotrophic Silver Lake was characterized by the indicator plant community of Littorelletea species (*Isoetes lacustris*, *Littorella uniflora, Lobelia dortmanna*), adapted to the litoral habitat. Some of them need a terrestrial phase to fulfill their full generative cycle (*Littorella uniflora*). *Lobelia dortmanna* are reported to set flowers and fruits mainly in a submerged status (Dierssen 1981). But, this species has already disappeared from Silver Lake, presumably caused by the pressure of the reed swamp species, of benthic algae as well as by the turbidity load during the eutrophication (E. Rachor, pers. comm.) and by overgrowing *Sphagnum*-species

across the littoral areas of the lake (own investigation). Under these influences *Isoetes lacustris* suffers, too. It is to be expected that this last occurrence of *Isoetes lacustris* in Lower Saxonia will vanish, if no deep-water (1-3 m) sub-populations can be re-established in the near future (E. Rachor, pers. comm.). The study confirms the presence of a considerable number of “new plant associations” (Table 2) that may be adapted to the present higher nutrient level of the lake and succeed in the course of eutropication, whereas the above mentioned indicator species are gradually decreasing (Buchwald and Hilbich 2008, Rachor 1998). It is also reported that the numbers of isoetids decreased drastically; and the abundances of species inhabiting eutrophic environments increased in many lakes in the last century (B. Van Geel, pers. comm.). Eutrophication and the decline of isoetid species of similar lake types in Germany and the Netherlands were observed in the last century (Schoff-Van Pelt 1973, Westhoff 1979, Wittig 1982, Arts 1990).

The result also point towards the changes of the hydrodynamic (e.g. seasonal water level, Fig. 21) and unfavourable conditions (temperature, light, nutrients) for the germination and seedlings of the indicator plant species (e.g. Wittig 1982, Schoff-Van Pelt 1973).

4.4 Does the filter-feeding effect of A. cygnea enable to shift the eutrophication status of Silver Lake?

The filter feeding Swan mussel ("Teichmuschel") *Anodonta cygnea* (L.) inhabits large ponds, lakes and slow moving waters, such as canals and (small) rivers with muddy bottoms. Its distribution is limited down to 10 m depth. Highest abundances (> 10 ind./m^2) are common between 2.5 and 6 m depth in southern Germany (Patzner et al. 1993). Taking in account its ecology and biological requirements, the average (mean) oxygen consumption of this bivalve as measured during this study is 3.071 mg d^{-1} at 10°C (Fig. 24) (Mean shell length 123.2 mm and shell free dry mass 6.1 g, Table 3). But, it should be noted that this bivalve can tolerate a wide range of temperatures and oxygen conditions (Müller and Patzner 1996). Therefore, in terms of temperature and other physical factors, which influence the average oxygen requirement of this bivalve, the current in vitro experiments (Fig. 24) may be easily used in the Silver Lake. *A. cygnea* prefers nutrient rich waters and is one of the most common freshwater bivalve species widespread across central Europe and the United Kingdom. They burrow into the substrate, normally with just the siphon tips exposed to filter particles from the water (Müller and Patzner 1996). The results of this study show that *A. cygnea* cannot ingest a significant amount of Chl-*a* (47.5 µg $ind^{-1}d^{-1}$) compared to the lake conditions. Here I want to show a rough calculation that is shown in Table 4.

Table 4 Rough calculation of Chl-*a* content of Silver Lake (Total water surface area = 6.3 ha)

Criteria	Average depth	Area covered [ha]	Volume [m^3]	Total volume (i +ii) m^3	Average conc. of Chl-*a* [mg/m^3]	Total Chl-*a* present in Silver Lake [g]
i) From shore to 3m depth	1.5m	2.0	30000	159000	14.3	2273.7
ii) From 3m depth to rest	3.0m	4.3	129000			

Total volume of the lake surface water down to 3 m depth is 159000 m^3 (Area from shore to 3 m depth is 2 ha and assuming that average depth is 1.5 m (<30.000 m^3), area of the rest part of the lake is 4.3 ha and assuming that phytoplankton can grow down to 3 m depth, so, the total volume is 30000 m^3 + 129000 m^3 = 159000 m^3). Wetzel (1983) shows that the average concentration of Chl-*a* in an eutrophicatic lake is 14.3 mg/m^3. So, total Chl-*a* present in Silver Lake surface water may be 2273.7 g. If we release 5000 *A. cygnea* then they can ingest 42.75 g Chl-*a* during 6 month. So they can ingest only 1.88% of the total Chl-*a* present in Silver Lake, which is not a significant amount. Therefore the study presumes that the filter feeding effects have not the sufficient potential for reducing the relatively high nutrient load under the present conditions.

4.5 Conclusions and proposals for restoration actions

From the discussion of water qualities, nutrient loading to the habitat, and the environmental conditions observed, the eutrophication apparently arise from a variety of natural and anthropogenic influences. Presumably the information

presented here suggests that some restoration of the naturally oligotrophic lake with its typical relict plant species can be achieved if it is managed in a well integrated system. That includes man awareness and biological methods to reduce the undesired nutrient load of the lake.

