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Long-term plankton studies at the lower Rhine/Germany

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Abstract

The river Rhine has lain under considerable anthropogenic stress of its water quality for 100 years. As early as 1905 the first results of studies of the plankton in the Rhine were published. Due to the long residence time of the water a real potamoplankton can develop and at the end of the Lower Rhine it reaches its highest density. The paper consists of two parts. At first an overview is given about the history of plankton studies in the Rhine. The second part is the presentation of results from a monitoring at the Lower Rhine from 1979 to 2004.

First systematic studies started at the beginning of the 20th century at the beginning of pollution. Our studies started during a phase of recreation from extreme pollution and eutrophication. Samples were taken at four stations: Bad Honnef, km 640, entrance to North Rhine-Westphalia, Düsseldorf, km 732, Duisburg, km 792 downstream large industrial effluents and big cities, Kleve-Bimmen, km 865 at the border to the Netherlands.

In the 1970s nutrients were high, especially phosphate 0.65 mg PO_4-P L^{-1} in 1979. After 1980 phosphate dropped to 0.11 mg PO_4-P L^{-1} in 2004 (mean values of the growing season). Ammonia was reduced from about 0.52 (1979) to 0.02 (2004) mg NH_4-N L^{-1}. Nitrate remained between 3.72 (1989) and 2.26 (2004) mg NO_3-N L^{-1} at a relatively high level. Oxygen concentrations were very low during the 1960s and 1970s, sometimes only 4 mg L^{-1} O_2. During our studies the oxygen increased up to 9 mg L^{-1} O_2 with a tendency to 11 mg L^{-1} O_2 in the last years. Chlorophyll *a* was estimated to be between 59 (1979) and 31 μg L^{-1} (1986) with short peaks up to 170 μg L^{-1} (1989). Since 1992 the mean values have varied between 30 (1993) and 21 μg L^{-1} (2004).

The floristic phytoplankton composition is characterised by the dominance of the centric diatom *Stephanodiscus hantzschii*. Other diatoms like *Skeletonema subsalsum*, *Skeletonema potamos* and *Asterionella formosa* were regularly present in smaller quantities. The second dominant group was coccale green algae. During the 1980s they formed up to 35% of the biomass. Since the 1990s their contribution to the phytoplankton became much smaller. This change corresponds with the increase of wastewater treatment and the diminution of nutrients. All the other groups of algae were present in minor quantities. During the time of higher trophy in the 1970s and 1980s the phytoplankton formed two peaks, in recent years only one peak has developed, depending on different flow conditions during the growing season and lower trophic state in the upstream parts of the river.

Excellent correspondence exists between cell number, biovolume and chlorophyll *a* content and the results of delayed fluorescence (DF) measurement. The trophic status in the Lower Rhine may be estimated as (moderate)

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eutrophic. The ecological status of the phytoplankton is good based on the requirements of the European Water Framework Directive (WFD).

The zooplankton consists mainly of rotatoria and larvs of *Dreissena polymorpha*. Grazing on phytoplankton seems to be mainly due to the large quantities of benthic *Dreissena* and the newly introduced mussel *Corbicula*.

Keywords: Large rivers; Rhine; Plankton; Potamoplankton; Phytoplankton; Ecology of large rivers; Assessment

Introduction

The River Rhine is a large river of outstanding importance in Europe. It can be subdivided into several parts, see Fig. 1. At the border of North Rhine-Westphalia, at km 640 from Constance, the Rhine enters the lowland. This 225.5 km long reach downstream is called the Lower Rhine and ends at the border to the Netherlands (km 865.5).

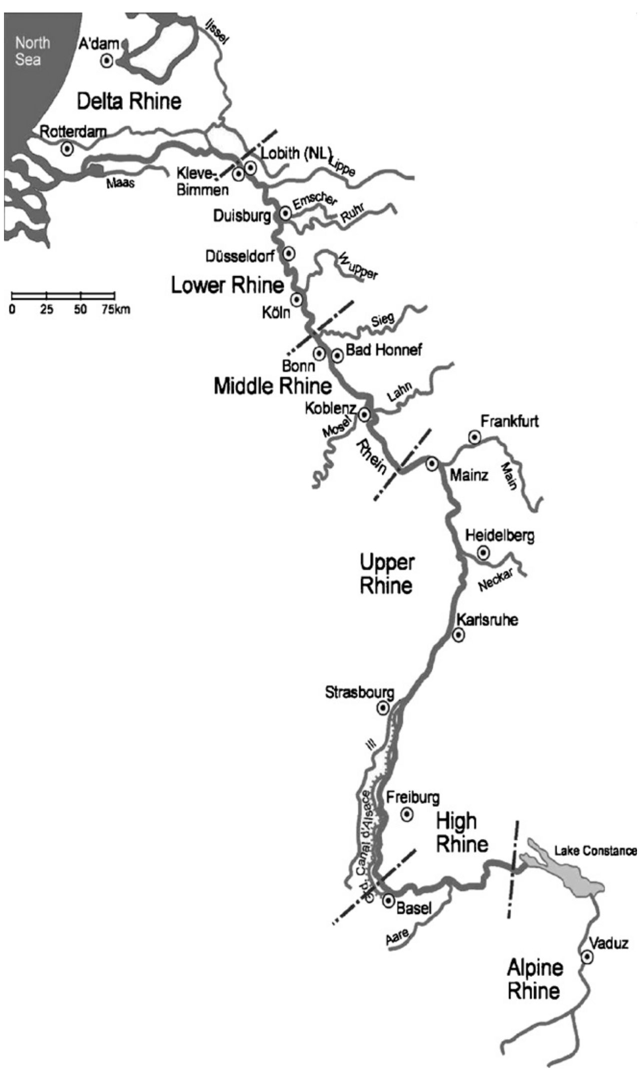

Fig. 1. Map of the Rhine catchment area.

The scientific investigation of the river already started 100 years ago by Lauterborn (1905, 1907–1911, 1910), Kolkwitz (1912) and Marsson (1907–1912). More surveys followed over time until the late 1960s, see later in this paper. Even at the beginning of the 20th century many reaches of the river were polluted because of point sources downstream cities and industries. With respect to the length, size and situation in the centre of Europe, the Rhine is used for water supply for the population, industry and agriculture. It receives huge quantities of sewage, heated effluents, water from coal and salt mines with high concentrations of chloride, and pollution by non-point sources especially from agriculture from Germany, Switzerland, France and the Netherlands. Besides this the River Rhine is a waterway of outstanding importance.

The pollution of the water increased with the highest intensity at the end of the 1960s. Since the 1970s the treatment of wastewater has increased and now nearly all is treated. But problems arise from the risk of accidental pollution, intensive shipping and non-point sources.

The Rhine and especially the Lower Rhine have come under intensive monitoring since the end of the 1960s of the 20th century because of its outstanding importance for the state North Rine Westfalia and with respect to the Netherlands.

The intensive monitoring programmes include physico-chemical parameters, organic micro pollutants, heavy metals, temperature, ecotoxicological tests, macrozoobenthos and plankton. The qualitative and quantitative monitoring of plankton in the Lower Rhine was introduced especially for controlling eutrophication, toxicity, possible effects of heated effluents and finally to observe biological changes. This paper gives in a first part an overview about the historical investigations and presents in a second part the findings of our own data from 1979 to 2004.

History of phytoplankton research of the Lower Rhine up to 1978

The development of phytoplankton in the Rhine starts with the outflow from Lake Constance and the Aare River. In the High Rhine and Upper Rhine plankton develops slowly, fed especially through the contributions of the dammed Neckar and Grand Canal d'Alsace. Significant contributions come as well from the dammed rivers Main and especially Mosel with high concentrations of plankton. In the 225.5 km long reach of the Lower Rhine (km 640–865.5) the plankton is able to increase significantly due to a residence time of 2–3 days depending on the flow. At the monitoring station in Kleve-Bimmen, later referred to as Bimmen, the phytoplankton reaches its highest concentration. Downstream in the Netherlands the Delta Rhine begins. Therefore the station Bimmen is very important with respect to the plankton.

The oldest known samples of planktonic and benthic algae from the Rhine are diatoms, taken by Christian Gottfried Ehrenberg near Cologne from 1852–1855. They are stored in the Berlin Museum of Natural History and were examined by Hofmann (2004). According to her results already in the middle of the 19th century the benthic diatoms indicated at several stations point sources of organic pollution, whereas the plankton indicated a low level of trophy. The dominant algae were centric diatoms: *Cyclotella pseudostelligera* (77.7%), *Cyclostephanos invisitatus* (42%) and *Stephanodiscus minutulus* (40.4%). Besides them Hofmann counted *Stephanodiscus hantzschii* (11%), *Cyclostephanos dubius* (6%) and *Cylotella meneghiniana* (1.2%). Rare species were *Asterionella formosa* (0.7%), *Fragilaria crotonensis* (1.0%), *Tabellaria flocculosa* (0.2%), forms of *Fragilaria ulna* and *Fragilaria arcus* less than 1%.

The oldest investigations of the whole Rhine were carried out at the beginning of the 20th century by Kolkwitz, Lauterborn and Marsson (l. c.). They observed polluting effluents from cities and the rapidly growing industry. A part of the significant changes downstream of cities and industrial effluents was mass development of *Sphaerotilus natans* Kütz. In general, the plankton was sparse and in the upper reaches of the Rhine influenced by that of Lake Constance and Swiss lakes. Diatoms and Chrysophyceae were dominant, coccale green algae were found only in small numbers of species. It is conspicuous that small Chrysophyceae and small centric diatoms were hardly noticed. Dominant diatoms were pennate forms. Centric diatoms were determined mainly to genus level, except *Cyclotella* (*C. bodanica*, *C. comta* and *C. meneghiniana*). *T. flocculosa* already decreased in frequency during the first decade of the 20th century and was no longer recognized by Kolkwitz (1912). Frequent species were especially *Tabellaria fenestrata*, *F. crotonensis* and *A. formosa*, *Cyclotella* species, especially *C. comta*, *C. meneghiniana* and taxa of the *Stephanodiscus* complex, *Aulacoseira* spp., *Melosira varians* and many varieties of the *F. ulna* complex could be found besides them. *Dinobryon* was the most frequent genus of the Chrysophyceae, and from the Dinophyceae *Peridinium* spp. and *Ceratium hirundinella* were frequently detected. Compared with the recent plankton the early authors mentioned only a low number of coccale green algae. *Pediastrum*, *Scenedesmus*, *Actinastrum hantzschii*, *Schroederia setigera* and *Ankistrodesmus* spp. were found regularly. The situation described here is related to the results in the Upper and Middle Rhine down to Mainz, but it can be assumed that the composition of algae in the Lower Rhine plankton was more or less the same downstream because at that time eutrophication and damming of the Neckar and Mosel did not yet exist. This was confirmed e.g. by the studies of Seeler (1936). Particularly significant was the regular presence of *Planktothrix rubescens* and *Planktothrix agardhii*. These blue green algae were introduced from Swiss lakes with the initial eutrophication in the lakes. The number of cells was low ($<100\,\mathrm{m\,L^{-1}}$ found in 1 mm counting chambers). In 1931 Leendertz collected handnet samples of diatoms in the Lower Rhine near Bonn and Grietherort (near Bimmen). This material was determined for the first time by M. Pohlmann, see Appendix Table A1.

The list of the planktonic diatoms is in relatively good accordance with the findings in our survey, especially with respect to the centric diatoms.

Seeler (1936) started a sampling in September 1933 from Strasbourg down to the North Sea at a low water level. He determined living samples and was able to subdivide the plankton in the Rhine into three sections:

- The first section was the stretch from Strasbourg to Mainz with low cell numbers $<1000\,\mathrm{cells\,m\,L^{-1}}$. Seeler estimated an inhibition of phytoplankton growth because of the wastewater from the Mannheim region.
- The second section was the stretch from Mainz down to the brackish water in the delta with "lively development of phytoplankton" and cell numbers between 2000 and 4000 $\mathrm{cells\,mL^{-1}}$. At that time the influence of the river Main was bigger than that of the free-flowing Mosel. In the Lower Rhine reach Seeler found distinctive differences in plankton growth at both sides of the river due to the different polluting effluents and the long mixing zones. Therefore, in the middle of the river the influence of wastewater was much lower. This situation is one of the permanent characteristics of the Lower Rhine. And Seeler determined that industrial wastewater had a stronger and longer lasting inhibiting effect on the phytoplankton compared with that of domestic wastewater. Downstream in the reach of self-purification in the Netherlands higher cell numbers could be found, up to 6000 $\mathrm{cells\,mL^{-1}}$.
- The third section was found in the delta region, the brackish water zone with dying plankton.

