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Effects of an extreme precipitation event on water chemistry and phytoplankton in the Swedish Lake Mälaren

Gesa A. Weyhenmeyer[1)], Eva Willén[2)] and Lars Sonesten[2)]

[1)] *Erken Laboratory, Department of Limnology, Evolutionary Biology Centre, Uppsala University, Norr Malma 4200, SE-761 73 Norrtälje, Sweden; present address: Department of Environmental Assessment, Swedish University of Agricultural Sciences, P.O. Box 7050, SE-750 07 Uppsala, Sweden (e-mail: gesa.weyhenmeyer@ma.slu.se)*

[2)] *Department of Environmental Assessment, Swedish University of Agricultural Sciences, P.O. Box 7050, SE-750 07 Uppsala, Sweden*

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Extreme events can often be ecologically more relevant than fluctuations in the mean climate. We studied the effects of an exceptionally rainy period in 2000 on 13 physical and chemical variables and on the phytoplankton biomass and composition in Lake Mälaren, the third largest lake in Sweden. The rainy period caused a distinct increase in the chemical loading, in particular the loading of organic carbon, into Lake Mälaren. As a consequence water color, measured as light absorption of filtered water, was up to 3.4 times higher in 2001 than ever recorded since 1965. In addition, reactive silica concentrations doubled, particle concentrations were the highest and conductivity was the lowest registered. The changes in physical and chemical conditions of Lake Mälaren in 2001 showed temporal and spatial differences depending on runoff processes in the catchment, water residence times and the type of variable. It is suggested that especially the increase in water color was responsible for the observed doubling in the cryptophycean biomass in Lake Mälaren in May 2001. The increase in water color and cryptophycean biomass was also observed in a nearby lake. Such increases required alterations in the treatment process of raw water from Lake Mälaren for the drinking water supply of Stockholm city.

Introduction

News about extreme precipitation events and consequent enormous floods are no rarity. Extreme events very often have serious and damaging effects on human society (Meehl *et al.* 2000). Floods are especially feared due to a risk of large loss of life and tremendous economic damage. According to recent climate models it is very likely that high floods will occur more frequently in certain areas in the near future (e.g. IPCC 2001, Prudhomme *et al.* 2002, Senior *et al.* 2002). Sweden is one of the areas where a higher frequency of heavy precipitation and extreme runoff events has been predicted (Bergström *et al.* 2001, Christensen *et al.* 2001, Rummukainen *et al.* 2001). The study of extreme events and their impacts on terrestrial and aquatic ecosystems has become an important issue (Easterling *et al.* 2000). Often a single extreme climatic event has a stronger impact on an ecosystem than a gradual climatic trend (Parmesan *et al.* 2000). A

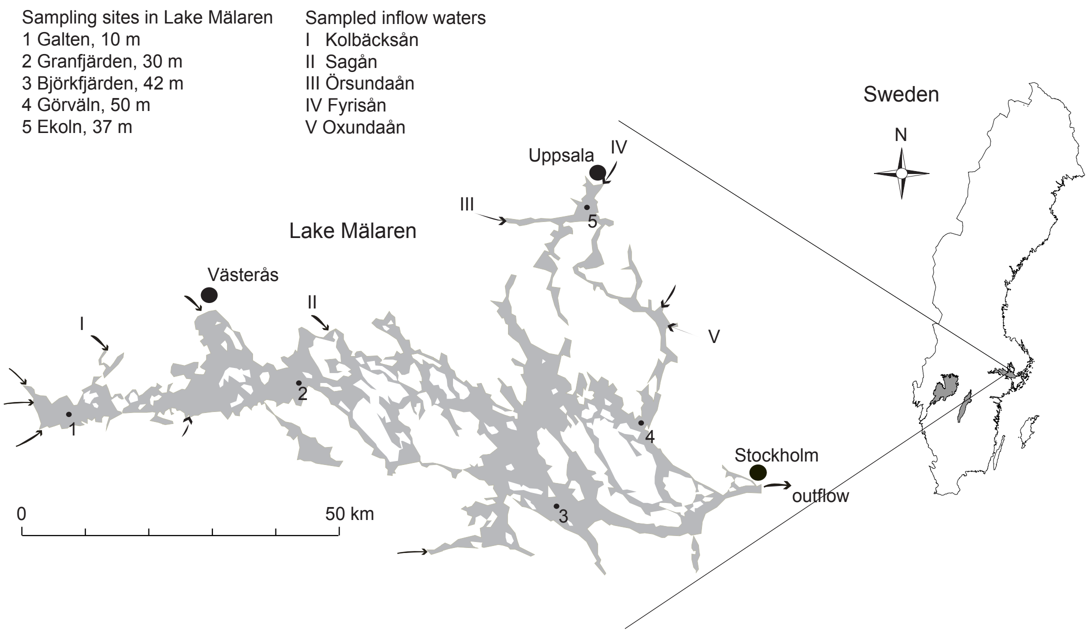

Fig. 1. Sampling sites in Lake Mälaren, inflow water locations and location of the meteorological stations at Västerås and Uppsala.

