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# Determination of the historical variation of the trophic state in lakes using sediment stratigraphies

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**Abstract.** Biogenic silica (BSi) and phosphorous (P) accumulation were investigated in sediment cores from Karlskärsviken, a bay of Lake Mälaren. The aim was to make use of BSi and P relations in sediment stratigraphies in order to investigate the historical nutrient trophy in a near shore lake environment since the Middle Ages, with focus on industrial times, and to evaluate anthropogenic influences on the bay's trophic state. The BSi accumulation in the sediments is a better indicator of former nutrient pelagic trophy than P accumulation in sediments and for this reason a BSi inferred P (BSi-P) water concentration is calculated. This method enables the determination of the background total phosphorous (TP) concentration (which is related to the reference conditions) in the investigated bay; this background TP is determined equal to  $0.020\text{--}0.022\text{ mg L}^{-1}$ . There is an increasing trend of BSi-P concentration in the bay since the Middle Ages to the present, about  $0.025\text{ mg L}^{-1}$ , with a small decrease in the inner bay section during the last decades. The P accumulation rate is not found to have changed since the 1960s and 1970s, which indicates that the P loading to Karlskärsviken has not decreased. In Karlskärsviken, the shallow inner section of the bay, where the water quality is dominated by loading from the bay catchment area, is less nutritious than the water in the outer section, which is influenced by the main streams from the western part of Lake Mälaren.

## 1 Introduction

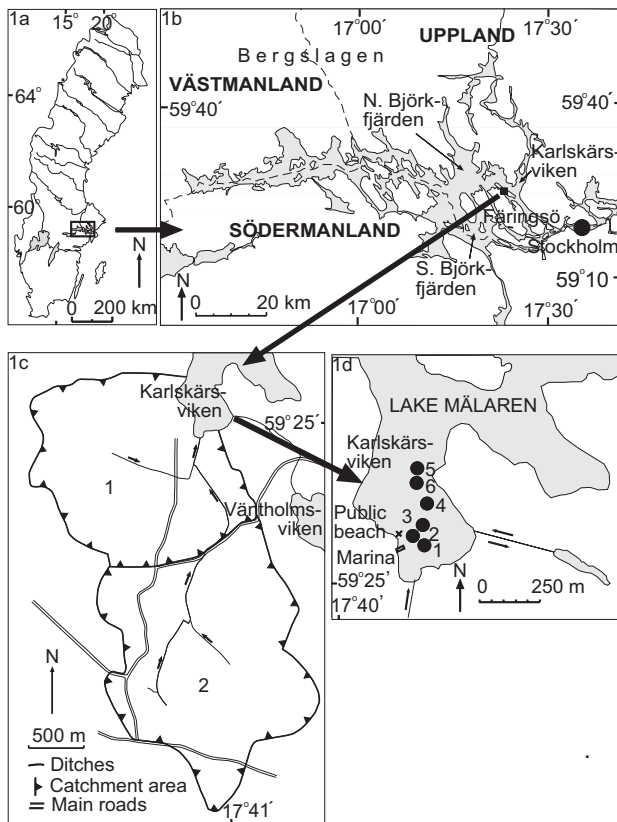
In the global problem of eutrophication, phosphorus (P) plays a crucial part, as a limiting nutrient in freshwater lakes, especially in Temperate Zone waters (Lund, 1972; Reynolds, 1984; Harper, 1992; Farmer et al., 1993; Persson, 2001). In

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Sweden, for instance, regular monitoring has been performed in the basins of the big lakes since 1965 (Willén, 1972). Historical nutrient enrichments are found in the sediments, but to estimate P concentrations in the past water column, these enrichments have to be interpreted.

Chemical processes control P in water and sediments, as chemical precipitate, adsorption, complex formation and biochemical reactions (Round, 1981; Boström et al., 1982). A consequence of these processes is that the P accumulation in sediments seldom reflects the P concentration in the contemporary water column. However, P in the water column is important to know, because it commonly determines the biomass maxima of phytoplankton, so when P levels are enhanced, algal growth, including silicon algae, diatoms, increases quickly (Andersson, 1994). In contrast to P, diatom frustules are indestructible in sediment, and consequently diatom accumulation provides a better signal of contemporary P in water than the P sediment accumulation does. Diatom frustules are therefore accepted as a nutrient criterion, as long as the diatom production is limited by the P concentration in water (Stoermer, 1984; Schelske et al., 1983 and 1986; Anderson et al., 1993; Bennion et al., 1996; Renberg, 1999). In Lake Mälaren, P is regarded to limit the vegetation (Persson et al.; 1990; SEPA, 1993).