The floristic composition in the freshwater part had not changed significantly since the earlier studies at the beginning of the 20th century.

In October 1953 Benisch (1954) performed a survey in the Lower Rhine. He had major problems investigating the plankton because of heavy water pollution by suspended particles from coal mining, ashes and flocks of *S. natans*. He could not count his samples because of large quantities of suspended inorganic particles from industrial effluents. However he did publish a list of organisms. As the most frequent typical planktonic algae he found *A. formosa* and *F. crotonensis*, frequent were *Microcystis*, *Closterium* spp., *Pandorina morum*, *Scenedesmus* spp., *Pediastrum* spp. Rare algae were *C. hirundinella*, *Dinobryon sertularia, Nitzschia actinastroides*, *T. fenestrata*, *Staurastrum* spp. and *A. hantzschii.* Benisch did not mention *Stephanodiscus*, but he mentioned*Cyclotella* spp., which is not mentioned by Kammel (1960). He frequently estimated sulphur bacteria, especially *Beggiatoa alba* (Vaucher) Trevisan.

In 1958 Czernin-Chudenitz published an extensive literature study and the results of a survey performed in November 1955 and March 1956. At first he estimated the halophilic diatom *Entomoneis paludosa* (W. Smith) Reimer from the river Mosel, which may be found exceptionally in the Lower Rhine, where it may also be introduced from the river Lippe with its high concentrations of chloride because of coal mining effluents. Leendertz (1931) first described *Thalassiosira weissflogii* together with a single specimen of *Thalassiosira bramaputrae* from the Lower Rhine which may be found nowadays as well.

According to the findings of Czernin-Chudenitz (1958) *S. hantzschii* was the dominant species in the plankton in the Middle Rhine and downstream. At a higher intensity he found the influence of water pollution including significant inhibitions of the phytoplankton, which could develop even after a significant reach of self-purification. His list includes many species and varieties. But sampling took place outside the growing season. He described *A. formosa*, *T. fenestrata*, *S. hantzschii*, as well as *T. bramaputrae*, *C. meneghiniana* and *Nitzschia acicularis*, as the most significant species (“Leading species”) of the Rhine. *Skeletonema potamos* and *Skeletonema subsalsum* were not mentioned. Within the Chlorophyceae he detected *A. hantzschii* and *Ankistrodesmus* spp. as frequent species everywhere. From the blue green algae he frequently found *Planktothrix rubescens* together with *P. agardhii.* Flagellates tolerant against organic pollution form a long part of his list. He mentioned *Phacus suecica* and *Selenochloris* sp. as typical species. *S. natans* was dominant everywhere in the Rhine. This wastewater bacterium formed large floating flakes together with dense stands at the stones of the banks, visible with the naked eye. It was a situation in the time of high water pollution which increased more and more until the middle of the 1970s in the 20th century. Generally the biological structure of the Rhine still existed, but to a great extent was overloaded by the effects of pollution with deserted reaches. Severe inhibitions of phytoplankton activity were measured by Knöpp as well (1968).

More or less at the time of the Czernin-Chudenitz survey, Kammel (1960) published a study about the plankton of the Lower Rhine at Cologne from 1955 to 1957, with more taxonomic emphasis to the heterotrophic taxa. The overwhelming portion of biota was phytoplankton, especially diatoms. During the spring peak in 1955 he found 2272 cells $m L^{-1}$, 1077 $m L^{-1}$ in 1956, and 3623 $m L^{-1}$ in 1957. Dominance of diatoms was about 99% of the total phytoplankton. The share of zooplankton (flagellates, ciliates and rotatoria) was between 2% and 6% of the total biomass with dominating flagellates, which reached 36–72% of total heterotrophic biomass. As most frequent diatoms Kammel (l. c.) recognized *F. crotonensis* together with *A. formosa* and *T. fenestrata*, with a peak in springtime (May) and a smaller one in the autumn (September/October). He only once found *S. hantzschii* in small quantities in April 1957. This finding of *Stephanodiscus* does not match the results from Czernin-Chudenitz (1958). Within the Chlorophyceae Kammel mentioned only a small number of species. *Actinastrum* sp. and *Scenedesmus quadricauda* s. l. were the most frequent. He found low cell numbers of coloured flagellates especially Chrysophyceae (e.g. *Synura uvella*, *D. sertularia*, and Euglenophceae, especially *Euglena viridis*. Microscopic animals were represented by a long list of pollution indicating Protozoa, heterotrophic flagellates and rhizopods, especially the most frequent *Rotifer vulgaris*, typical for heavily polluted waters.

Backhaus and Kembal (1978) undertook a survey on the High and Upper Rhine and published an extensive list of taxa. They noticed the dominance of *S. hantzschii* from the entrance of the plankton-rich dammed Neckar and the Grand Canal d'Alsace, associated with a big increase of coccale green algae, especially *Dictyosphaerium* spp., μ-algae and Rhodomonadaceae. *Nitzschia acicularis*, *A. formosa and F. crotonensis* were frequent, but of secondary importance. The authors accentuated the lack of *Cyclotella* species, and they could not find *S. subsalsum* or *S. potamos* during their survey in 1974, but later these diatoms were recognized in this part of the river (Backhaus pers. comm.). *T. fenestrata*, originally the dominant plankton species in the Upper Rhine, was only present in very low quantities. The dominance of *Stephanodiscus* could be recognized in the early 1970s as well in the Lower Rhine by Heuss (1975).

Surveys of Phytoplankton in the Lower Rhine from 1979 to 2004

Since 1979 phytoplankton monitoring has been carried out including qualitative and quantitative analysis in the Landesumweltamt NRW (formerly Landesamt für Wasser und Abfall). Most of the time zooplankton was estimated as well. This program in the Lower Rhine (the North Rhine-Westfalia reach) is part of national (Arbeitsgemeinschaft der Länder zur Reinhaltung des Rheins (ARGE Rhein), Deutsche Kommission zur Reinhaltung des Rheins (DK Rhein) and international monitoring programmes (International Commission for Protection of the Rhine (IKSR). Our studies started in the recovery phase after the intensified sewage treatment in the entire catchment area.

Material and methods

Sampling – Sampling stations and procedure

The Lower Rhine runs in total over 225 km within the state North Rhine-Westfalia with a mean flow velocity of about 5 km h^{-1}. The travel time was at MQ 44 h 1976 $m^3 s^{-1}$ at gauge Bonn (1991–2000). Depending on flow it fluctuated from MNQ to MHQ between 55 and 30 h.

Sampling stations

Bad Honnef, km 640 right bank, is located near Bonn at the entrance of the Rhine in the state of North Rhine-Westfalia at the beginning of the Lower Rhine reach. Upstream the plankton-rich tributaries Neckar, Main and Mosel flow into the river.

Düsseldorf, km 732 right bank, is located downstream from the effluents of the urbanized and industrialised region Cologne-Dormagen-Leverkusen and the river Wupper.

Duisburg, km 792 middle of the river, is located downstream from Düsseldorf with more sewage introduction and the mouth of the river Ruhr.

Kleve-Bimmen, km 865 left bank, (later referred to as Bimmen), is located on the left bank, at the German–Dutch border and at the end of the Lower Rhine reach. Downstream, the Rhine divides into its delta. The main tributaries in this reach are the rivers Emscher and Lippe, entering from the right side. The river Emscher was for a long time the biggest polluter of the Rhine, now its water is treated near the mouth. Until now the Lippe has a high load of chloride from coal mines. At the border between Germany and the Netherlands no complete mixing exists. The chemical and biological situations including plankton are somewhat different on both sides. Therefore there is another monitoring station, Lobith, on the right side in the Netherlands, see the map, Fig. 1.

Sampling

Sampling of plankton was carried out weekly as random hand sampling. The samples were taken at the same time each day in the downstream direction. Sampling was carried out over the year, but in the following text only the data from the growing season (March 1 to October 31) are presented as recommended by the European Framework Directive (EC 2000).

Methods

- *Chlorophyll a*: Chlorophyll *a* was measured as pigment concentration according to the German standard DIN 38 412-L 1 with the dichromate method, data correction according to Nusch (1980). From 1979 to 1987 a Zeiss-Photometer PM 4 was used, and later a Beckman UV-visual spectral photometer, model DU 50, was used.
- *Phytoplankton counting*: The samples were preserved with the JKJ-solution according to Utermöhl (1958) in glass bottles and counted within 8 weeks. For analysis an inverted microscope (Zeiss) was used with a magnification up to 630 $\times$. Quantitative estimation of the algae was preceded by counting diametric stripes. Since 2003 the counting program Opticount has been in use. Solitary diatoms were counted with the inverse microscope according to their size classes. Their final determination was done to genus or species level with Photomicroscope II (Zeiss). The diatoms were cleaned with oxygen peroxide according to Van der Werff (1955) and embedded in Aroclor or Naphrax. The taxonomy follows Mauch et al. (2003). Additionally living samples were examined for determination.
- *Biovolume*: Cell measuring was conducted with a measuring ocular. Since 1996 the software AnalySIS (SIS Münster) has been used with digital measuring and simultaneous volume calculation. For details of the method see Pohlmann and Friedrich (2001).
- *Fluorometric measurements*: Since 1984 measurements of fluorescence have been carried out especially to detect toxic effects. Firstly an apparatus from EOS was used, for details see Nusch (1980), in 1985 it was replaced by a Turner Fluorometer. Delayed fluorescence (DF) came into use in 1995. During the development of equipment and software a cooperation was undertaken between Gerhardt and Bodemer from the University of Regensburg and the authors, see Bodemer et al. (2000); Gerhardt and Bodemer

(1998). Measurements were done in the lab in the morning of the day after sampling.

Zooplankton: Sampling was done together with the sampling of phytoplankton in a 2-weekly rhythm. One litre was preserved living and cooled for transportation and overnight storing. Next morning it was filtered through a 50 μm net. The remains were preserved with formaldehyde (10%) plus one drop of detergent in 500 mL. Taxonomic determination and counting all the remains followed within 6 months.

Chemical–physical parameters: The chemical and physical parameters were measured in the frame of the North Rhine-Westfalia River Monitoring Program. The analysis was done according to the German standard methods (DIN) or according to the Lab Journal of the North Rhine-Westfalia Environmental Agency.

Global radiation: The data of global radiation were determined by the German Weather Service at Bocholt, near the monitoring station Bimmen. The data used here are the daily means in $J\,cm^{-2}\,d^{-1}$ from the day of phytoplankton sampling and the 3 days before.

Discharge: The quantitative data of the flow at the gauges Bonn, Düsseldorf, Duisburg-Ruhrort and Rees were made available by the Water and Shipping Office Duisburg. For treatment in this paper the daily means of the sampling data were used.

Results from Lower Rhine from 1979 to 2004

All the presented data of physical and chemical analysis, chlorophyll *a* and plankton refer to the growing season from March 1 to October 31. Outside the growing season cell numbers and chlorophyll content were very low ($\leqslant 1\,\mu g\,L^{-1}$ chlorophyll *a*). The treated data for flow, physico-chemical and biological measurements refer to the days of the biological samplings. If there were no data available for the same day, the results of the nearest date were used for this presentation.