single unusual event is able to extensively change the ecosystem structure and function within a short time period. Therefore, there is a need for research that focuses on impacts of exceptional events. Patten *et al*. (2001) carried out a comprehensive study on the effects of a seven-day experimental controlled flood on the chemistry and biology of the Colorado River, U.S. Although the test flood was only about 10% of the pre-dam spring snowmelt floods (Schmidt *et al*. 2001), effects on the physics and chemistry of the Lake Powell reservoir, and on the aquatic food chain in the Colorado River were pronounced (Hueftle and Stevens 2001, Shannon *et al*. 2001, Valdez *et al*. 2001). However, the effects did not seem to be long-lasting. Shannon *et al*. (2001) and Valdez *et al*. (2001) reported that macroinvertebrates, filamentous algae and fish recovered within three months after the flood. In other ecosystems, especially in terrestrial ecosystems, complete recovery might take a much longer time or never happen. An extended drought in New Mexico in the 1950s, for example, caused the boundary between pine and piñon-juniper woodland to shift by 2 km, where it remains today (Allen and Breshears 1998).

In this study we focus on an extraordinary event in Sweden. The autumn/early winter of the year 2000 was very rainy so that monthly precipitation exceeded all previously registered values at many locations. At Västerås in the catchment of Lake Mälaren, for example, the monthly precipitation in November was 123 mm, which is 71 mm higher than the precipitation November reference normal 1961–1990 and 20 mm higher than the next highest precipitation event since 1860 (SMHI 2000). Already in July 2000 an unusual precipitation event had occurred in the same area with 72 mm precipitation within one single afternoon. As a consequence of these high amounts of precipitation, water discharges of several running freshwaters reached unusually high values (SMHI 2000). Here we hypothesize that such a rainy period can cause exceptional physical, chemical and biological conditions in a lake as compared with those in the previous years. To test the hypothesis we analyzed physical, chemical and biological conditions in Lake Mälaren after the precipitation event in 2000 and compared these with previous conditions. We chose Lake Mälaren because long term data (since 1965) are available for this lake. As a final step of the study, the results of Lake Mälaren were compared with monitoring data from a small lake, situated close to Lake Mälaren. The small lake was chosen because it was subjected to the same climatic conditions as Lake Mälaren.

Study site and data material

Lake Mälaren (Fig. 1) belongs to Sweden's largest lakes with a surface area of 1120 km^2, a volume of 14.03 km^3, a mean depth of 12.8 m (max depth: 63 m) and a mean water turnover time of 2.8 years (Kvarnäs 2001). Its catchment area of 22 603 km^2 is dominated by forests and wetlands (70%), arable lands and meadows (20%) and lakes (10%). The yearly mean total phosphorus concentrations in the central, least affected part of Lake Mälaren at Björkfjärden during the ice-free periods was around 23 μg l^{-1} in the past 20 years (Wilander and Persson 2001). In Lake Mälaren, water samples have frequently been taken on a monthly basis during the main growing season from May to October (i.e. ice-free period) since 1965 (at the lake sites Galten, Görväln and Ekoln) or since 1967 (at Granfjärden and Björkfjärden). Additional water samples for chemical determinations have been collected below the ice cover in March. Samples have always been determined by one and the same laboratory except of the years 1996 and 1998. To get a homogeneous data set with comparable methods we needed to exclude these two years from the time series. While data on water temperature and water chemistry in surface waters from the national data set of monthly monitoring (Table 1) were used from 1965 to 2001, data on phytoplankton were considered only from 1979 to 2001. Before 1979 sampling

Table 1. Degrees of explanation of the regressions of the mean (July to December) water discharge of Kolbäcksån on lake chemical variables and phytoplankton measured at the beginning of the following year (i.e. March for chemical variables and May for phytoplankton) at Granfjärden, the lake site that is mostly influenced by Kolbäcksån, from 1967 to 2001 (for chemical variables) and 1979 to 2001 (for phytoplankton). ** indicates significant at the $p < 0.01$ level, * significant at the $p < 0.05$ level and n.s. not significant. The number of observations is 33 for chemical variables and 21 for phytoplankton due to the missing years 1996 and 1998.