Different model studies have been performed (ter Braak and van Dam, 1989; Bradshaw and Anderson, 2001) to determine quantitatively the relationship of diatom species to total phosphorous (DI-TP). Diatom species in sediments were used to reconstruct past P concentrations in water in a study in Björkfjärden, Lake Mälaren, (Renberg, 1999). These results gave to high values,  $10\text{--}20\text{ }\mu\text{g L}^{-1}$ , which probably is due to the particular diatom flora caused by the elongated creation of Lake Mälaren and the brackish water inflows until modern times. This high uncertainty makes these models questionable to apply in Lake Mälaren, as the P concentrations there oscillate between 20 and  $40\text{ }\mu\text{g PL}^{-1}$ . Schelske et al. (1983) have shown that the amount of diatom cells and



**Fig. 1.** (a) Sweden. (b) Lake Mälaren with Karlskärsviken to the north of Färingsö, (c) The catchment area to Karlskärsviken and (d) Karlskärsviken with the locations of the sampling points. (d) The tributary ditch is marked with one arrow and the rest of the former strait between Karlskärsviken and Väntholmsviken with two arrows. (c) 1. The original catchment area. 2. The enlarged catchment area since 1951. Maps by Sven Karlsson.

biogenic silica (BSi) is almost identical in the sediments and used the percentages of BSi in sediments as criterion of nutrient enrichment. BSi is also used in this study with the base material from the same ecosystem.

Diatoms have also other requirements than nutrients, like light and silica (Rühland and Smol, 2005; Mackay et al., 2005; Paus et al., 2005; Katsuki and Takahashi, 2005), and their presence in sediments can also be influenced by episodic events, such as storms. When lakes are covered by ice during long periods, diatom production is less than in years with hardly any ice and long and warm summers trigger the production. Silica is needed for diatom prosperity, and consequently a decrease in the abundance of diatoms can be due to silica deficit in the water column. Schelske et al. (1986) showed that a high BSi concentration and likewise high BSi  $TP^{-1}$  (biogenic silica and total phosphorous ratio) or BSi  $BAP^{-1}$  (biogenic silica and bio available phosphorous ratio) ratios in sediment stratigraphies followed by a decrease in BSi sediment concentration and in the ratios BSi  $TP^{-1}$  or

BSi  $BAP^{-1}$  indicate that the diatoms has not profited on the BAP as they had during the preceding period. This BSi decrease simultaneous with a constant or increased P, may be due to Si deficit in the water column.

The aim of this study is to make use of BSi and P relations in sediment stratigraphies in order to investigate the historical trophic state in a near shore lake environment since the Middle Ages, with focus on industrial times, and to evaluate anthropogenic influences on the bay's trophic state. This environment is here represented by Karlskärsviken, a bay in Lake Mälaren. The investigation period extends over the last 800 years, equal to the freshwater stage of Lake Mälaren, but with particular focus on the last century and on establishing the background nutrient trophic in such a near shore environment, which is expected to be dominated by the loading from its catchment area.

## 2 Materials and methods

### 2.1 Site description

Lake Mälaren (Fig. 1b), located to the west of Stockholm, is characterized as eutrophic like all shallow lakes in the European lowland areas (Miljödepartementet, 1991 and Foy and Withers, 1995). Lake Mälaren has a large catchment area and a very long shoreline including numerous islands, bays, capes and points, with the consequence that the precipitation directly on the lake only accounts for about 10 % of the total water inflow to the lake (Willén, 2001). The water quality of such a lake is sensitive to nutrient and pollutant loading from the tributaries (Persson, 2001). In the lowlands, the tributaries often are drainage ditches from arable land and densely populated areas. The main tributary to the studied bay, Karlskärsviken (Fig. 1d), is a ditch from the south, to which waste water from about 160 households and drainage water from cultivated fields in the catchment area is connected (Fig. 1c). The average TP outflow from this ditch was measured 1997–2000 and found to be  $94 \text{ kg TP yr}^{-1}$ . Notable parts of this settle in the macrophyte zone, from which no sample is collected.