Results 1979–2004

Chemical and physical data

Discharge, global radiation and temperature

Discharge: The discharge of the Lower Rhine is the result of that from the Alps and the tributaries in the catchment area in the southern mountain regions. The Rhine has a mean flow of 1500–4000 $m^3\,s^{-1}$ at the end of the Lower Rhine. Significant for the development of the plankton are the frequent peaks of run-off, regularly lasting only a few days depending on the weather conditions. An increase of the flow reduces the concentration of plankton, which subsequently rises slowly. By closer examination of the annual means of discharge, global radiation and water temperature from 1979 to 2004 a slight incremental tendency can be observed. From 1979 to 1989 the mean water temperature during the growing season was about 15–16 °C, from 1998 to 2004 at 16.6 to 17.8 °C, see Fig. 2 above. The same tendency is mentioned by Schmitz (2004) for air temperature in Düsseldorf.

Chloride, electrical conductivity and pH

Fig. 2 (middle) presents the mean values for chloride, electrical conductivity and pH. In general, the water can be considered as alkaline. The relatively high concentrations of chloride are an effect of effluents rich in chloride from salt and coal mining, and even the treated urban effluents contain more chloride than they would under natural conditions. This is also indicated by the high conductivity. During the 1980s and the beginning of the 1990s the mean concentrations of chloride varied between 140 and 190 $mg\,L^{-1}$. Afterwards they declined because of reduction measures to 80–145 $mg\,L^{-1}$ in the 1990s. A significant influence of the measured relatively high concentrations upon the plankton is not visible. However, the influence on pH can be stated by its increase at high phytoplankton density and activity, especially diurnal variations and finally because of flow variations (see Fig. 3).

Nutrients

In Fig. 2 the development of the main nutrients necessary for plankton growth is presented. The most striking impression is the reasonable reduction of phosphorus because of several measures for reducing the effluents. Nevertheless the P concentrations remain high enough for plankton growth. According to Hamm (1991) 160–200 $\mu g\,L^{-1}$ phosphorus is tolerable for dammed rivers, allowing the development of 100 bis 150 $\mu g\,L^{-1}$ chlorophyll *a* (90 percentile). From the Middle Rhine to the end of the Lower Rhine the river is a deep free-flowing river with high turbulence but with a long residence time.

The reduction of nitrogen concentrations refers only to ammonia (NH_4), but nitrate (NO_3) remains high at a level between 3.72 (1989) and 2.26 mg NO_3-$N\,L^{-1}$ (2004).

Silicon

Silicon as an essential element for the growth of diatoms varied to a great extent over the year between 4 and 6 $mg\,L^{-1}$ Si. Even during spring peaks 0.5 $mg\,L^{-1}$ remained available for diatom growth. These findings were confirmed by Bergefeld et al. in 1998 for the Middle Rhine, where the authors could identify short-term silicon limitation for diatoms only at the mouth of the dammed Mosel with much higher numbers of diatoms than in the Rhine. De Reuijter van Steveninck

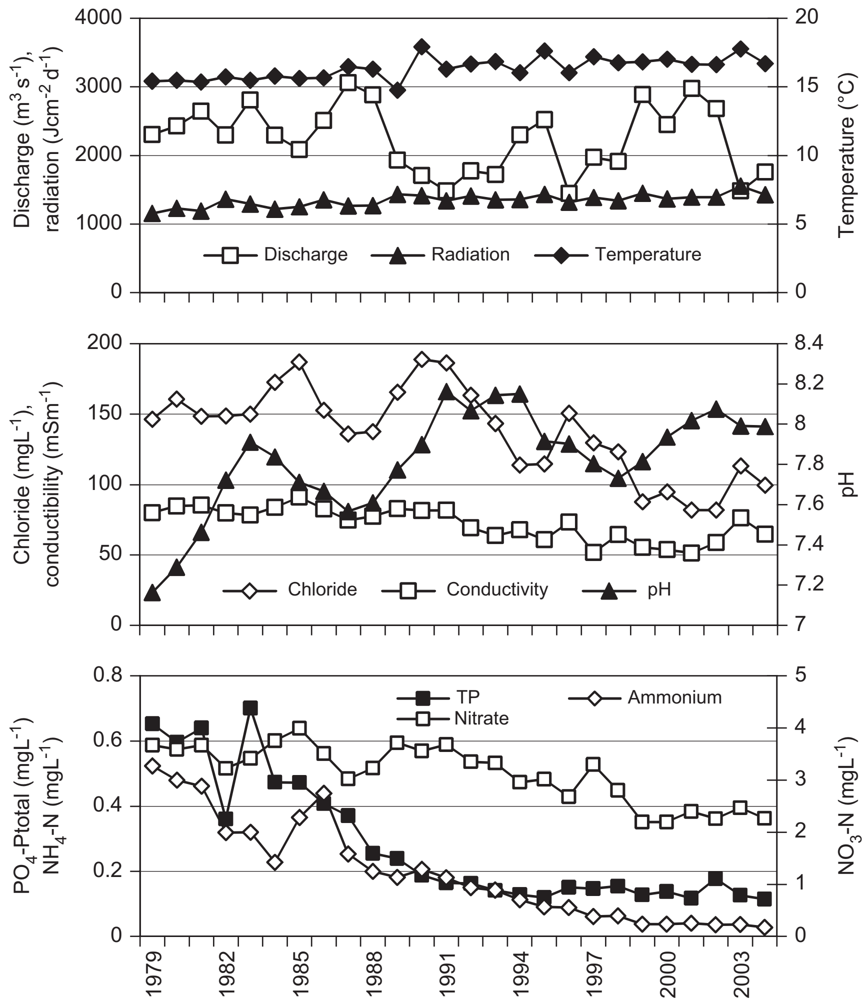

Fig. 2. Discharge, global radiation, temperature and physico-chemical data.

Above: discharge ($m^3 s^{-1}$), global radiation ($J cm^{-2} d^{-1}$, daily means) and water temperature (°C)
Middle: chloride ($mg L^{-1}$) pH and conductibility ($mS m^{-1}$)
Below: phosphorus ($mg L^{-1}$), nitrate-N ($mg L^{-1}$) and ammonia-N ($mg L^{-1}$),
Lower Rhine at Bimmen, annual means values of growing season 1979–2004.

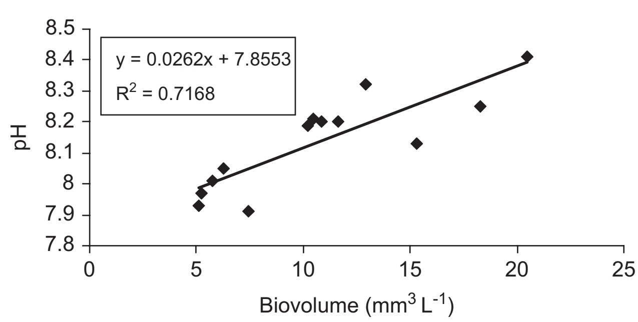

Fig. 3. Correlation between pH and biovolume ($mm^3 L^{-1}$) of phytoplankton in the Lower Rhine at Bimmen 01.04.–24.06.2003, chlorophyll mean value 46.1 $\mu g L^{-1}$ ($n = 13$).

et al. (1990) postulated silicon limitations only for the Delta Rhine; see also Admiraal and van der Vlugt (1990).

Oxygen

The mean values of the oxygen content in the lower Rhine during the time of our observations are presented in Fig. 4. Earlier, in the time from 1955 to 1957, pollution of the Rhine increased and the oxygen content varied between 12 $mg L^{-1}$ in January and 7 $mg L^{-1}$ in July (Kammel 1960). Later, during the phase of highest load with organic substances in the 1960s and 1970s of the last century, yearly means were only at about 4 $mg L^{-1}$, and short-term concentrations in the summer dropped to 2 mg O_2 $mg L^{-1}$ in 1971 (ARGE Rhein 1972; Stock 1981; DK-Rhein 2006). After this period the oxygen recovered to concentrations without danger for aquatic life due to extensive wastewater treatment in industries and cities. The oxygen production by phytoplankton was an additional contribution for the increase of oxygen in the Lower Rhine, and for diurnal changes at a high level (Friedrich and Viehweg 1984). From 1979 to 1988 the mean values were estimated at between 7 and 9 mg $O_2\,L^{-1}$ and from 1992 over 9 with a tendency to 11 mg $O_2\,L^{-1}$ in the following years, sometimes with higher extremes. A direct correlation between the mean values of oxygen and chlorophyll is not visible, mainly because of many other natural variables like flow and global radiation.

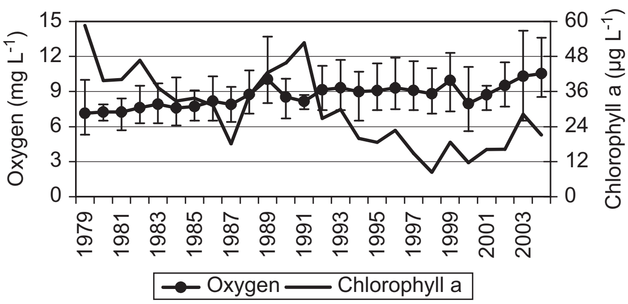

Fig. 4. Oxygen concentrations (mg L^{-1}), annual mean values, minima, maxima and chlorophyll *a* (µg L^{-1}), Lower Rhine at Bimmen, growing season 1979–2004.

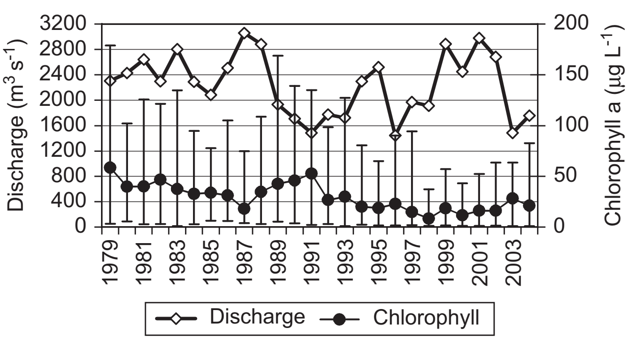

Fig. 5. Chlorophyll *a* (µg L^{-1}), mean values, minima and maxima, and discharge ($m^3\,s^{-1}$), annual mean values of growing season, Lower Rhine at Bimmen, 1979–2004.

Phytoplankton

Chlorophyll *a*

The development of chlorophyll concentrations as an expression of the phytoplankton biomass is presented in Fig. 5. In general the mean values varied very much from year to year, from 1979 to 1991 between 19 and 60 µg L^{-1} and since 1992 between 8 and 30 µg L^{-1} chlorophyll. Exceptions are 1987/88 with high run-off during the growing season and low phytoplankton. The chlorophyll *a* contents from 1989 to 1993 and 1996 to 1998 reflect distinctly dry years with high phytoplankton concentrations. In the time from 1992 to 2004 the chlorophyll fluctuated on a lower level between 10 and 28 µg L^{-1} with the tendency to higher concentrations. The general correlation of chlorophyll content with the global radiation was superimposed by the complexity of the origin of discharge and the introduction of plankton from the upstream reach (LfU 1993; Backhaus et al. 1980; IKSMS 1999; Admiraal et al. 1994). From 1979 to 1993 chlorophyll peaks could be detected with more than 100 µg L^{-1}, from 1998 until 2004 the variation was only between 37 and 83 µg L^{-1} chlorophyll.

Diatoms were predominant. Green algae had a much lower share, see Fig. 6. The very low contribution of Cryptophyceae is visible in the figure only from 1979 to 1981, 1990 and Chrysophyceae 1985–87, 1994–2003. All the time Cyanobacteria had a very low share. Therefore, the correlation between chlorophyll and biovolume is very high in the Lower Rhine, see Fig. 7 and Friedrich &Viehweg (1987).