Variable	r^2
Water color (Color) (measured as light absorption of 0.45 µm filtered water at 420 nm in a 5 cm cuvette)	0.64**
Suspended particulate matter (SPM) (measured as light absorption of unfiltered water at 420 nm in a 5 cm cuvette)	0.47**
Reactive silica (Si)	0.42**
Conductivity	0.19**
pH	0.18*
Total phosphorus (Tot P)	0.18*
Phosphate-phosphorus (PO_4-P)	n.s.
Total nitrogen (Tot N)	n.s.
Nitrate-nitrogen (NO_3-N) (nitrate-nitrogen includes nitrite-nitrogen which is less than 5% of the sum nitrate-nitrite-nitrogen (Anders Wilander pers. comm.))	n.s.
Ammonium-nitrogen (NH_4-N)	n.s.
Oxygen	n.s.
Surface water temperature (Temperature)	n.s.
Alkalinity	n.s.
Biomass of Cryptophyceae	0.30**
Biomass of Bacillariophyceae	0.19*
Total phytoplankton biomass (Total biomass)	n.s.
Biomass of Cyanobacteria (Cyano)	n.s.
Biomass of Dinophyceae (Dino)	n.s.
Biomass of Chrysophyceae (Chryso)	n.s.
Biomass of Chlorophyceae (Chloro)	n.s.
Biomass of other phytoplankton groups (Others)	n.s.

of phytoplankton was carried out mainly in the surface layer (0–1 m) in Lake Mälaren. This kind of sampling might give deviating results from the sampling after 1979 where phytoplankton has been sampled in the whole epilimnion.

From 1996 the monthly lake monitoring program was reduced from six to four sampling occasions per year. In order to achieve a comparable data set, only data from the months March, May, July and September were considered in this study. Furthermore, only the five lake sites where both chemical and biological measurements have been carried out were chosen (Fig. 1). For more information about the monitoring program and analyses *see* Willén (2001).

In addition to data on water temperature, water chemistry and phytoplankton in Lake Mälaren, water discharge and chemical data from the monthly monitoring of five inflow waters (Fig. 1) were used. The five inflow waters are regarded as important inflow waters, making up about 40% of the total discharge to Lake Mälaren (Wallin *et al*. 2000). The monthly monitoring of the inflow waters began in 1965, with the exception of Oxundaån where the monitoring started in 1968. The loading of seven chemical variables from the five inflow waters were calculated by multiplying the monthly chemical concentrations in the inflow waters by the monthly mean water discharge. The chemical loading of total organic carbon has been available since 1997. Before that the chemical oxygen demand was measured instead. The chemical oxygen demand (COD_{Mn}) was translated into total organic carbon (TOC) with the equation: $TOC = COD_{Mn}/1.10$ (Wilander 1988).

Apart from physical, chemical and biological lake data, the Swedish Meteorological Institute provided daily data on precipitation from Västerås and Uppsala (Fig. 1) and monthly data on Lake Mälaren's water level for the time period 1961–2001.

The results of Lake Mälaren were compared with the results of Övre Skärsjön, a small lake (1.65 km^2), 40 km northwest of the westernmost part of Lake Mälaren. For this lake data of monthly monitoring (February, May to October) since 1988 are available. The same laboratory carried out all analyses in this lake as in Lake Mälaren and the same methods were used.

Results

Precipitation, water discharge and chemical loading

In the western part of Lake Mälaren at Västerås (Fig. 1), the sum of precipitation from July to December in 2000 was 523 mm. Such high precipitation has never been registered since 1961. Especially rainy were July, November and December with monthly precipitations exceeding 100 mm. Accordingly, the water discharge in that area, represented by the water discharge of Kolbäcksån, reached exceptionally high values during these months (Fig. 2). The most extreme water flow was in November 2000 being twice as high as the second highest water flow recorded since 1965 at that time of the year. The water discharge in November 2000 exceeded the 1965–1999 mean of 32 ± 20 m^3 s^{-1} by 150 m^3 s^{-1}, corresponding to an excess of more than 7 standard deviations. The high water discharge in 2000 led to unusually high loadings of total organic carbon and reactive silica in Kolbäcksån, being almost twice as high as ever measured before (Fig. 3). The peak was less pronounced for nutrients such as phosphorus and nitrogen.

The rainy period caused very high water levels from August 2000 to January 2001. The most extreme water level was reached in December 2000 being almost half a meter above the mean December water level from 1968 to 1999 and thereby reaching 0.89 m above sea level.

In the northeastern part of Lake Mälaren at Uppsala (Fig. 1) the sum of precipitation from July to December in 2000 was high with 433 mm yet not exceptionally high. Accordingly, here also water discharges (Fig. 2) and loadings were high but not exceptionally high.

Changes in lake water chemistry after the precipitation event

Among all chemical variables tested, water color showed the strongest relationship to water discharge in Lake Mälaren (Table 1). In addition, suspended particulate matter and reactive silica showed a strong relationship to water discharge.