This ditch was dug in 1951 and increased the drainage area of Karlskärsviken to the double, which is about 560 ha today (Fig. 1c). The bay of Karlskärsviken, situated to the north of the island of Färingsö, covers about 20 ha and has an average depth of about 3 m (2.90–3.45 m in the studied sites). The bottom gradient is  $<1\%$ , which is common in the western part of Lake Mälaren. The eastern shore is rocky and steep but the western shore has a broad transition zone with reeds between the open water and the low lying shore meadows. At present, close to the outlet, the ditch is overgrown by macrophytes and both organic and inorganic phosphorous rich particles are deposited there as explained by Benoy and Kalff (1999).

## 2.2 Methods overview

### 2.2.1 Transferring BSi into P water concentrations

To establish the historical trophic states, the BSi concentrations were measured (Fig. 2a) in sediment cores taken in the bay and transferred into P concentration, denoted BSi-P. Schelske et al. (1986) have shown that there is a relationship between P concentration in water and BSi (with genesis diatom frustules) concentration in sediments. The transfer here is based on the present trophic state, which is known both by the measured TP concentration in the water column and the stored BSi in the uppermost sediments (0–0.5 cm). The transfer factor is based on 12 measuring in Karlskärsviken and in three surrounding bays. In all locations, the relation between BSi  $\text{mg L}^{-1}$  and TP  $\mu\text{g L}^{-1}$  was about 0.00068. There was no clear variability in this ratio (within 0.00001). It should be observed that this measuring was performed in modern time, i.e. during the period 2001–2002 and cores 5 and 6 in 2003. There is always an uncertainty to estimate past times values by values from modern time, but this transfer factor is at least based on measuring from the surroundings with about the same ecosystem.

To evaluate the anthropogenic nutrient influence, the background P concentration has to be estimated. Lake Mälaren never had a freshwater stage without anthropogenic impact, as the region was populated at the time, when the former brackish water bay was altered into a freshwater lake. The present P concentrations are compared to these from the middle of the nineteenth century, which here are regarded as background P concentrations.

P concentrations in the sediments were also measured in order to calculate the BSi  $\text{TP}^{-1}$  and BSi  $\text{BAP}^{-1}$  ratios, as a decrease of BSi concentration in the sediments, reflecting pelagic and benthonic diatom production, may be caused by Si deficit in the water column, when the P supply is sufficient. A high BSi value indicates that all environmental factors controlling diatom growth are in the optimum range, e.g. the pelagic Si, P concentration, light and temperature. A depletion of pelagic Si (indicated by a decrease in BSi) may follow this optimum condition, if the Si reservoir in the water column is consumed and the recycling is slow, as it is years with low water outflow from the catchment area. Peaks in the above mentioned ratios at the same depth as a peak in BSi concentration followed by a decrease of these ratios may consequently be associated with pelagic Si depletion (Schelske et al., 1986), resulting in BSi concentration decrease and a coinciding P concentration peak. At such occasions, Si is probably the limiting element and the BSi stored in the sediments does not indicate the contemporary pelagic P concentration. In the basins of Lake Mälaren, it is found that Si depletion,  $\leq 5 \mu\text{g L}^{-1}$  bio available Si, occurs some years during April–May (Lännergren, 1998), when the diatom production reaches its climax.

**Table 1.** Year versus depth (cm) in the cores.

Year/core	1	2	3	4	5	6
2000		0	0	0	0	0
1973	4		15	16	17	18
1953	10		20			
1945	16		23	27	31	32
1935	17		24	29	33	34
1918					38	48
c. 1850	25		33	38	49	51
c. 1550	46			70	102	
c. 1200	68	66		108	148	