The reduction of chlorophyll in the Lower Rhine is correlated with the decrease of phosphate and ammonia due to the enhanced treatment of wastewater and reduction of phosphate in detergents within the entire river system. This raised oligotrophication in Lake Constance since 1980 with diminution of phytoplankton (Gaedke 1998). But Kümmerlin (1998) identified that

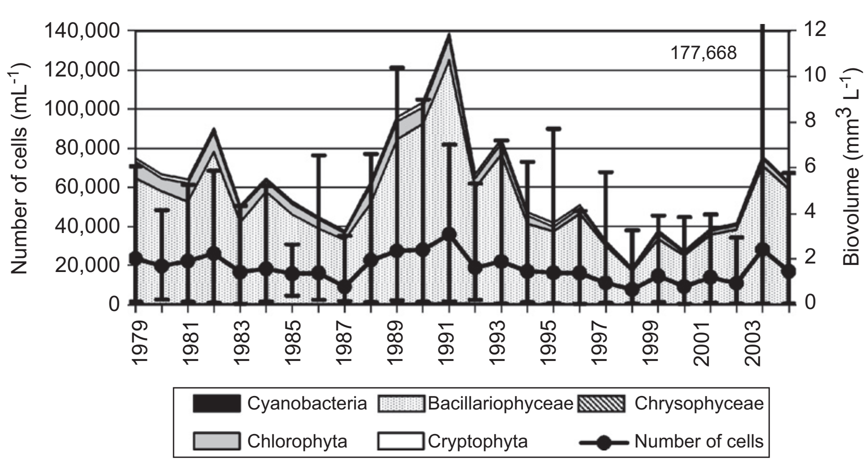

Fig. 6. Biovolume of the main algal groups ($mm^3\,L^{-1}$) and total cell number (cells m L^{-1}), the mean values, minima and maxima of cell numbers, growing season, Lower Rhine at Bimmen, 1979–2004.

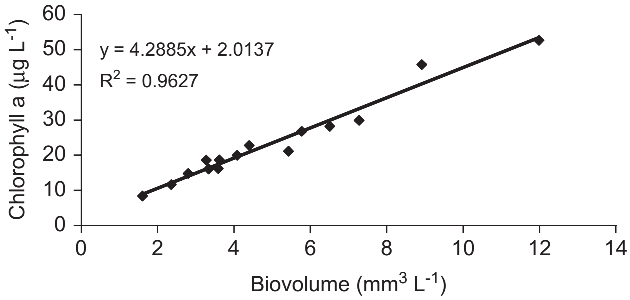

Fig. 7. Correlation between chlorophyll *a* and biovolume, 1990–2004, $N = 15$ Lower Rhine at Bimmen.

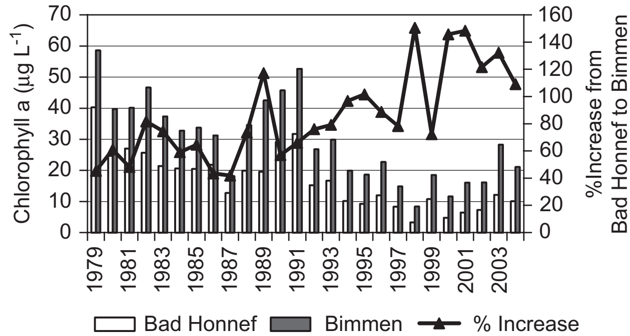

Fig. 8. Chlorophyll *a* concentration ($\mu g\,L^{-1}$) at Bad Honnef and Bimmen, mean values and increase of chlorophyll *a* concentration (%), 1979–2004.

the correlation between biomass and phosphate contents diminishes with the reduction of nutrients. "These findings suggest that the dominance of bottom-up control is replaced by a larger variety of factors regulating algal standing stocks which include grazing and weather conditions." (l.c. p. 111) Inhibition of algal growth by toxic effluents could only be found until 1983 in the Lower Rhine near Duisburg. After closing the emitting industry it could no longer be detected (Friedrich and Viehweg 1984), (LWA 1985), (Friedrich et al. 1992).

The intensity of discharge is of high importance for phytoplankton development. During low and medium flow phytoplankton growth is high in the upstream areas and therefore the starting concentration at the entrance to the Lower Rhine is also relatively high. During a flowing time of 2–3 days in the Lower Rhine the algae can grow unless there is a huge quantity of benthic feeders in the river. At high discharge plankton concentrations in the upstream part of the river are lower and the flushing effect diminishes the phytoplankton population. These influences sometimes overlay the general trend. This is one of the reasons for the changes from year to year. The Lower Rhine is the most suitable reach for phytoplankton growth. From 1979 to 1987 the phytoplankton decreased because of the mentioned phosphorus reduction in the effluents. This significant decline of phytoplankton was found in the entire Rhine and Mosel (IKSR 2002; IKSMS 1998, 1999). On the other hand, growth conditions improved and the growth rates along the Lower Rhine have risen more than 100% in the last years. Fig. 8 demonstrates the increase between Bad Honnef and Bimmen. During 1979–1987 the increase was about 50–70%. Later a short period of higher chlorophyll content followed and phytoplankton increased more steeply. Since 1992, at a minor level of chlorophyll, much higher growth rates could be estimated, see also Tubbing et al (1994). This higher growth rate may be an effect of higher water transparency due to the lower concentration of suspended solids, but there are no data available.

Taking net growth of phytoplankton into consideration we assume that in the fast-flowing and turbulent Lower Rhine loss by sedimentation is more or less negligible, but grazing is an important factor. According to Schöl et al (2002) and Ietswaart et al. (1999) the intensity of grazing is subject to great fluctuations in the Rhine. A comparable situation is reported from the river Mosel by IKSMS (1998, 1999) and Müller et al. (1996). With the improvement of water quality since the beginning of the 1970s the zebra mussel *Dreissena polymorpha* has spread out and formed extended stands. Since 1988 *Corophium curvispium* (Sars) (Crustacea, Amphipoda) has spread out, while *Dreissena* has not only declined in the Rhine but in the Mosel as well (Bachmann et al. 2001). The most recent change within the benthic feeders is the outspread of *Corbicula* spp. (O. F. Müller) (Mollusca, Bivalvia), which is now the most abundant mussel in the Rhine and its share in reducing phytoplankton cannot be ignored.

Chlorophyll–fluorescence

Besides the classical extraction method of detecting chlorophyll *a* according to the German standard procedure (DIN 38 412-L16, 1985), the spontaneous fluorescence (Friedrich and Viehweg 1987) and since 1996 DF excitation spectroscopy has been measured according to the method of Gerhardt and Bodemer (1998), Friedrich et al. (1998), which allows the differentiation of algal groups with different pigmentation: Cyanobacteria, Chrysophyta (incl. Bacillariophyceae, Chrysophyceae, Dinophyta, Xanthophyceae), Chlorophyta (incl. Euglenophyceae and Conjugatophyceae) and Cryptophyta. Fig. 9 demonstrates the good agreement of DF with the results of ethanol extraction and biovolume according to microscopic counting. This shows the usefulness of DF in determining the main algal groups in plankton instead of more complicated methods, especially for many or very frequent measurements, also see Becker et al. (2006).

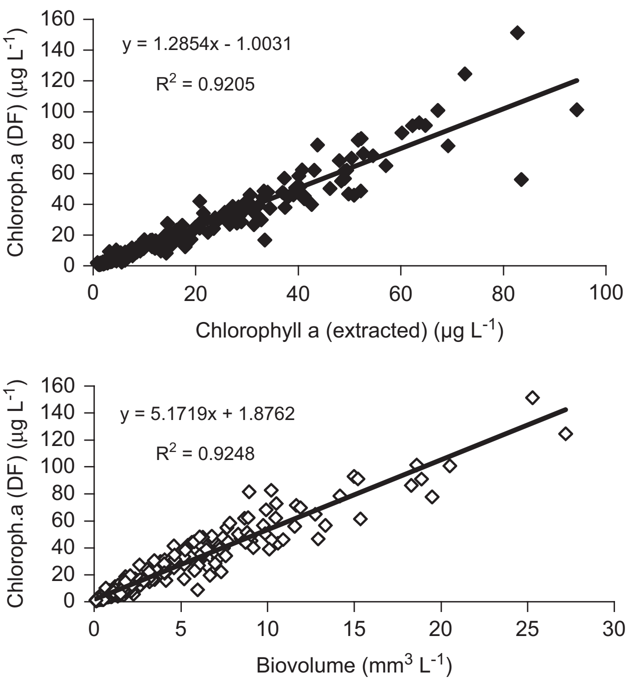

Fig. 9. Measurements of chlorophyll with delayed fluorescence spectroscopy (DF).

Above: correlation of DF (%) with extracted chlorophyll (µg L^{-1})
Below: correlation of DF (counts s^{-1}) with biovolume (mm^3 L^{-1}), $N = 289$, Lower Rhine at Bimmen 1996–2004.

Flora

During the time of our investigations the floristic composition of the phytoplankton was characterised by centric diatoms. The most frequent species was *S. hantzschii* with a share of up to 80%. Other small centric and pennate diatoms were regularly present with significant variation in cell number from year to year. The subdominant group was coccale green algae with the main emphasis during the summer and a share of up to 35% of phytoplankton cell number. Cryptophyceae were represented mainly by *Rhodomonas minuta* incl. var. *nannoplanctica.* Cyanobacteria regularly appeared mainly in winter, especially *Planktothrix* (*P. agardhii* and *P. rubescens*) and some tiny coccale forms. Due to their small size the biovolume of cyanobacteria is very low, see Fig. 6.

The cell numbers at the Lobith station, opposite Bimmen on the other (right) side of the Rhine, were somewhat higher (IKSR 2002). This can be explained with the insufficient mixing of the water of the Rhine with that from the tributaries and effluents. These differences between Bimmen and Lobith could also be recognized for many other quality parameters.

An extensive list of phytoplankton species and their volume is published by Pohlmann and Friedrich (2001). Appendix A gives a list of the algae found in the Lower Rhine during our surveys. Table 2 includes only the frequent and significant species from 2004. It is representative for the time between 1990 and 2004 with changing order of priority (Table 1).

The seasonal sequence of the algae corresponded with that usually found in big rivers. In March the growing season started with centric diatoms, especially *S. hantzschii.* Green algae and other groups were rare at that time. In April a short bloom of *A. formosa* followed together with *F. crotonensis* and *Diatoma tenuis.* In June the proportion of centric diatoms diminished and simultaneously green algae increased to their maximum in summer. In late summer a lower increase of centric diatoms followed, and at the end of October the planktonic vegetation time ended. It should be mentioned that in the 1980s besides a spring peak of phytoplankton, a second one followed in summertime, see Fig. 10.

Only one peak in spring has been detected since the middle of the 1990s and a general smaller amount of phytoplankton. During wintertime cell numbers were very low. In winter blue green algae, especially *Planktothix* species, were entering the Rhine from Lake Constance and the Aare (Tubbing et al. 1994; IKSR 1997, 2002). In the dammed Mosel with a lower discharge and long residence time, Cyanobacteria develop much more during springtime (Bergfeld et al. 1998).

The change of the floristic composition during the time from 1979 until 2004 primarily depends on the changes in the upstream part of the Rhine especially because of re-oligotrophication in Lake Constance. Backhaus and Kembal (1978) realized that downstream river Neckar and Grand Canal d'Alsace no more significantly changed the planktonic flora that existed in the Upper Rhine with *Stephanodiscus* as the dominant plankter. In contrast, at least with the beginning of our studies in 1979, a variety of small centric diatoms in the Lower Rhine was estimated. *Cyclotella atomus*, *Cyclotella cyclopunctata*, *C. meneghiniana* occurred regularly. Irregularly together with related genera and in small quantities occurred *Cyclotella ocellata*, *pseudostelligera*, *radiosa*, *stelligera. Cyclotella comensis* found in the samples from 1852 by Hofmann (2004) could never be retrieved.