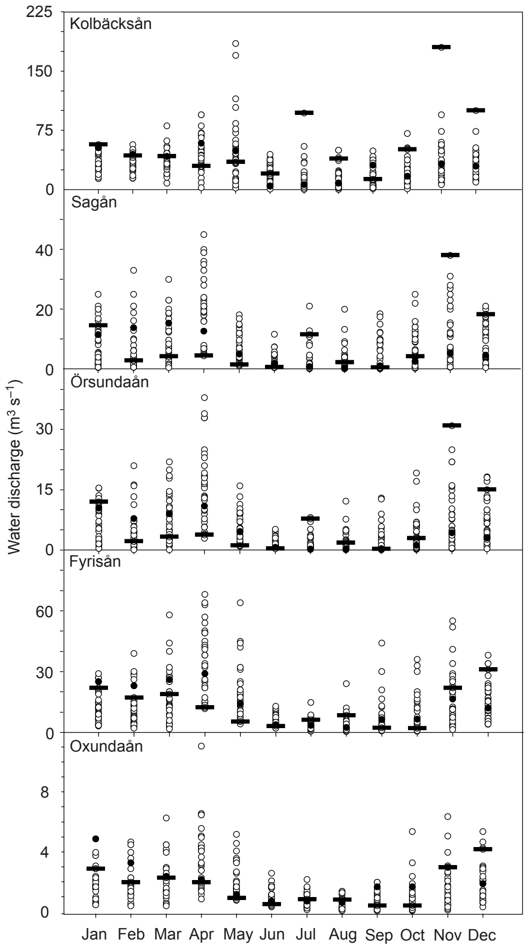

Fig. 2. Monthly mean water discharge values for five inflow waters of Lake Mälaren from 1965 to 2001, respectively for Oxundaån 1968 to 2001. The horizontal bars incidate the monthly mean water discharges in 2000, the filled circles indicate the monthly mean water discharges in 2001.

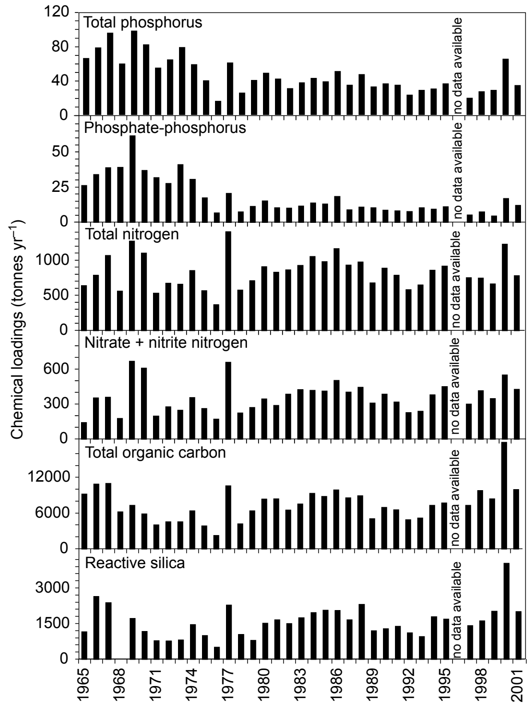

Fig. 3. Annual chemical loadings of Kolbäcksån into Lake Mälaren from 1965 to 2001.

Conductivity, pH and total phosphorus concentrations were also significantly related to water discharge but the relationships were weak. The stronger the dependence of a variable was to water discharge the stronger was the response of the variable to the rainy period in the second half of 2000. At the beginning of 2001 water color was either exceptionally high or higher than normal at all stations in Lake Mälaren (Table 2). At Galten in the western part of the lake water color, measured as light absorption of filtered water, reached a value of up to 0.28 $A_{420/5}$. Such a high value has never been measured before anywhere in Lake Mälaren. At Björkfjärden in the central part of the lake water color in May 2001 differed most markedly from the water color of previous years. Here the water color was 3.4 times higher than ever measured before at this site in May in the time period 1965 to 2001, reaching 0.14 $A_{420/5}$. The water color at this site in May exceeded the 1967–2000 mean by 0.1 $A_{420/5}$, corresponding to an excess of more than 7 standard deviations. The water color remained high at all stations in the lake during the whole year 2001 (Table 2).

The amount of suspended particulate matter in the lake was also related to water discharge (Table 1) and showed a clear response to the rainy period in 2000. In March and May 2001 the amount of suspended particulate matter was either exceptionally high or higher than normal at all stations in Lake Mälaren (Table 2).

Other water chemical variables that showed unusual values at two or more stations at the same time in 2001 were reactive silica and conductivity (Table 2). Concentrations of reactive silica reached maximum in 2001 as compared with those in all previous years, especially in the central part of the lake (up to 2.3 mg l^{-1}). In contrast, conductivity reached exceptionally low values, especially in the western part of the lake (as low as 7.1 mS m^{-1} (25 °C) at Galten).