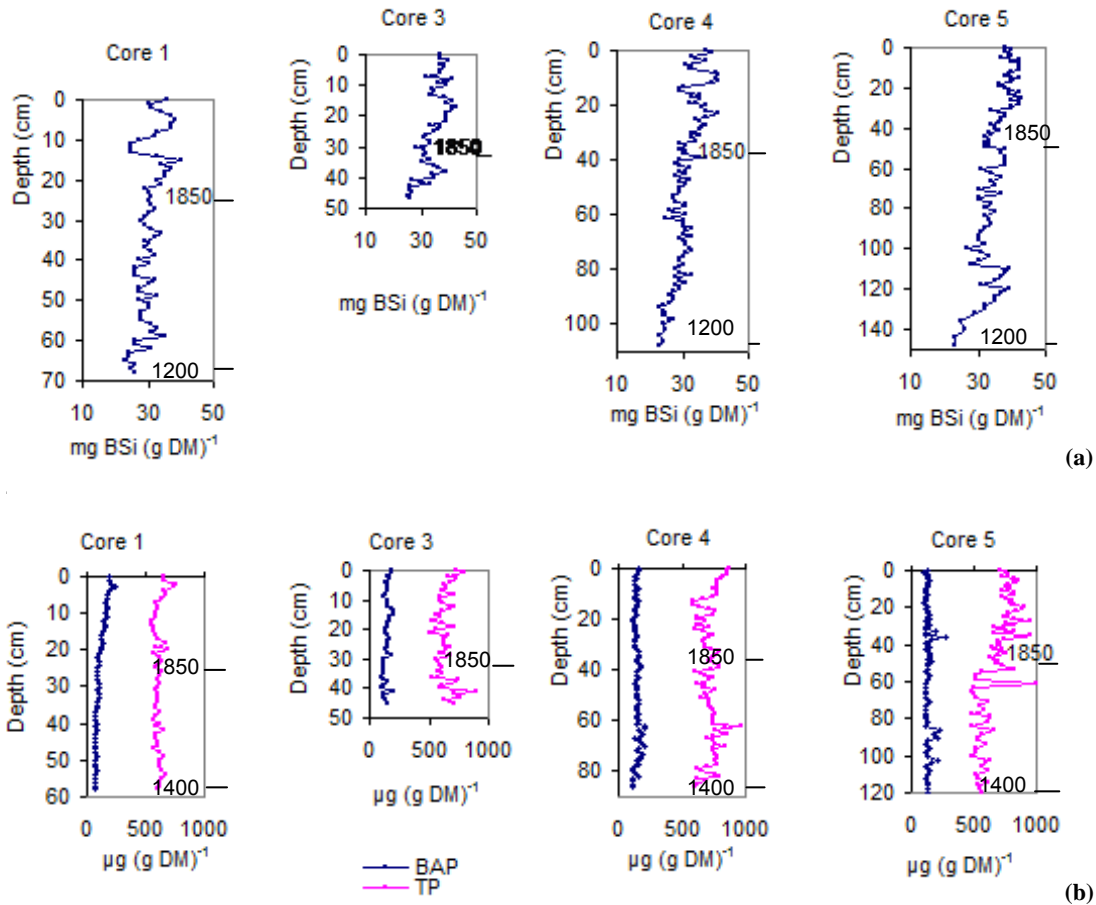
Climatic changes give often the same results as the variations in Si supply. In modern times, the climate is well controlled and consequently it is known when the BSi decreases simultaneously with a BAP increase may be caused by climate changes. Comparing the warm period in the 1930s and the cold 1940s and other equal periods, these oscillations are measurable.

### 2.2.2 Dating

The sediments were earlier dated by the author (Table 1 from Olli, 2008). Sediment dating for medieval times is based on the presence of brackish and freshwater diatoms, as Lake Mälaren turned to a freshwater lake during that period, for modern times on the number of SCPs (spheroidal carbonaceous particles, which is fly-ash particles from fossil combustion) and by isotope Cs-137 analysis. The transition from brackish to freshwater was elongated by various transgression and regression phases, which have been recognized in other studies (Åse, 1980; Miller and Robertsson, 1982; Ambrosiani, 1981; Miller and Hedin, 1988) and also here in Karlskärsviken, which facilitate the dating. The content of the isotope Cs-137 was established in core 3. The history of SCP presence in sediments is established by Griffin and Goldberg (1975, 1979), Wik (1992), Odgaard (1993), Rose et al. (1990, 1995, 1999, 2001), Bindler et al. (2002) and Renberg et al. (2001), on which the dating of modern sediments in Karlskärsviken is based.

These results showed that the dating is not exact, as each cm covers 2–15 years.

The dating of the thirteenth century and 1850 are approximate, while the SCP dating catches the World War years very clear and also the European industrial progresses, crises and also the progresses in eliminating the exhausts from fossil fuel combustion. The BSi decrease in the 1940s catches the cold years in the early 1940s, which means that the dating 1945 could be 1944. The knowledge of the local activities during the second half of the twentieth century has also been used for chronological control.