A species of special interest is the diatom *S. potamos*, which is one of the most widespread phytoplankton organisms in big rivers and in the meantime well known from all big rivers in Central Europe (Steinberg et al. 1987; Reynolds and Descy 1996; Kusel-Fetzmann 1997; Mischke pers. comm. 2006). This diatom is not listed in older species lists, but it was present e.g. in the river Danube during high eutrophication (Schmidt 1991). In the Lower Rhine it was observed since the middle of the 1970s when it was not reported from the Upper Rhine. The frequency of *S. potamos* varied very much. In 1990

Table 1. Dominance and steadiness (⩾0.5%) of the most frequent phytoplankton taxa in 2004, Lower Rhine at Bimmen, $n = 35$

Taxon	Dominance (%)	Steadiness (%)	Cells (mL^{-1})
Stephanodiscus hantzschii	23.71	100.0	4877.8
Skeletonema potamos	13.62	91.4	2801.8
Skeletonema subsalsum	9.93	97.1	2043.3
Cyclotella spp.	6.61	100.0	1360.5
Stephanodiscus minutulus	6.13	77.1	1261.6
Chlorophyceae non det.	4.11	100.0	846.0
Picoplankton	2.74	100.0	563.9
Cyclotella atomus	2.07	62.9	426.7
Marvania geminata	1.89	51.4	389.8
Spermatozopsis exsultans	1.88	7.4	387.5
Chroococcales non det.	1.80	100.0	371.3
Cyclostephanos invisitatus	1.71	82.9	351.0
Rhodomonas lacustris incl. var. *nannopl.*	1.55	100.0	319.8
Dictyosphaerium subs./Pseudodicty. jurisii	1.04	65.7	213.2
Chlamydomonas spp.	0.95	100.0	194.6
Stephanodiscus neoastrea	0.85	54.3	174.2
Asterionella formosa	0.83	82.9	171.2
Merismopedia spp. D. < 2 μm	0.62	2.9	128.0
Chrysochromulina parva	0.56	28.6	115.2
Coelastrum microporum	0.56	60.0	114.5
Pseudananbaena constricta	0.55	14.3	112.8
Nitzschia acicularis-s.l.	0.54	94.3	111.1
Nitzschia spp.	0.54	100.0	110.3
Hortobagyiella verrucosa	0.54	71.4	110.1

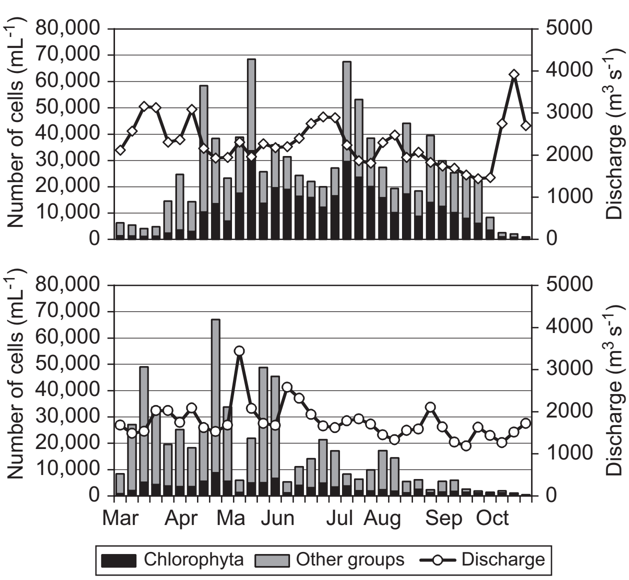

Fig. 10. Comparison of phytoplankton development in 1982 and 2004.

Above: 1982, high cell numbers all over growing season, two peaks, high share of Chlorophyta
Below: 2004, lower cell numbers, especially late summer and autumn, low share of Chlorophyta.

it developed densities up to 6000, dropped down to 1100–3000 and came up in 2003 to new peaks of up to 8600 cells m L^{-1}.

Although the pennate diatoms are not as frequent as centric ones they are reasonable and very indicative. The most remarkable species is *A. formosa*, forming a spring peak every year and mean values over 100 cell m L^{-1}. Besides that, only *F. ulna* and *D. tenuis* were present in mean cell numbers > 100. *F. crotonensis* and *T. flocculosa* were rare and could be found mainly as single specimen, but 100 years ago they were frequent in the Upper Rhine.

Within the *Chlorophyceae Dictyospaerium* spp., *Chamydomonas* spp., *Scenedesmus* spp., *Oocystis* spp., *Monoraphidium* spp., *Coelastrum* spp. *Crucigenia* spp. *Marvania geminata* and *Hortobagyella verrucosa* made up the main part of green algae, while *A. hantzschii*, *Pediastrum* spp., *Tetrastrum* spp. developed in smaller numbers. *Spermatozopsis* was found first in 1993 and Marvania in 2000. Some small Chlorophyceae and μ-algae were counted in greater quantities, but could not be determined, see Appendix A. *Rhodomonas lacustris* incl. var. *nannoplanctica* was the main representative of Cryptophyceae and *Chrysochromulina parva* of Chrysophyceae.

The contribution of the Lower Rhine tributaries to the plankton was not noticeable. It mainly depends on their low contribution to the discharge of the Rhine and to their more or less eutrophic status with comparable species composition and – except the River Ruhr – their low plankton density. Remarkable influence in addition to the Upper Rhine came from the Rivers Main and

Mosel. Lange-Bertalot (1974) described the dominance of *S. hantzschii* together with *C. meneghiniana* for the Main near its mouth in summer. This is in accordance with our observations. We found *C. meneghiniana* as well more frequent at higher saprobity at the beginning of our studies. The recently published results from the river Mosel are very close to the results from Bimmen. One exception is the lack of *Planktothrix* species, entering through the Upper Rhine (IKSMS 1998, 1999; IKSR 2002). As explained earlier, a correct comparison of the recent species list with those of earlier times is not possible. The results from 1954 during a high degree of saprobity by Czernin-Chudenitz (1958) and Kammel (1960) were overlapped by heterotrophic and saprophytic organisms, and the findings of Czernin-Chudenitz belong to months outside the growing season.

The results presented in this paper were elaborated after the time of the highest pollution, in the first years on a high level of trophy. Within the 25 years the change in the species list is quite small. However, the share of coccale green algae in the total cell number and in relation to the diatoms is particularly notable and the most remarkable change in the floristic composition, see Figs. 6 and 10.

The bloom in summertime is much smaller now in comparison with the late 1970s and 1980s. The shift from green algae to diatoms is in accordance with the decrease of phosphorus and ammonia, one more indicator for decreasing trophic status of the Rhine, see Fig. 2.

Zooplankton

Within the monitoring of zooplankton it could be dealt with rotatoria, planktonic veliger larvs of *D. polymorpha* and crustacea: Protozoa were not determined as only fixated zooplankton was available. Crustacea were recognized only occasionally as single specimen.

Dominant rotifers were *Keratella cochlearis* incl. f. *tecta*, *Keratella quadrata*, *Brachionus calyciflorus*, *Brachionus angularis* and *Brachionus urceolaris*. Subdominant were *Gastropus stylifer*, *Polyarthra dolichoptera-vulgaris* and *Synchaeta tremula-oblonga. Cephalodella* spp., *Colurella uncinata*, *Dipleurochlanis proatula. Filinia longiseta*, *Lecane* spp., *Lepadella* spp. *Trichocerca* spp. and *Notholca squamata* could be determined in small numbers or rarely. The total number of animals per litre was more or less in accordance with the phytoplankton, as it is known in general. The highest numbers were found in 1990–1992 and 2002 with mean values for *K. cochlearis* 200 and 300 specimen L^{-1} and most of the years >100 specimen L^{-1} as mean values within the growing season. *B. calyciflorus* was the next frequent with >100 specimen L^{-1}. Only in the early 1990s *K. quadrata*, *B. angularis* and *Polyarthra* spp. could be found in frequencies of about 100 animals L^{-1}. *F. longiseta* was rare all the time.

Seasonally the pelagic larvae of *D. polymorpha* occurred. Crustacea (*Daphnia* sp. and juvenile Copepods) could only be found exceptionally and from the protozoans mainly *Arcella* and peritrich ciliates. Results of recent investigations about protozoans and colourless flagellates have been published by Schmitz (1986), Prast et al. (2003), Weitere et al. (2005) and Scherwass and Arndt (2005). The quantity of zooplankton reflects the drop of phytoplankton since the middle of the 1990s, illustrated in Fig. 11, but there is no significant change in the dominance of the species, see Fig. 12. The larvae of *Dreissena* were also estimated in lowering quantities, reflecting the decrease of adult animals in the last years, and probably the changes in chlorophyll content in the upstream part of the river.

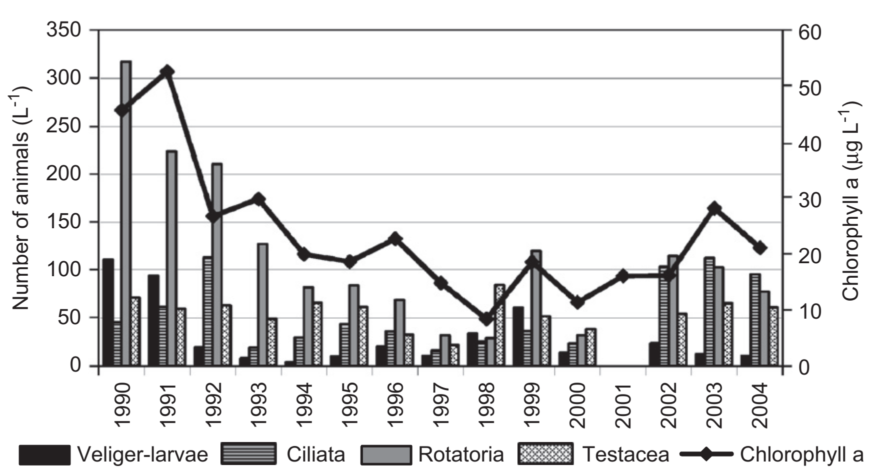

Fig. 11. Main components of zooplankton, compared with chlorophyll, mean numbers of specimen, growing season, Lower Rhine at Bimmen, 1979–2004.

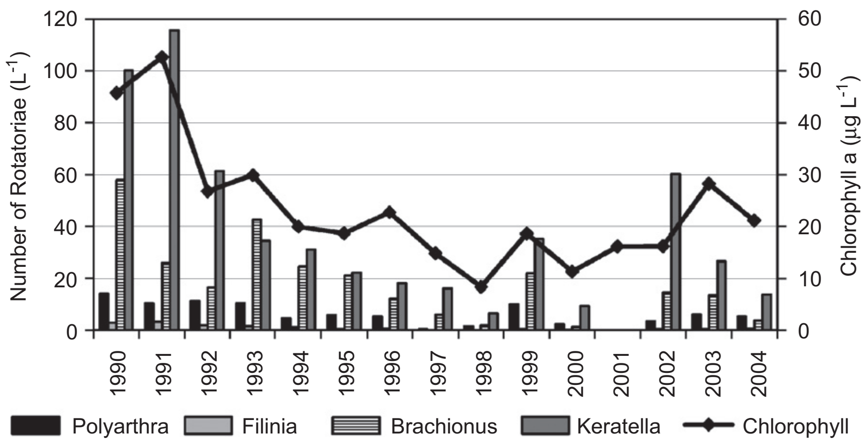

Fig. 12. Main genera of rotifers (animals L^{-1}) and chlorophyll *a* ($\mu g\, L^{-1}$), 1990–2004, mean value of growing season (2001 no zooplankton data), Lower Rhine at Bimmen.

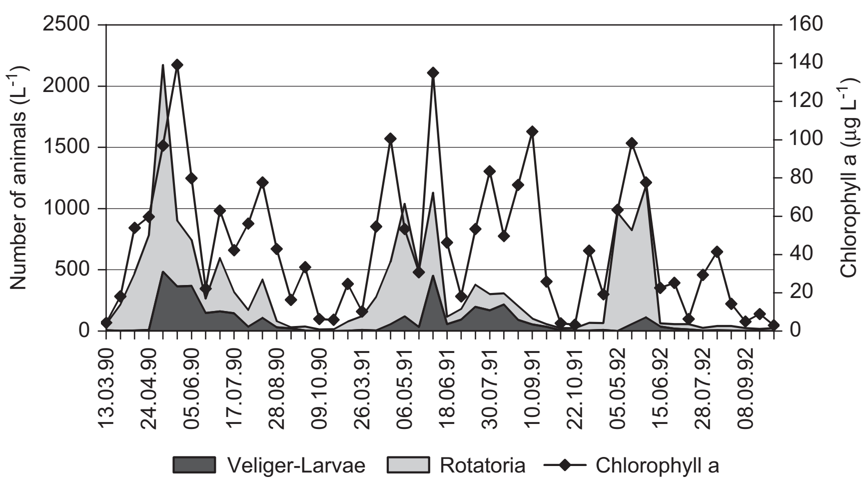

Fig. 13. Veliger larvae of *Dreissena polymorpha* (animals L^{-1}), rotifers (animals L^{-1}) and chlorophyll *a* ($\mu g\, L^{-1}$), seasonal changes from March 1990 to October 1992 Lower Rhine at Bimmen.