Except for the water-discharge dependent variables — water color, suspended particulate matter, reactive silica and conductivity — the other water physical/chemical variables tested showed no coherent abnormalities after the rainy

Table 2. Physical and chemical conditions at five sites in Lake Mälaren in 2001 compared with the longterm conditions in 1965–2001 (Galten, Görväln and Ekoln), or in 1967–2001 (Granfjärden and Björkfjärden). min = the values of 2001 are the lowest ever measured for the specific month, ↘ = the values of 2001 are below the 25% quartile, n = the values of 2001 are within the 25% and 75% quartile, i.e. the values are normal, ↗ = the values of 2001 are above the 75% quartile, and max means that the values of 2001 are the highest ever measured for the specific month. Missing years are 1996 and 1998. For information on the variables *see* Table 1.

	Mar	May	Jul	Sep	Mar	May	Jul	Sep
	Temperature				Tot N			
Galten	n	↗	↗	n	n	↘	↘	n
Granfjärden	n	n	↗	n	n	↘	↘	↘
Björkfjärden	n	n	n	n	n	↗	n	n
Görväln	↗	↗	↗	n	↗	↗	↗	↗
Ekoln	n	↗	↗	n	n	n	n	n
	Oxygen				PO_4-P			
Galten	↗	↗	↘	n	n	n	↘	n
Granfjärden	n	↘	n	↗	↗	n	n	n
Björkfjärden	↗	min	n	n	↗	↗	n	n
Görväln	n	↘	n	n	↗	n	n	↘
Ekoln	↗	n	n	n	n	↘	↘	n
	pH				Tot P			
Galten	↘	max	↘	n	n	n	n	n
Granfjärden	↘	n	n	↗	n	n	n	n
Björkfjärden	↘	↘	↘	n	↗	↗	↗	↗
Görväln	n	n	n	n	↗	n	n	n
Ekoln	↘	↘	n	n	n	↘	n	↘
	Conductivity				SPM			
Galten	min	↘	min	n	↗	↗	↗	n
Granfjärden	↘	min	min	min	max	↗	↗	↗
Björkfjärden	↘	min	min	min	max	max	max	max
Görväln	↘	n	↘	↘	max	max	↗	↗
Ekoln	n	n	↘	n	↗	↗	n	n
	Alkalinity				Color			
Galten	↘	n	n	n	max	↗	max	↗
Granfjärden	n	n	n	n	max	↗	max	max
Björkfjärden	n	n	n	n	max	max	max	max
Görväln	n	↗	n	n	max	max	max	max
Ekoln	↗	n	n	n	↗	↗	max	↗
	NH_4-N				Si			
Galten	n	n	n	n	↗	↘	n	↘
Granfjärden	n	n	↗	n	↗	↗	↗	n
Björkfjärden	n	↗	↗	↘	max	max	max	n
Görväln	n	↗	↗	↘	n	max	↗	↘
Ekoln	↗	n	↗	n	↗	↗	↗	↗
	NO_3-N							
Galten	n	min	↘	n				
Granfjärden	↘	↘	↘	↘				
Björkfjärden	↗	n	n	↗				
Görväln	n	↗	n	↗				
Ekoln	n	↘	n	n				

period in 2000 at the lake sites. Alkalinity was the water chemical variable in the lake that remained most normal after the rainy period (Table 2).

Most water chemical records observed in 2001 were registered in the central part of the lake at Björkfjärden. Here, fifteen records occured, while the lake sites Görväln and Granfjärden showed seven records. The lake sites with most influence of inflow waters such as Galten and Ekoln presented only five and one water chemical record respectively in 2001. Records were found throughout the year but most records were observed in May. In September the water chemistry started to normalize again and only a few records, i.e. records in water color, suspended particulate matter and conductivity, could be observed (Table 2).

Table 3. Phytoplankton biomass at five sites in Lake Mälaren in 2001 compared with the longterm phytoplankton biomass in 1979–2001. min = the values of 2001 are the lowest ever measured for the specific month, ↘ = the values of 2001 are below the 25% quartile, n = the values of 2001 are within the 25% and 75% quartile, i.e. the values are normal, ↗ = the values of 2001 are above the 75% quartile, and max = the values of 2001 are the highest ever measured for the specific month. Missing years are 1996 and 1998. For abbreviations see Table 1.

	May	Jul	Sep	May	Jul	Sep
	Total biomass			Chryso		
Galten	max	↗	n	↗	↗	↗
Granfjärden	n	n	max	n	↗	↗
Björkfjärden	n	↗	n	n	max	n
Görväln	↗	↗	n	n	↗	n
Ekoln	n	n	↘	↗	↗	↗
	Cyano			Bacillario		
Galten	n	n	↗	max	n	n
Granfjärden	n	n	max	n	n	max
Björkfjärden	n	↗	n	n	max	↗
Görväln	↗	max	n	↗	↗	n
Ekoln	n	n	n	n	n	n
	Crypto			Chloro		
Galten	max	n	↗	↗	↗	↗
Granfjärden	max	↘	max	n	n	↗
Björkfjärden	max	↗	n	n	↗	↗
Görväln	max	n	n	↗	n	max
Ekoln	↗	↗	n	↗	n	n
	Dino			Others		
Galten	n	n	↗	max	max	max
Granfjärden	n	n	max	↗	n	↗
Björkfjärden	n	↘	n	max	↗	n
Görväln	n	min	n	n	↗	↗
Ekoln	↗	n	n	↗	↗	↗