**Fig. 2.** Concentrations of (a) BSi ( $\text{mg BSi L}^{-1}$ ) and (b) BAP and TP ( $\mu\text{g PL}^{-1}$ ), both (a) and (b) in sediments vs. depth in the cores 1, 3, 4 and 5, Karlskärsviken. The figures are scaled to be comparable with respect to time. (a) The BSi concentration starts about 1200 AD with about  $25 \text{ mg (g DM)}^{-1}$  and has increased to  $37 \text{ mg (g DM)}^{-1}$  in 2000. (b) The BAP and TP concentrations start at about 1400 AD BAP with about  $100\text{--}200 \mu\text{g (g DM)}^{-1}$  with an increasing trend only in core 1 since the Middle Ages. In core 5 the TP water concentration increases in the middle of the 19th century and in core 4 in the very recent sediments.

### 2.2.3 Sediment accumulation rates

Sediment accumulation rates from the earlier study are used to establish the BSi accumulation rates from BSi concentration and sediment accumulation rates from the time when Lake Mälaren had got freshwater until today. The sediment accumulation rates indicate that the section further out in the bay is influenced by other drainage areas than the inner section is. The outer part of the bay is and has been since the Middle Ages, strongly influenced by the main water streams coming from the western parts of Lake Mälaren, where many towns and big industries are situated, while the water quality in the inner section is dominated by the loading from the catchment area, see Sect. 2.1.

### 2.3 Field work

In Karlskärsviken the P concentrations in the water column was measured twice a month (once the ice covered period) during 1998 and controlled in 1999 and 2000. In 2001–2003, sediment cores were taken in the bay in a section from the above mentioned ditch outlet to the outer section of the bay (Fig. 1d). All the core locations are outside the macrophyte zone. In the macrophyte zone the sediments have been dredged, and no historical information is archived there. A 1 m long Russian peat corer was used for the cores 1, 2, 4 and 5, all taken in winter when the bay was covered by ice. A turbidity-meter was used to measure the water depth and to know where to start the coring. The cores 1 and 5 were two meters long and core 2 one meter. Core 4 was 10 m, in order to establish the sediment accumulation since the retreat of the ice cover. The cores 3 and 6 were taken with a freeze corer, which restricted the length of these cores as they

**Table 2.** B Si-P ( $\mu\text{g TP L}^{-1}$ ) concentration and the corresponding depth in brackets, date from diatom and fly-ash analyses.

Year/Core	1	3	4	5	6	Mean value
2000	25	25	25	26	26	25,2
1973	25 (4 cm)	27 (15 cm)	24 (16 cm)	27 (17 cm)	27 (18 cm)	26
1945	23 (16 cm)	22 (23 cm)	23 (27 cm)	23 (31 cm)	23 (32 cm)	23
1935	25 (17 cm)	25 (24 cm)	25 (29 cm)	26 (33 cm)	25 (34 cm)	25
1850	20 (25 cm)	21 (33 cm)	20 (38 cm)	22 (49 cm)	22 (51 cm)	21
1200	18 (68 cm)	–	16 (108 cm)	16 (148 cm)	–	17

just are dropped down. The length of core 3 was 48 cm and core 6 was 65 cm in length. The upper 40 cm of core 2 were strongly perturbed and could not be dated.

#### 2.4 Laboratory work

All cores were sectioned into 1 cm slices until the depth of 70 cm and below that into 2 cm slices. The first cm was sliced 0–0.5 and 0.5–1 cm. The slices were freeze-dried and prepared for analyses as follows. BSi concentration in the sediments was determined colorimetrically in a spectrophotometer. The samples were prepared according to the method elaborated by De Master (1981), but 2%  $\text{Na}_2\text{CO}_3$  was used instead of 1% and, accordingly, the HCl concentration had to be doubled. Using 1% the diatom frustules were not completely dissolved. Three samples from every level were analyzed and every sample was measured three times, which gave an average value. The samples with anomalous results were repeatedly analyzed two or three times. For example, the unexpected results from core 1 were controlled very carefully. Selected samples were checked in a light-microscope to make sure that the diatoms were dissolved. P was analysed in respect to bio available phosphorous (BAP), and total phosphorous (TP) according to Psenner et al. (1984).

#### 2.5 Lithology

The cores consist of clay and gyttja clay in the uppermost sediments. The uppermost 5 cm in core 1 was empty, probably caused by loose sediment content. The organic content was about 4% in the uppermost sediments in all the cores and a little less than 2% during the Middle Ages. In core 1 the organic content dropped below 2% during the years of water undertakings. At the depth 5.70 in core 4, the sediment is influenced by the ice retreat.