Fig. 13 shows the reflection of the phytoplankton spring peak by the zooplankton, especially during spring bloom of phytoplankton. Larvae of *Dreissena* had their highest density in springtime as well, with a tendency to reduced numbers over the years in accordance with the lower stands of adult animals in the last decade. Their reduction is due to several reasons. Major interactions are competition with *Corophium curvispinum* Sars (Crustacea, Amphipoda), which invaded the entire River since the end of the 1980s (IKSR 2005a), and the loss of large stands of adult benthic *Dreissena* due to very low water levels in summer, especially in 2003 (IKSR 2004). More biotic or abiotic factors may have an adverse effect upon *Dreissena* (Bachmann et al. 2001), including competition with the new, invasive mussels *Corbicula fluminea* (O. F. Müller) and *Corbicula fluminalis* (O. F. Müller).

In the Appendix Table B1 the zooplankton species found during our survey are listed, including benthic species in the samples.

Ecological assessment of the phytoplankton in the Lower Rhine

For the assessment of lakes and plankton-dominated rivers chlorophyll *a* is in use as an indicator of trophy. It reflects the trophic status very well with the exception of blooming blue green algae. Therefore, a German system for the assessment of plankton-dominated rivers was developed on the basis of chlorophyll *a* content (LAWA 2002). The assessment was based on the interpretation of data from 3 successive years. According to this approach the Lower Rhine was in eutrophic (to polytrophic) status during the 1980s. Since 1992 chlorophyll concentrations

Table 2. Assessment of the ecological quality of the phytoplankton in the Lower Rhine 1992–2004 based on WFD (data taken from LUA 2006)

Year	Total phytoplankton index	Ecological class
1992	2.57	Moderate
1993	2.57	Moderate
1994	2.53	Moderate
1995	2.23	Good
1996	2.23	Good
1997	2.27	Good
1998	1.9	Good
1999	2.58	Moderate
2000	2.22	Good
2001	2.22	Good
2002	2.23	Good
2003	2.72	Moderate
2004	2.41	Good

were significantly lower and the trophic status could be estimated for the periods 1983–1985 and 1998 and 2000 as eutrophic with a tendency to mesotrophic. According to the European Water Framework Directive (WFD) (EC 2000) indicative phytoplankton taxa and additional parameters are to be used for assessing the ecological status. The procedure is a multimetric approach providing an index (Mischke 2005; Mischke et al. 2005). The transfer of the indices to the quality classes is very good: index <1.5; good: index >1.5–<2.5; moderate: index 2.5–<3.5; insufficient: index 3.5–<4.5; bad: index 4.4–5.0. According to this assessment the Lower Rhine has changed since 1992 from moderate to good, see Table 2.

The table also shows the interannual change of the phytoplankton index although there was no significant change of anthropogenic impacts. Taking the natural variations of weather and flow conditions into consideration the Lower Rhine can be assessed as in good ecological status with respect to the metric phytoplankton. This assessment is confirmed by the International Rhine Commission in a report on the plankton in 2000 (IKSR 2005b). In that paper the problem of assessment of river phytoplankton is discussed in more detail. Downstream in the Delta Rhine with its branches, the hydraulic and growth conditions for phytoplankton and zooplankton change significantly. Therefore, the location Bimmen is an outstanding place to estimate the plankton of the free-flowing Rhine and for assessment according to WFD, because here the maximum of phytoplankton will be reached.

Conclusions

Looking back on plankton research in the river Rhine a comparison beginning 100 years ago until now is difficult. Many times the older samples were collected outside the growing season; the taxonomy of algae was different and not as well developed as it is nowadays. Not all forms described in older reports could be assigned to the modern taxonomy. Sampling methods were different (net sampling with a mesh size of 20 μm and only sparse plankton, use of 1 cm^3 counting chambers because the inverted microscope did not yet exist). Nevertheless, a relatively good picture of the plankton can be developed. We conclude that 100 years ago and sometime later the phytoplankton was of low quantity and was composed of dominating pennate and centric diatoms, accompanied by some Chrysophyceae and a few Cryptophyceae, Dinophyceae and Chlorophyceae. In the first decade of the 20th century the first changes in the dominance took place. *C. comensis* disappeared, and *A. formosa* together with *F. crotonensis* became frequent. But first signs of eutrophication existed through filamentous blue green algae from the upstream lakes. Significant developments of *S. natans* indicated local pollution of the river. This increased more and more until the early 1970s. During the time of highest pollution eutrophication could not develop. However, many heterotrophic species and some tolerant algae were frequent. With the construction of wastewater plants, pollution decreased to a low level, the oxygen content rose and because of nutrient enrichment eutrophication took place until the initial control of phosphate in the 1980s. After this time the plankton density dropped down and the species diversity came up. A general extensive description of the scientific research of the Rhine ecosystem from the very beginning up to the middle of the 1990s is published by Tittizer and Krebs (1996).

A good comparison is only possible with the diatom flora, based on historical samples by Ehrenberg, from 1852 to 1855 (see Hofmann 2004) and Leendertz from 1931 (Pohlmann 2004, see Appendix Table A1). The results of recent determinations on the basis of modern taxonomy show a lot of centric diatoms existing in the middle of the 19th century and are part of the recent plankton, see Appendix Table A2. It can be assumed in the older papers sometimes *S. hantzschii* or *Cyclotella* include some more species. The second result is that the recent diatom assemblage is close to that of the middle of the 19th century as a result of the recuperation of the water quality.

The time from 1979 to 2004 can be divided in a first part up to about 1980 with significant eutrophication, two high plankton peaks in summer and early autumn. Centric diatoms, mainly *S. hantzschii*, dominated with up to 80% of cell number, accompanied by a great variety of green algae with maxima of about 35% of cell number, while the other groups contributed only a small portion to the total. The intensity of plankton growth during the 2–3 days flow in the Lower Rhine showed a great variety from year to year, depending on the discharge. This is as well reflected by the concentrations of nutrients and the other physico-chemical parameters. After the reduction of nutrients, especially phosphate the quantity of phytoplankton decreased and the mean values of chlorophyll went down from 59 (1979) and 31 $\mu g\,L^{-1}$(1986) to 29 (1993) and 21 $\mu g\,L^{-1}$ (2004). Smaller values of phytoplankton were recognized in years of extreme high effluents. With the recuperation of the Rhine a higher species diversity of centric diatoms could be estimated, and now it is close to the situation of the middle of the 19th century. The diversity of green algae is high, but all the other groups do not play a remarkable role, except the filamentous blue green algae, typical for the winter plankton. Good correlation exists between cell number and biovolume. For the discrimination of algal groups with different pigmentation, Cyanobacteria, Chrysophyta (incl. Bacillariophyceae, Chrysophyceae, Dinophyta, Xanthophyceae), Chlorophyta (incl. Euglenophyceae and Conjugatophyceae) and Cryptophyta the delayed fluorescence technique was used with success and it could be demonstrated as a suitable method for screening. Rotatoria built the main part of zooplankton, especially *Keratella* and *Brachionus.* Despite their grazing together with the benthic mussels *Dreissena* and *Corbicula* an increase of phytoplankton along the Lower Rhine could be estimated all the time. During the last years the growth has been higher with a tendency to more than 100% growth within 2–3 days flow in the Lower Rhine. The recuperation of the water quality in the river could be confirmed by the ecological assessment according to the requirements of the European WFD as in good status.

Acknowledgments

We have to thank our colleagues in the North Rhine-Westfalia Environmental Agency for long-term excellent cooperation, the German Weather Service for the provision of the data on global radiation from the station Bocholt, the Water and Shipping Office Duisburg for quantitative data of the discharge and Roland Paschmann, LANUV NRW for the map of the Rhine (Fig. 1). We would like to thank Wilfried Schönborn very much for his services in preparing the paper, the reviewers for their helpful remarks, the editor Walter Geller for his kind help and last but not least Ms. Deborah Connolly for linguistic assistance.

Appendix A

Phytoplankton found in the plankton of the Lower Rhine 1979–2004 – Part 1 Bacillariophyceae (Table A1).

Planktonic algae in the Lower Rhine – Part 2 Algae without diatoms (Table A2)

Table A1. Phytoplankton found in the plankton of the Lower Rhine 1979–2004 Part 1 Bacillariophyceae

Taxon	Author	Ehrenberg, 1852–54 Cologne det. Hofmann 2004	Leendertz 1931 det. Pohlmann 2004	Hofmann 2004	Friedrich and Pohlmann
Bacilariophyceae					
Centrales					
Acanthoceras zachariasii	(Brun) Simonsen				X
Actioncyclus normanii	(Gregory) Hustedt			X	X
Aulacoseira ambigua	(Grunow) Simonsen				X
Aulacoseira granulata	(Ehrenberg) Simonsen	X	X	X	X
Aulacoseira granulata var. *ang.*	(O.Müller) Simonsen				X
Aulacoseira islandica	(O.Müller) Simonsen		X		X
Aulacoseira muzzanensis	(Meister) Krammer				X
Aulacoseira subarctica	(O.Müller) Haworth				X
Aulacoseira spp.	Thwaites	X		X	X
Centrales $\leqslant 5\,\mu m$ Durchmesser		X		X	X
Cyclostephanos dubius	(Fricke) Round	X	X	X	X
Cyclostephanos invisitatus	(Hohn & Hellermann) Th., St. & Hak.	X	X	X	X
Cyclotella atomus	Hustedt	X	X	X	X
Cyclotella comensis	Grunow	X			
Cyclotella cyclopuncta	Hakansson & Carter	X	X	X	X
Cyclotella meneghiniana	Kützing	X	X	X	X

Table A1. (*continued*)

Taxon	Author	Ehrenberg, 1852–54 Cologne det. Hofmann 2004	Leendertz 1931 det. Pohlmann 2004	Hofmann 2004	Friedrich and Pohlmann
Cyclotella ocellata	Pantocsek			X	
Cyclotella pseudostelligera	Hustedt	X	X	X	X
Cyclotella radiosa	(Grunow) Lemmermann	X	X	X	X
Cyclotella spp.	(Kützing) Brebisson	X	X	X	X
Cyclotella stelligera	Cleve & Grunow	X		X	
Melosira varians	J.G.Agardh	X	X	X	X
Pleurosira laevis	(Ehrenberg) Compére				X
Skeletonema potamos	(Weber) Hasle				X
Skeletonema subsalsum	(Cleve-Euler) Bethge	X		X	X
Stephanodiscus alpinus	Hustedt			X	X
Stephanodiscus binderanus	(Kützing) Krieger				X
Stephanodiscus hantzschii	Grunow	X	X	X	X
Stephanodiscus minutulus	(Kützing) Cleve & Moeller	X	X	X	X
Stephanodiscus neoastrea	Hakansson & B. Hickel			X	X
Stephanodiscus spp.	Ehrenberg				X
Thalassiosira lacustris	(Grunow) Hasle		X		X
Thalassiosira weissflogii	(Grunow) Fryxell & Hasle		X	X	X
Pennales					
Achnanthes lanceolata compl.	in Krammer & Lange-Bertallot (1981)	X	X	X	X
Achnanthes minutissima	Kuetzing	X		X	
Amphora spp.	Ehrenberg				X
Anomoeoneis spp.	Pfitzer				X
Asterionella formosa	Hassall	X	X	X	X
Bacillaria paradoxa	Gmelin				X
Brachysira neoexilis	Lange-Bertalot	X			
Caloneis bacillum	(Grunow) Cleve	X		X	
Caloneis spp.	Cleve				X
Cocconeis neothumensis	Krammer	X			
Cocconeis pediculus	Ehrenberg	X		X	X
Cocconeis placentula	Ehrenberg	X		X	X
Cymatopleura elliptica	(Brebisson) W. Smith			X	X
Cymatopleura solea	(Brebisson) W. Smith	X			X
Cymbella spp.	J.G. Agardh	X		X	X
Denticula kuetzinggii	Grunow	X			
Denticula tenuis	Kuetzing	X			
Diatoma ehrenbergii	Kuetzing	X			
Diatoma mesodon	(Ehrenberg) Kützing	X			X
Diatoma moniliformis	Kützing	X		X	X
Diatoma tenuis	J.G. Agardh	X	X	X	X
Diatoma vulgaris	Bory de Saint Vincent	X		X	X
Diatoma spp.	Bory de Saint Vincent	X			
Diploneis spp.	Ehrenberg	X			
Entomoneis paludosa	(W. Smith) Reimer	X			X
Eunotia arcubus	Noerpel & Lange-Bertalot	X			
Eunotia bilunaris	(Ehrenberg) Mills	X			
Fragilaria arcus var. *arcus*	(Ehrenberg) Cleve	X			X
Fragilaria capucina distans s.l.	Desmazieres	X		X	X
Fragilaria construens	(Ehrenberg) Grunow	X		X	
Fragilaria crotonesis	Kitton	X		X	X
Fragilaria ulna var. *acus*	(Kuetzing) Lange-Bertalot	X		X	X
Fragilaria ulna var. *ulna*	(Nitzsch) Lange-Bertalot	X		X	X
Fragilaria ulna-angustissima	Krammer & Lange-Bertalot		X	X	X