Changes in the phytoplankton biomass after the precipitation event

Among all phytoplankton groups tested only the biomass of the flagellate group Cryptophyceae was significantly related to water discharge at the $p < 0.01$ level (Table 1). In May 2001, after the unusual precipitation event, the biomass of Cryptophyceae reached the highest measured values at four of five lake sites (Table 3; up to 1.33 mm^3 l^{-1} at Granfjärden; median biomass in Lake Mälaren in May: 0.04 to 0.35 mm^3 l^{-1}). At Ekoln the biomass of Cryptophyceae was comparatively high in May 2001 but not exceptionally high for that lake site. At Björkfjärden the strongest relative increase in the biomass of the Cryptophyceae was observed, being 19 times higher in May 2001 than the May median from 1979 to 2001 and 1.6 times higher than measured earlier at that lake site. Here the cryptophycean biomass in May exceeded the 1979–2000 mean by 0.65 mm^3 l^{-1}, corresponding to an excess of more than 4 standard deviations. The increase in the cryptophycean biomass caused that the proportion of the cryptophycean to the total phytoplankton biomass increased from 10% ± 14% to 39% in 2001. The May biomass of Cryptophyceae could be related to water temperatures and water color in May (Table 4), a

Table 4. Prediction (standard least squares model) of the Cryptophyceae biomass by water temperature and water color (measured as light absorption of filtered water) at five sites in Lake Mälaren in May 1979–2001 and at one site in Övre Skärsjön in May 1988–2001. The number of observations in Lake Mälaren is 21 due to the missing years 1996 and 1998. n.s. means not significant.

Lake/sites	r^2	p
Mälaren		
Galten	n.s.	n.s.
Granfjärden	0.42	< 0.0075
Björkfjärden	0.85	< 0.0001
Görväln	0.60	< 0.0004
Ekoln	0.46	< 0.004
Övre Skärsjön	0.48	< 0.03

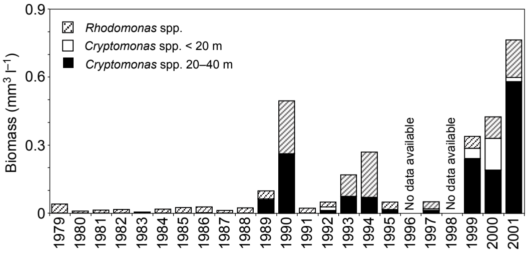

Fig. 4. Main species of Cryptophyceae at Björkfjärden in Lake Mälaren in May from 1979 to 2001.

month when Lake Mälaren is usually completely mixed. The relationship was especially strong at Björkfjärden, where the distinctive increase in the biomass of Cryptophyceae in May 2001 comprised an increase in the biomass of intermediate-sized *Cryptomonas* spp. (20–40 μm). The biomass of all other taxa belonging to the group of Cryptophyceae remained more or less the same as before (Fig. 4). Also in summer the biomass of the mentioned size-group of *Cryptomonas* spp. increased at all lake sites except Ekoln. At that time very large *Cryptomonas* spp. (> 40 μm) occurred. The biomass of Cryptophyceae remained high (0.14–1.19 $mm^3\ l^{-1}$) until July 2001 at two out of five sites and began to normalize at these sites in September (Table 3).

Apart from Cryptophyceae, no other phytoplankton group with an appreciable biomass showed exceptional biomass values at more than one lake site in May 2001. Exceptional biomass values at more than one lake site were only reached for some rare phytoplankton groups with a low biomass that are put together in the group of other phytoplankton (Table 3). Here higher than normal biomasses were observed for the groups Prasinophyceae (at Galten, Görväln and Ekoln), Raphidophyceae (at Galten and Björkfjärden) and Euglenophyceae (at Galten and Granfjärden). The appearance of Raphidophyceae was most conspicuous. This group has never been registered in the water column in spring but in May 2001 it was observed in the water column during this season. The increase in Raphidophyceae comprised an increase in *Gonyostomum semen*, which now and then is recorded in low biomass in late summer.

Most of the unusual phytoplankton biomass records were detected in the western part of Lake Mälaren at Galten and Granfjärden and least in the northeastern part at Ekoln. Cyanophyceae and Dinophyceae were the phytoplankton groups that showed least abnormal biomass values in Lake Mälaren in 2001.