Direct precipitation, surface and plant evaporation are the principal source and loss of lake water respectively. There is no direct strong inflow to the lake. Thus, water level increases during the winter season and decreases during the summer season. The main external sources of nutrients to the lake may be surface runoff from the adjacent agricultural land, holiday lodging area and the surrounding area of the lake and inputs via the atmosphere. The lake and its surrounding area is a nature reserve, but still now it's used for holiday lodging, bathing and angling. Such kind of activities increases the nutrient concentrations and also disturbs the habitats of Littorelletea communities in the shallow area.

At the end of summer, leaves from trees from embankments add few nutrients by decomposition. According to the present results it is clear that the nutrient concentration has been increasing in Silver Lake. It's also clear that nitrogen and phosphorus concentrations are above the limits for an oligotrophic lake. As a result, the light dependent *Isoetes lacustris* and *Littorella uniflora* are declining, which are much endangered species in Germany. *Typha spp.* grow very densely in many sections of the shore and outcompete *Isoetes lacustris*. The present study concludes that despite the nutrient load and apparently eutrophicated water, however, it is still possible to measure the detailed eclological end biological conditions and further restore the lake as natural conservator to save the traditional ecosystem. To manage a good water

condition for a typical northern German lake, the proposals for restoration actions are as follows (not further considering the use of *Anodonta cygnea*):

Pumping/sucking sediment

Carbon and nutrient contents are higher in the deep area, and accumulated sediment thickness including nutrients tends to increase in Silver Lake. Removal of accumulated sediments and nutrients from the lake bottom can increase the depth by taking out the sediment with a suction pipe (or dredging) and at the same time remove nutrients. This may also influence rooted aquatic vegetation, deepen the water body, increase the lake volume and improve the water quality, and reduce and control especially phosphorus levels in the contaminated sediments.

Harvest macrophyte populations

Harvesting specific macrophyte populations from/around the lake, e.g *Typha angustifolia, Nuphar luteaum, Phragmites australis, Potamogeton spp., Nymphaea alba* and others may be a choice. *Typha angustifolia* is very abundant in the north-east to south-east part of Silver Lake. Its roots and rhizomes take up nutrients from the surrounding area and store them. When their roots decompose they also increase the nutrient level in the lake again. It is suggested to remove them and other species like *Nuphar luteaum*, *Phragmites australis* and *Nymphaea alba* with their roots in late summer; this will reduce the internal productivity of the water body and remove phosphorus that is stored in the plant.

Need to be aware of bathing and holiday logging people

Every summer bathing and holiday logging people come for recreation. They also increase the nutrient level in the lake in the following ways

- through excess food and any other organic waste materials into the lake,
- cleaning of the skin in the water,
- urine (from children) can add ammonia etc. in the lake system,
- destruction of plants.

So it is essential to setup some regulations concerning the awareness for bathing and holiday people on a bill board, e.g., not to throw food or waste materials into the lake and not to destroy littoral plants

Need to be aware of angling people

Angling people release different fish of fingerling size such as pike, (*Esox lucius* "Hecht"), pike-perch, (*Lucioperca sandra,* "Zander"), perch, (*Perca fluviatilis, "*Barsch"), Carps (*Cyprinus carpio,* "Karpfen") etc. in the lake every year. Among them pike, pike-perch and perch are top predators. They feed other fish, which consume zooplankton. Thus zooplankton may increase and better control the phytoplankton, Carps are polyphagous and they feed or at least destroy *Littorella uniflora, Isoetes lacustris* from the shore area. Anglers import excess food for fish bait.

Thus, the Silver Lake authority is suggested to set up the following rules and regulations of the angling people:

- allow to release some selected fingerlings such as pike, pike-perch and perch but not allow to release carps

- not allow to throw excess fish food into the lake
- to prohibit to damage the vegetation e.g. by trampling or rowing boat

Hypolimnic aeration

Oxygen (or air) may be pumped into the deep water (oxygen depleted layers) during summer to maintain oxygen in this layer to limit phosphorus release from sediments and generally improve the water conditions. A windmill or photovoltaic elements may be used to drive the pump.

Decidious trees and plant materials

To cut down the decidious trees from most of the bank area and remove live and dead material from the water edge. When leaves and other plant materials decompose, they also add nutrients into the lake.

Controlling fertilizer use

Farmers may use high doses of fertilizer and pesticides on their land, which is almost adjacent to the lake. So, it is recommended to control the fertilizer and pesticides use by the farmers up to 150 m from the lake. The authority may need to pay them a compensation for not use or reduce fertilizers.

Finally, it is recommended to continue and expand the research on the Lake e.g. to better understand water renewal, the influences of littoral plants on the nutrient cycling, the competitive role of algae as well as the overgrowth , possible dystrophication effects from the adjacent raised bog, role of top predator fish on the nutrient regime.

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