### 3 Results

#### 3.1 Pelagic P and BSi concentration

The used pelagic P concentrations are yearly average values. In late autumn and winter, the pelagic P concentrations are al-

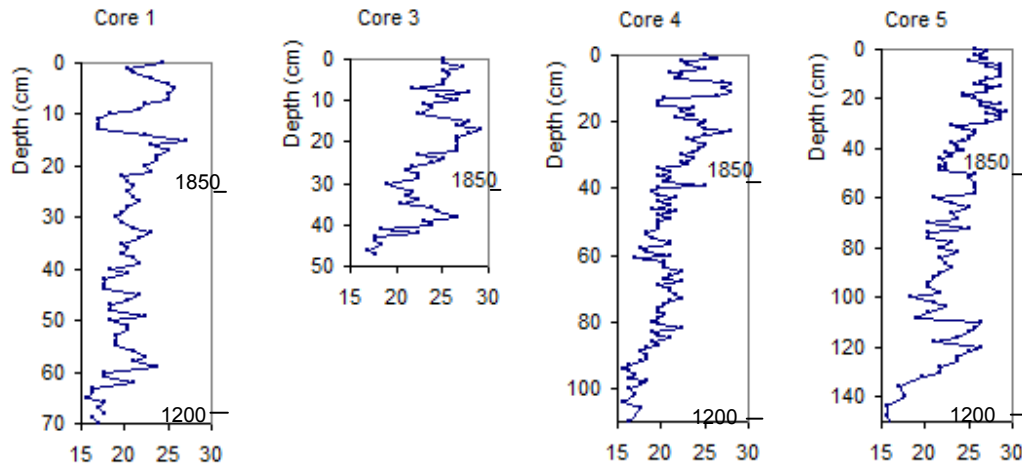
ways high, about  $0.040 \text{ mg L}^{-1}$ , where after they decrease to almost 0 in summer. The BSi concentration in the sediments shows an increasing trend since the Middle Ages (Fig. 2a) from about  $25 \text{ mg BSi (g DM)}^{-1}$  to  $37 \text{ mg BSi (g DM)}^{-1}$  at present. The P concentrations in sediments oscillate between 600 and  $900 \mu\text{g TP (g DM)}^{-1}$  (Fig. 2b) and there is no consistently increasing or decreasing trend, but for the BAP in core 1, as that for BSi concentrations. The P concentrations in the sediments were established to calculate the ratios  $\text{BSi TP}^{-1}$  and  $\text{BSi BAP}^{-1}$  for controlling whether there is a possibility that the pelagic Si deficit has diminished the BSi concentration in the sediments. This might have occurred in recent times, e.g. in: core 1 at 1 and 2 cm, core 3 at 0 and 3 cm, core 4 at 0 and 5 cm and core 5 at 0, 5 and 14 cm.

#### 3.2 Reconstructed P values

In the Middle Ages the general uplift of the ground created the freshwater Lake Mälaren. At the beginning of that stage, the BSi-TP concentration in Karlskärsviken is estimated  $16\text{--}18 \mu\text{g TP L}^{-1}$  (Fig. 3 and Table 2). About 1850, the P concentration had increased to  $20\text{--}22 \mu\text{g TP L}^{-1}$ . Between 1850 and 1950 Karlskärsviken became more nutritious and the BSi-TP concentration rose to  $25\text{--}27 \mu\text{g TP L}^{-1}$  (Fig. 3). The 1920s and 1930s were periods of drainage undertakings at the island of Färingsö, which increased the nutrient loading to the lake. Additionally, the temperature rose in the 1930s (Moberg et al., 2005 and Briffa, 2000), resulting in short winters, which is a trigger of algal production. The hard climate with long periods of ice-cover lakes during the World War II is reflected in the sediments with lower diatom production in all the sediment cores (Fig. 3 and Table 2). The diatoms responded immediately to the more convenient conditions that followed and the BSi-P concentration rose.

After 1950 the BSi-P concentration has oscillated between 20 and  $30 \mu\text{g TP L}^{-1}$  with lower values in the inner section of the bay and higher further out. In average, a slight decrease of BSi-P concentration is discernible during the last decades (Table 2). This conforms to the results from the monitored program (Persson et al., 1990; SEPA, 1993, 2006).