Table A1. (*continued*)

Taxon	Author	Ehrenberg, 1852–54 Cologne det. Hofmann 2004	Leendertz 1931 det. Pohlmann 2004	Hofmann 2004	Friedrich and Pohlmann
Fragilaria spp.	Lyngbye	X		X	X
Frustulia vulgaris	(Thwaites) de Toni	X			
Gomphonema spp.	Ehrenberg	X	X	X	X
Gyrosigma acuninatum	(kuetzing) Rabenhorst	X			
Gyrosigma spp.	Hassall				X
Hantzschia amphioxys	(Ehrenberg) Grunow	X			
Mastogloia smithii var. *lacustris*	Grunow	X			
Meridion circulare	(Greville) J.G. Agardh	X		X	X
Navicula capitata var. *capitata*	Ehrenberg	X			X
Navicula gregaria	Donkin	X		X	X
Navicula lanceolata	Ehrenberg	X	X	X	X
Navicula menisculus	Schumann	X			
Navicula menisculus var. *grunowii*	Lange-Bertalot	X		X	
Navicula spp	Bory de Saint Vincent	X		X	X
Navicula tripunctata	(O.Müller) Bory de Saint Vincent	X		X	X
Navicula viridula s.l.	Krammer & Lange- Bertalot	X			X
Neidium spp.	Pfitzer				X
Nitzschia acicularis -s.l.	(Kützing) W. Smith	X	X	X	X
Nitzschia fruticosa	Hustedt	X		X	X
Nitzschia spp.	Hassall	X		X	X
Pinnularia sp.	Ehrenberg	X		X	X
Rhizosolenia abbreviata	(C.Agardh) Lange-Bertalot	X		X	X
Rhizosolenia longiseta	Zacharias				X
Simonsenia delognei	(Grunow) Lange-Bertalot	X			
Stauroneis spp.	Ehrenberg	X			X
Surirella angusta	Kuetzing	X			
Surirella brebissonii	Krammer & Lange-Bertalot	X			X
Surirella minuta	Brébisson in Kützing	X			X
Tabellaria flocculosa	(Roth) Kützing	X	X	X	X

Table A2. Planktonic algae in the Lower Rhine, Part 2 Algae without diatoms

Taxon	Author	Year
Cyanoprokaryota		
Chroococcales		
Aphanocapsa delicatissima	W. & G.S.West	1912
Aphanocapsa spp.	Nägeli	1849
Aphanothece minutissima	(West) Komárková-Legnerová et RG	1994
Aphanothece smithii	Komárková-Legnerová et RG	1994
Chroococcus limneticus	Lemmermann	1898
Chroococcus spp.	Nägeli	1849
Coelosphaerium dubium	Grunow in Rabenhorst	1865
Coelosphaerium kützingianum	Nägeli	1849
Cyanodictyon planctonicum	B.Meyer	1994
Gloeocapsa spp.	Kützing	1843
Lemmermanniella pallida	(Lemmermann) Geitler	1943
Merismodia spp.	Meyen	1839
Microcystis aeruginosa	Kützing	1845
Microcystis spp.	Kützing ex Lemmermann	1907

Table A2. (*continued*)

Taxon	Author	Year
Synechococcus spp.	Naegeli	1849
Woronichinia compacta	(Lemmermann) Komárek & Hindák	1988
Woronichinia naegeliana	(Unger) Elenkin	1933
Chroococcales (single cells) non det.	Wettstein	1923
Chroococcales (colonies) non det.	Wettstein	1923
Nostocales		
Anabaena circinalis	Rabenhorst ex Bornet & Flahault	1888
Anabaena spp.	Bory de Saint Vincent ex Bornet & Flahault	1886
Aphanizomenon spp.	Morren ex Bornet & Flahault	1888
Oscillatoriales		
Komvophoron constrictum	(Szafer) Anagnostidis & Komárek	1988
Limnothrix planctonica	(Woloszynska) M.E.Meffert	1988
Limnothrix redeckei	(Van Goor) Meffert	1988
Lyngbya hieronymusii	Lemmermann	1905
Lyngbya spp.	C.A.Agardh ex Gomont	1892
Phormidium spp.	Kützing ex Gomont	1892
Planktolyngbya limnetica	(Lemmermann) Komárková-Legnerová & Cronberg	1992
Planktolyngbya spp.	Anagnostidis & Komárek	1988
Planktothrix agardhii	(Gomont) Anagnostidis & Komárek	1988
Planktothrix rubescens	(de Candolle ex Gomont) Anagnostidis & Komárek	1988
Planktothrix spp.	(Gomont) Anagnostidis & Komárek	1988
Pseudanabaena catenata	Lauterborn	1915
Pseudanabaena constricta	(Szafer) Lauterborn	1915
Hormogonales non det.	G.F. Atkinson	1905
Heterocontophyta		
Chrysophyceae		
Chrysococcus biporus	Skuja	1939
Chrysococcus spp.	Klebs	1892
Dinobryon bavaricum	Imhof	1890
Dinobryon divergens	Imhof	1890
Dinobryon divergens var. schauinslandii	(Lemmermann) Brunnthaler	1901
Dinobryon sertularia	Ehrenberg	1835
Dinobryon suecicum	Lemmermann	1904
Dinobryon spp.	Ehrenberg	1833
Erkenia subaequiciliata	Skuja	1948
Mallomonas akrokomos	Ruttner in Pascher	1913
Mallomonas spp.	Perty	1851
Ochromonas spp.	Wyssotzki	1887
Syncrypta globosa	(Schiller) Bourrelly	1835
Synura uvella	Ehrenberg	1835
Chrysoflagellatae aloricat	Fritsch in G.S.West & Fritsch	1927
Chrysoflagellatae loricat	Fritsch in G.S.West & Fritsch	1927
Chrysolykos planctonicus	Mack	1951
Xanthophyceae		
Centritractus belenophorus	Lemmermann	1900
Dichotomococcus curvatus	Korshikov	1939
Goniochloris fallax	Fott	1957
Goniochloris mutica	(A.Braun) Fott	1960
Pseudostaurastrum hastatum	(Reinsch) Chodat	1928
Tribonema monochloron	Pascher & Geitler	1925
Tribonema spp.	Derbes & Solier	1856
Xanthophyceae non det.	P. Allorge ex Fritsch	1935

Table A2. (*continued*)

Taxon	Author	Year
Haptophyta		
Haptophyceae		
Chrysochromulina parva	Lackey	1939
Cryptophyta		
Cryptophyceae		
Chroomonas cf. *nordstedtii*	Hansgirg	1892
Cryptomonas marssonii	Skuja	1948
Cryptomonas rostratiformis	Skuja	1948
Cryptomonas spp.	Ehrenberg	1838
Rhodomonas lens	Pascher & Ruttner	1913
Rhodomonas lacustris var. lacustris	Pascher & Ruttner	1913
Rhodomonas lacustris var. nannoplanctica	(Skuja) Javornicky	1976
Cryptophyceae non det.	Fritsch in G.S.West & Fritsch	1927
Dinophyta		
Dinophyceae		
Ceratium hirundinella	(O.F.Müller) Dujardin	1841
Gymnodinium spp.	F. Stein	1878
Peridinium umbonatum s.l.	F. Stein	1883
Peridinium spp.	Ehrenberg	1830
Dinophyceae non det.	Fritsch in G.S.West & Fritsch	1927
Euglenophyta		
Euglenophyceae		
Euglena cf. *tripteris*	(Dujardin) Klebs	1883
Euglena spp.	Ehrenberg	1830
Lepocinclis spp.	Perty	1852
Phacus pyrum	(Ehrenberg) Stein	1878
Phacus spp.	Dujardin	1841
Strombomonas spp.	Deflandre	1930
Trachelomonas hispida	(Perty) Stein em. Deflandre	1926
Trachelomonas oblonga	Lemmermann	1899
Trachelomonas volvocina	Ehrenberg	1833
Trachelomonas spp.	Ehrenberg	1833
Chlorophyta		
Prasinophyceae		
Nephroselmis olivacea	Stein	1878
Tetraselmis bichlora	(Ettl H. et O.) Norris et al.	1980
Chlorophyceae		
Volvocales		
Carteria spp.	Diesing em. France	1893
Chlamydomonas spp.	Ehrenberg	1834
Chlorogonium spp.	Ehrenberg	1837
Eudorina elegans	Ehrenberg	1831
Gonium pectorale	O.f. Müller	1773
Gonium sociale	(Dujardin) Warming	1876
Hafniomonas spp.	Ettl et Moestrup	1980
Lobomonas spp.	Dangeard	1898
Pandorina morum	(O.F.Müller) Bory de Saint Vincent	1824
Pascherina tetras	(Korshikov) P.C.Silva	1959
Phacotus lenticularis	(Ehrenberg) F. Stein	1878
Pteromonas angulosa	(Carter) Lemmermann	1900
Pteromonas aculeata	Lemmermann	1900
Pteromonas aequiciliata	(Gicklorn) Bourrelly	1947
Pteromonas spp.	Seligo	1887

Table A2. (*continued*)