Effects of the precipitation event on a lake close to Lake Mälaren

Maximum levels of water color as a consequence of the rainy period in 2000 were registered not only in Lake Mälaren but also in Övre Skärsjön, a lake located about 40 km northwest of the westernmost part of Lake Mälaren. In Övre Skärsjön the lake water has never been so brownish as registered in May 2001 as comparing with the water color in 1988–2001 (light absorption of filtered water: 0.24 $A_{420/5}$; previous years: 0.08–0.19 $A_{420/5}$). Also the cryptophycean biomass in Övre Skärsjön was exceptionally high in May 2001 as compared with that in previous years (0.017 $mm^3\ l^{-1}$; previous years: 0–0.011 $mm^3\ l^{-1}$). Like in Lake Mälaren, the cryptophycean biomass in May could be predicted by water temperature and water color (Table 4).

Discussion

Effects of an unusually rainy period on water color and phytoplankton

In Lake Mälaren, water color was the variable that responded most clearly to the rainy period in 2000. Unusually high water discharges in the western part of the lake in 2000 and a consequent very high loading of total organic carbon including humic substances into the lake in late 2000/early 2001 (Fig. 3) caused the lake water to become brownish (Table 2), first in the western part of the lake and finally also in the central part. The increase in water color in 2001 was in the same order of magnitude as the increase in water discharge in 2000, since the excess for water color in 2001 was also up to 7 standard deviations as compared with the water color in the previous years. The effect of the rainy period on water color in Lake Mälaren in 2000 was lasting throughout the following year. As Wetzel (2001) pointed out, humic compounds tend to have long residence times in lakes since their degradation by aquatic microflora proceeds slowly. Such a long-lasting effect of an extreme event on water color has also been observed by Riis and Sand-Jensen (1988) in the Danish Grane Langsø.

Water color is correlated with the dissolved organic carbon (e.g. Pace and Cole 2002) that has earlier been related to changes in precipitation (e.g. Clair *et al.* 1994, Dillon and Molot 1997, Correll *et al.* 2001). Clair *et al.* (1999) suggested that the export of dissolved organic carbon in Canada is going to increase by approximately 14% under the predicted climate change with increases in runoff. Such an increase can strongly affect both the quantity and the quality of light that is available for phytoplankton (Phlips *et al.* 2000). Also the phytoplankton vertical distribution has been observed to be affected by dissolved organic carbon (Christensen *et al.* 1996). In Lake Mälaren and also in Övre Skärsjön, the increase in water color coincide with an increase in the cryptophycean biomass. At the beginning of 2001 when the water became very brownish the cryptophycean biomass was the highest recorded since the 1970s. Cryptophyceae belong to the phytoplankton group that are mobile and therefore has an ability to maintain an elevated position in the water column (Reynolds 1984). As this group of algae is a good competitor under increased nutrient conditions (Lepistö and Holopainen 2003) like those in Lake Mälaren, it is expected from other field observations and laboratory studies (e.g. Morgan and Kalff 1979, Dokulil 1988) that these flagellates outcompete other phytoplankton groups when the light climate declines. In Lake Mälaren especially large *Cryptomonas* spp. (> 20 μm) responded to the brownish lake water. Such large *Cryptomonas* spp. are rather unusual in the lake nowadays but they were more frequent before the phosphorus input was reduced in the mid 1970s.

The biomass of Cryptophyceae remained high during the summer stratification when also the water color and the water level were still high. In autumn when both the water level and the water color in Lake Mälaren started to decrease, the biomass of cryptophycean flagellates began to normalize again. The biomass of Cryptophyceae could, however, not solely be explained by variations in water color over the whole period from 1979 to 2001. Apart from water color, water temperatures in spring, corresponding to the time of water turnover, needed to be included in the PLS model in order to predict the cryptophycean biomass (Table 4). At Björkfjärden, for example, as much as 85% of the variation in the cryptophycean biomass in May could be explained by spring water temperatures and water color (Table 4). At other lake sites the prediction of the cryptophycean biomass by water color and water temperature alone was less powerful. Here other factors like e.g. nutrient concentrations and phytoplankton species competition may become important. Also the water discharge seems to be important for the determination of the cryptophycean biomass (Table 1), indicating that Cryptophytes might be imported to the lakes via the rivers. However, an import of Cryptophytes via rivers is rather unlikely because in that case also other phytoplankton groups that frequently occur in the river should be affected by the water discharge which we were unable to observe (Table 1). It is more likely that the relationship between water discharge and the biomass of Cryptophyceae results from an effect of water discharge on water color that again affects the biomass of the cryptophycean biomass.

Not only the biomass of Cryptophytes increased along with an increase in water color but also the biomass of the small group of Euglenophyceae. Like cryptophyceans, euglenophyceans are considered to be opportunistic, living in heterotrophic environments. Euglenophyceans are often associated with increased levels of dissolved organic matter, and they have therefore been used as environmental indicators of such conditions (Graham and Wilcox 2000). Also prasinophycean and raphidophycean flagellates responded to the rainy period in 2000. These algae are known to tolerate high amounts of organic matter (Palmer 1969). According to Rosén (1981) the species *Gonyostomum semen*, belonging to the Raphidophyceae and more frequently found in Lake Mälaren nowadays, is a very good indicator of humic lakes in Sweden. An increase in the biomass of raphidophycean and prasinophycean flagellates in Lake Mälaren in 2001 might therefore directly be related to the increase in water color after the rainy period in 2000.