Core 1, which represents the inner section of the bay, has in previous studies by the author shown anomalies between



**Fig. 3.** The reconstructed BSi-TP concentration (BSi-TP L<sup>-1</sup>) in the water column. The figures are scaled to be comparable with respect to time. There is an increasing nutrient trend in the cores but more pronounced further out in the bay, represented by the cores 4 and 5, than in the inner section, represented by core 1. The cores 1, 4 and 5 start at the level, when Lake Mälaren got fresh water about 1200 AD as indicated by diatom analyses. 1850 AD is shown.

14 and 10 cm concerning fly-ash particles, carbon concentration, lead concentration and here also for BSi concentration (Fig. 2a). This increment with anomalies is interpreted to have been deposited during the years when the new ditch was dug and a public beach and a marina (a harbour with moorings for private boats) were constructed, which resulted in a very high sediment accumulation rate. The respective layer was excluded from the analysis results.

### 3.3 The ratios BSi TP<sup>-1</sup>, BSi BAP<sup>-1</sup> and Si deficit

Simultaneous peaks in BSi, BSi TP<sup>-1</sup> and BSi BAP<sup>-1</sup> show that the diatom production is optimally. The following decrease of BSi concentration may depend on Si depletion in the water column, as diatoms need both silica and phosphorous to multiply (Schelske et al., 1986). If a decrease of BSi is caused by BAP deficit, the ratio BSi BAP<sup>-1</sup> remains high, when the diatom production declines. In Karlskärsviken, the peaks in BSi concentration and in the ratios BSi TP<sup>-1</sup> and BSi BAP<sup>-1</sup> followed by decreases (Fig. 4a and b) coincide in modern sediments, which indicates that a Si deficit reduces the diatom production in the bay. The bio available Si is provided to Lake Mälaren from its catchment area and years with low precipitation the Si renewal in late spring-summer may fail. In shallow areas, as in a bay, not much Si is stored and Si depletion occurs. Consequently, the BSi-P decrease after a peak may underestimate the real epilimnic P concentration. In the past, when the water was deeper, more Si was stored in the water column and Si depletion was not as frequent as today.

### 3.4 BSi accumulation rates

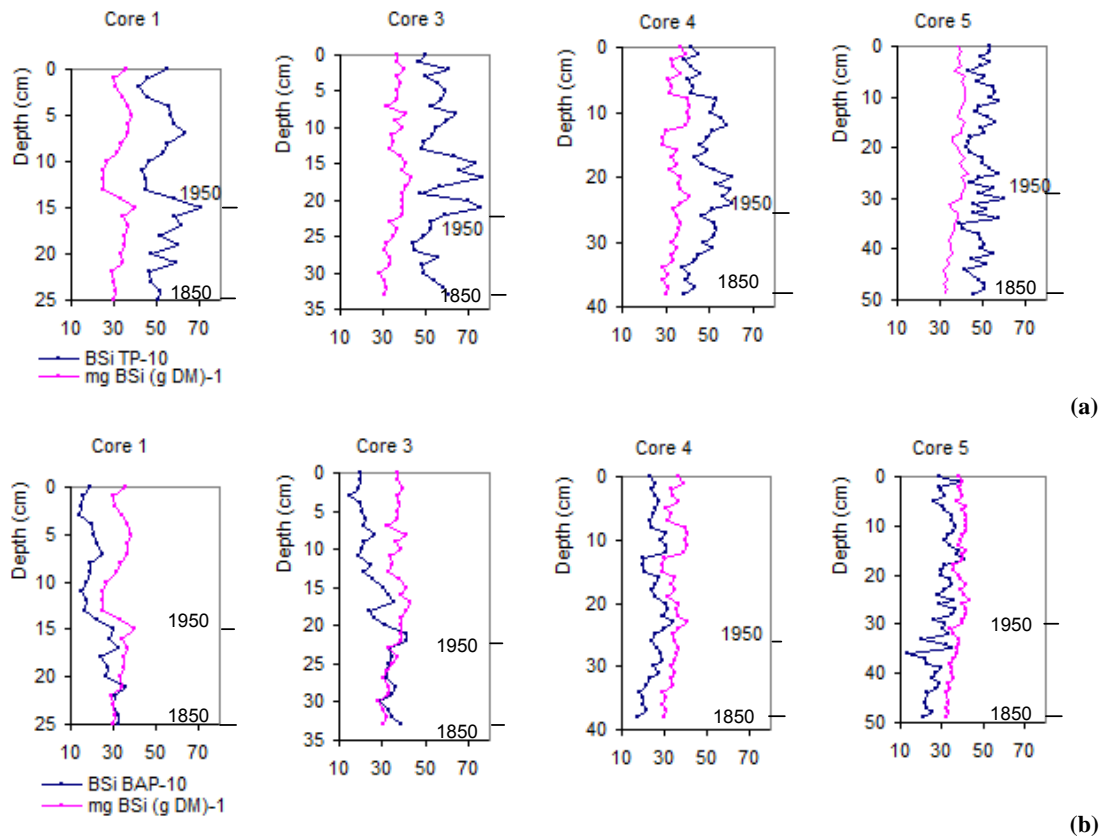
In Karlskärsviken, the sediment accumulation rate is found to have increased considerably, especially in the twentieth century (Olli, 2008). From about 1200 until 1850 the BSi accumulation rate increased by 25% (Fig. 5). During the next century this rate also increased by 25% and was about 1.9 mg B Si cm<sup>-2</sup> yr<sup>-1</sup> at the end of World War II. After that, this rate increased dramatically by 300% in 20 years and reached 4.4 mg BSi cm<sup>-2</sup> yr<sup>-1</sup> in the 1960s and 1970s, which still remains the present rate, without signs of any decrease.