Taxon	Author	Year
Sphaerellopsis fluviatilis	(Stein) Pascher	1927
Spermatozopsis exsultans	Korshikov	1913
Volvocales non det.	Oltmanns	1904
Chlorococcales		
Actinastrum hantzschii	Lagerheim	1882
Amphikrikos minutissimus	Korshikov	1953
Amphikrikos nanus	(Fott & Heynig) Hindák	1977
Ankistrodesmus fusiformis	Corda	1838
Ankistrodesmus gracilis	(Reinsch) Korshikov	1953
Ankistrodesmus spiralis	(Turner) Lemmermann	1908
Ankyra ancora	(G.M.Smith) Fott	1957
Ankyra judayi	(G.M.Smith) Fott	1957
Ankyra lanceolata	(Korshikov) Fott	1957
Ankyra spp.	Fott	1957
Chlorotetraedron incus	Komárek & Kovacik	1985
Closteriopsis acicularis	(G.M.Smith) Belcher & Swale	1962
Coelastrum astroideum	De Notaris	1867
Coelastrum microporum	Naegeli in A.Braun	1855
Coelastrum sphaericum	Naegeli	1849
Coelastrum spp.	Naegeli	1849
Coenochloris hindakii	Komárek	1979
Coenochloris spp.	Korshikov	1953
Crucigenia fenestrata	(Schmidle) Schmidle	1900
Crucigenia lauterbornii	(Schmidle) Schmidle	1900
Crucigenia quadrata	Morren	1830
Crucigenia tetrapedia	(Kirchner) W. & G.S.West	1902
Crucignia spp.	Morren	1830
Crucigeniella apiculata	(Lemmermann) Komárek	1974
Crucigeniella crucifera	(Wolle) Komárek	1974
Crucigeniella neglecta	(Fott & Ettl) Komárek	1974
Crucigeniella rectangularis	(Nägeli) Komárek	1974
Crucigeniella spp.	Lemmermann	1900
Diacanthos belenophorus	Korshikov	1953
Dicellula planctonica	Svirenko	1926
Dictyosphaerium pulchellum	Wood	1872
Dictyosphaerium subsolitarium	Goor	1924
Didymocystis bicellularis	(Chodat) Komárek	1973
Didymocystis inermis	(Fott) Fott	1973
Didymocystis lineata	Korshikov	1953
Didymocystis planctonica	Korshikov	1953
Didymogenes anomala	(G.M.Smith) Hindák	1974
Didymogenes palatina	Schmidle	1905
Eutetramorus fottii	(Hindák) Komárek	1979
Eutetramorus planctonicus	(Korshikov) Bourrelly	1964
Eutetramorus spp.	Walton	1918
Gloeocystis spp.	Naegeli	1849
Granulocystopsis coronata	Hindák	1977
Kirchneriella contorta	(Schmidle) Bohlin	1897
Kirchneriella obesa	(W.West) Schmidle	1893
Kirchneriella spp.	Schmidle	1893
Komarekia appendiculata	(Chodat) fott & Komárek	1981
Korshikoviella limnetica	(Lemmermann) P.C.Silva	1959
Lagerheimia ciliata	(Lagerheim) Chodat	1895
Lagerheimia genevensis	Chodat	1895
Lagerheimia marssonii	Lemmermann	1900
Lagerheimia wratislawiensis	Schröder	1897

Table A2. (*continued*)

Taxon	Author	Year
Lagerheimia spp.	Chodat	1895
Micractinium bornhemiense	(Conrad) Korshikov	1953
Micractinium quadrisetum	(Lemmermann) G.M.Smith	1916
Micractinium pusillum	Fresenius	1858
Monoraphidium arcuatum	(Korshikov)) Hindák	1970
Monoraphidium circinale	(Nygaard) Nygaard	1979
Monoraphidium contortum	(Thuret) Komárková-Legnerová	1969
Monoraphidium griffithii	(M.J.Berkeley) Komárková-Legnerová	1969
Monoraphidium komarkovae	Nygaard	1979
Monoraphidium tortile	(W. & G.S.West) Komárková-Legnerová	1969
Monoraphidium spp.	Komárková-Legnerová	1969
Neodesmus danubialis	Hindák	1976
Nephrochlamys subsolitaria	(G.S.West) Korshikov	1953
Nephrochlamys spp.	Korshikov	1953
Nephrocytium agardhii	Naegeli	1849
Oocystis lacustris	Chodat	1897
Oocystis marssonii	Lemmermann	1898
Oocystis spp.	A.Braun	1855
Paradoxia multiseta	Svirenko	1928
Pediastrum boryanum	(Turpin) Meneghini	1840
Pediastrum duplex	Meyen	1829
Pediastrum simplex	Meyen	1829
Pediastrum tetras	(Ehrenberg) Ralfs	1844
Pediastrum spp.	Meyen	1929
Planktosphaeria gelatinosa	G.S.West	1918
Polyedriopsis spinulosa	Schmidle	1899
Pseudoschroederia robusta	(Korshikov) E.Hegewald & Schnepf	1986
Quadrigula pfitzeri	(Schröder) (G.M.Smith)	1920
Quadricoccus laevis	Fott	1948
Quadricoccus spp.	Fott	1948
Raphidocelis sigmoidea	Hindák	1977
Raphidocelis spp.	Hindák	1977
Scenedesmus aculeolatus	Reinsch	1877
Scenedesmus acuminatus	(Lagerheim) Chodat	1902
Scenedesmus acutus	Meyen	1829
Scenedesmus armatus	Chodat	1913
Scenedesmus bernardii	(G.M.Smith)	1916
Scenedesmus bicaudatus	Dedusenko	1925
Scenedesmus costato-granulatus	Skuja	1948
Scenedesmus denticulatus	Lagerheim	1882
Scenedesmus disciformis	(Chodat) Fott & Komárek	1960
Scenedesmus ecornis	(Ehrenberg) Chodat	1926
Scenedesmus intermedius	Chodat	1926
Scenedesmus linearis	Komárek	1974
Scenedesmus obtusus	Meyen	1829
Scenedesmus opoliensis	P.G.Richter	1896
Scenedesmus ovalternus	Chodat	1926
Scenedesmus quadricauda	(Turpin) Brébisson sensu Chodat	1913
Scenedesmus sempervirens	Chodat	1913
Scenedesmus serratus	(Corda) Bohlin	1902
Scenedesmus spp.	Meyen	1829
Schroederia setigera	(Schröder) Lemmermann	1898
Schroederia spp.	Lemmermann	1898
Siderocelis kolkwitzii	(Naumann) Fott	1934
Siderocoelis ornata	(Fott) Fott	1934
Siderocystopsis fusca	(Korshikov) Swale	1964
Sphaerocystis planctonica	(Korshikov) Bourelly	1966

Table A2. (*continued*)

Taxon	Author	Year
Tetrachlorella alternans	(G.M.Smith) Korshikov	1939
Tetrachlorella spp.	Korshikov	1939
Tetraedron caudatum	(Corda) Hansgirg	1888
Tetraedron minimum	(A.Braun) Hansgirg	1888
Tetraedron regulare	Kützing	1845
Tetraedron triangulare	Korshikov	1953
Tetraedron spp.	Kützing	1845
Tetrastrum glabrum	(Roll) Ahlstrom & Tiffany	1934
Tetrastrum heteracanthum	(Nordstedt) Chodat	1895
Tetrastrum komarekii	Hindák	1977
Tetrastrum punctatum	(Schmidle) Ahlstrom & Tiffany	1934
Tetrastrum staurogeniaeforme	(Schröder) Lemmermann	1900
Tetrastrum triacanthum	Korshikov	1939
Tetrastrum triangulare	(Chodat) Komárek	1974
Treubaria cf. *euryacantha*	(Schmidle) Korshikov	1953
Treubaria schmidlei	(Schröder) Fott & Kovacik	1975
Treubaria triappendiculata	Bernard	1908
Chlorophyceae non det.		
Ulvophyceae		
Ulotrichales		
Catena viridis	Chodat	1900
Elakatotrix spp.	Wille	1898
Gloeotila spiralis	Chodat	1902
Hortobagyiella verrucosa	(Heynig) Hindák	1976
Koliella longiseta	(Vischer) Hindák	1963
Koliella spiralis	Kuosa	1988
Koliella spp.	Hindák	1963
Marvania geminata	Hindák	1976
Planctonema spp.	Schmidle	1903
Conjugatophyceae		
Desmidiales		
Closterium aciculare	T.West	1860
Closterium acutum var. variabile	(Lemmermann) Willi Krieger	1935
Closterium leibleinii	Kützing ex Ralfs	1848
Closterium limneticum	Lemmermann	1899
Closterium moniliferum	(Bory de Saint Vincent Ehrenberg ex Ralfs	1848
Closterium spp.	Nitzsch ex Ralfs	1848
Cosmarium impressulum f. minor	Croasdale	1956
Cosmarium spp.	Corda ex Ralfs	1848
Staurastrum paradoxum	Meyen ex Ralfs	1848
Staurastrum spp.	Meyen ex Ralfs	1848
Zygnematales		
Mougeotia spp.	C.Agardh	1824

Appendix B

Animals found in plankton samples of the Lower Rhine 1986–2004 (Table B1).

Table B1. Animals found in plankton samples of the Lower Rhine 1986–2004

Taxon	Author	Year
Rhizopoda		
Arcella spp.	Ehrenberg	1838
Assulina spp.	Greeff	
Centropyxis aculeata	(Ehrenberg) Stein	1830
Cyphoderia ampulla	(Ehrenberg) Schlumberger	1840
Difflugia spp.	Leclerc	1815
Euglypha spp.	Dujardin	1841
Heleopera spp.	Leidy	1879
Testacea non det.		
Rotatoria		
Anuraeopsis fissa	(Gosse)	1851
Ascomorpha ecaudis	(Perty)	1850
Ascomorpha ovalis	(Carlin)	1843
Ascomorpha spp.	(Perty)	1850
Asplanchna spp.	Gosse	1850
Bdelloidea non det.		
Brachionus angularis	Gosse	1851
Brachionus bidentata	(Anderson)	1889
Brachionus calyciflorus amphiceros	(Ehrenberg)	1838
Brachionus calyciflorus	(Pallas)	1776
Brachionus leydigi	(Cohn)	1862
Brachionus quadridentatus	(Hermann)	1783
Brachionus spp.	Pallas	1776
Brachionus urceolaris	(O.F.Müller)	1773
Brachionus urceolaris fo. *nilsoni*	(Ahlstrom)	1940
Brachionus urceolaris fo. *variabilis*	(Hempel)	1896
Cephalodella gibba	(Ehrenberg)	1832
Cephalodella spp.	Bory de Saint Vincent	1826
Collotheca mutabilis	(Hudson)	1885
Collotheca spp.	Harring	1913
Colurella spp.	Bory de Saint Vincent	1824
Colurella uncinata	(O.F.Müller)	1773
Conochilus spp.	Ehrenberg	1834
Conochilus unicornis	Rousselet	1892
Dicranophorus spp.	Nitzsch	1827
Epiphanes spp.	(Ehrenberg)	1832
Euchlanis dilatata	(Ehrenberg)	1832
Euchlanis spp.	Ehrenberg	1832
Filinia longiseta	(Ehrenberg)	1834
Filinia longiseta longiseta	(Ehrenberg)	1834
Filinia passa	(O.F.Müller)	1786
Floscularia spp.	Cuvier	1798
Gastropus cf. *hyptopus*	(Ehrenberg)	1838
Gastropus stylifer	(Imhof)	1891
Hexarthra mira	(Hudson)	1871
Hexarthra spp.	Schmarda	1854
Kellicottia longispina	(Kellicott)	1879
Keratella cochlearis f. *cochlearis*	(Gosse)	1851
Keratella cochlearis f. *tecta*	(Gosse)	1851
Keratella quadrata	(O.F.Müller)	1786
Keratella spp.	Bory de Saint Vincent	1822
Lecane arcuata	(Bryce)	1891
Lecane bulla	(Gosse)	1851
Lecane luna	(O.F.Müller)	1776
Lecane lunaris	(Ehrenberg)	1832
Lecane spp. *(Monostyla)*	(Bartos)	1959
Lepadella ovalis	(O.F.Müller)	1786
Lepadella spp.	Bory de Saint Vincent	1826
Monommata spp.	Bartsch	1870
Mytilina spp.	Bory de Saint Vincent	1836
Notholca acuminata	(Ehrenberg)	1832
Notholca caudata	Carlin	1943
Notholca labis	(Gosse)	1887
Notholca spp.	Gosse	1886
Notholca squamula	(O.F.Müller)	1786
Platyias quadricornis	(Ehrenberg)	1832
Ploesoma hudsoni	(Imhof)	1891
Polyarthra dolichoptera	(Idelson)	1925
Polyarthra major	(Burckhardt)	1900
Polyarthra spp.	Ehrenberg	1834
Polyarthra vulgaris	(Carilin)	1943
Pompholyx spp.	Gosse	1851
Pompholyx sulcata	(Hudson)	1885
Proales spp.	Gosse	1886
Rhinoglena frontalis	(Ehrenberg)	1853
Scaridium spp.	(Ehrenberg)	1830
Synchaeta spp	(Ehrenberg)	1832
Synchaeta tremula/oblonga Gruppe		
Testudinella cf. *patina*	(Hermann)	1783
Testudinella spp.	Bory de Saint Vincent	1826
Trichocerca spp.	Lamarck	1801
Trichotria spp.	Bory de Saint Vincent	1827
Trichotria tetractis	(Ehrenberg)	1830

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