Apart from water color and phytoplankton also other variables that were related to water discharge (Table 1) such as suspended particulate matter, reactive silica concentrations and conductivity showed a long-lasting (more than 3 months) response to the high water discharge in 2000 (Table 2). Conductivity was the only measured lake variable that showed exceptionally low levels in Lake Mälaren in 2001. Conductivity was earlier found to decrease with an increase in water discharge (e.g. Komai 1996). In Lake Mälaren the low levels of dissolved ions are most probably due to a dilution effect caused by the very high amounts of inflowing water. The high water discharges in 2000 lead to unusually low levels of conductivity in the inflow waters and consequently also to unusually low levels in the lake. No further lake variable showed a clear response to the rainy period in 2000, since their direct association with runoff processes in the catchment area seems to be weak (Table 1).

Spatial and temporal differences in the effects of a rainy period on lake water quality

Changes in lake water chemistry and biology as a response to the rainy period in 2000 were not equally pronounced all over Lake Mälaren. Most obvious differences occurred due to spatial differences in the amount of rain in the western and northeastern parts of the lake. While precipitation and water discharge were exceptionally high in the western part of the lake in 2000, precipitation and water discharge in the northeastern part of the lake were not unusual. As a result, lake sites that received water from the western part of the lake such as Galten, Granfjärden, Björkfjärden and partly Görväln showed exceptional water chemical and consequently also biological conditions in 2001. In contrast lake sites that received water only from the northeastern part such as Ekoln had relatively normal chemical and biological conditions in 2001.

Spatial differences in the effects of a rainy period on lake water chemistry occur also as a result of different time lags. Immediate effects of a rainy period on water chemistry should be observed at lake sites close to inflow waters. In this study we did not have measurements of lake water chemistry right after the rainy period. Our first measurements were carried out in March 2001, three months after the heavy rain. At that time Galten, the lake site that is most influenced by inflow waters, showed two deviating lake water chemical records while Björkfjärden, located in the central part of the lake, showed three unusual water chemical records (Table 2). Thus, it appears that it is mainly the water residence time that determines when the records were registered at different sites in Lake Mälaren. At lake sites where the residence time was very short, for example at Galten (theoretical water residence time: about 26 days), the effects of the rainy period on lake water chemistry were probably short-lasting, and therefore no longer detectable by the first sampling in March 2001. In contrast, effects of the rainy period were fully visible in the central part of Lake Mälaren at Björkfjärden where the water residence time is much longer (1.8 years). Consequently, most water chemical records were registered at this lake site in 2001. Görväln is also located in the central part of Lake Mälaren but here the water residence time is shorter than at Björkfjärden (0.4 years). In addition, Görväln receives water from both the western and the northeastern part of the lake. Since water chemical records were only observed in the western part of the lake but not in the northeastern part, records at Görväln were less pronounced than at Björkfjärden.

Consequences of an unusually rainy period

An unusually rainy period causes primarily a large import of humic substances via rivers into lakes. This import put the drinking water quality at risk as humus contributes to excess microorganism growth in water distribution systems, causing secondary problems such as diseases, taste and odor (Löfgren *et al.* 2003). To avoid such problems expensive treatments for the raw water become necessary (Volk *et al.* 2002). In addition, lake ecosystems undergo drastic changes with an increase in humic substances since humus affects the transport and bioavailability of inorganic and organic nutrients, the toxidity of heavy metals, and the surface water acidity (Löfgren *et al*. 2003). Also light conditions in the lakes are determined by the amount of humic substances that again influence the biomass of Cryptophyceae as shown for Lake Mälaren and Övre Skärsjön. Taking into account that water color is likely to increase in the future due to present trends of a warmer and wetter winter/spring climate in Sweden (Rummukainen *et al*. 2001), there is a risk that also the cryptophycean biomass will increase in spring. An increase in the cryptophycean biomass can have various effects on a lake ecosystem, e.g. it can strongly affect the competition with other algae groups like Chrysophyceae and Bacillariophyceae which usually dominate the spring season. If Cryptophyceae increase in spring at the expense of Bacillariophyceae the whole ecosystem might undergo drastic changes because of the ability of Cryptophyceae to exploit both dissolved organic and bacterial carbon (Tranvik *et al*. 1989). In addtion, an increase in Cryptophyceae can have an effect on the bacterioplankton community composition (Lindström 2000). Conclusively, both an increase in the cryptophycean biomass and the water color might affect the quality of lake water and influence the food web.

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