## 4 Discussion

### 4.1 Water depth and trophic state

From the first fresh water stage in Lake Mälaren about 1200 AD until 1850, the sediment up silting was about 0.5–1 m and the land upheaval of about 3.5 m lowered the water depth from about 8 m to 3.5–4.2 m. These changes normally result in an increasing nutrient trophy (Ahl, 1979). The lake water is also more nutritious in its shallow sections than in its deeper parts (Lännergren, 1998), assuming that the tributaries are the same. Ahl (1979) writes about eutrophication that the effect of the lowering of the lake surface has been more serious than the effect of increasing nutrient loading. The increase from 17 μg BSi-PL<sup>-1</sup> to 21 μg BSi-PL<sup>-1</sup> (Table 2) and from 1.2 mg BSi cm<sup>-2</sup> yr<sup>-1</sup> to 1.5 mg BSi cm<sup>-2</sup> yr<sup>-1</sup> (Fig. 5) during the period 1200–1850 may be a normal effect of the above mentioned morphological changes. From that period until 1950, however, both the BSi accumulation rate and the BSi-P content increased much





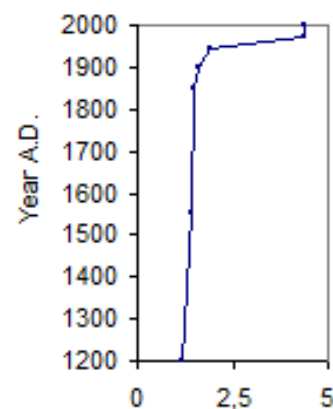
**Fig. 4.** (a) BSi concentrations in sediment and the ratio BSi TP<sup>-1</sup> and (b) BSi concentrations in sediment and the ratio BSi BAP<sup>-1</sup> vs. depth in the cores 1, 3, 4 and 5. The figures start about 1850 AD and are scaled to be comparable with respect to time. A peak in the ratios BSi TP<sup>-1</sup> or in BSi BAP<sup>-1</sup> and a peak in BSi concentration at the same level may indicate pelagic Si depletion. If the following BSi decrease depends on Si deficit, the P concentration is not the limiting factor for diatom production and other vegetation may take advantage of the nutritious water. The BSi concentration decrease between 14 and 10 cm in core 1 represents the years of construction 1951–1953 with a very high sediment accumulation rate and does not show the pelagic nutrient conditions.

faster, by about the same percentage, 25%, as in the previous 650 yr period but in only a hundred years.

#### 4.2 Increased water inflow

After about 1950, many former rills, small ditches, in the catchment area were turned into gullies by excavators, here the main tributary ditch (Fig. 1), and the outflows of particles increased both the sediment and the B Si accumulation rates. When considering only the BSi concentration in the sediments (Table 2), the nutrient trophity may be viewed as having slightly decreased during the last decades. This interpretation conforms to the results in the monitored programs (SEPA, 2006). However, this is questionable, when the sediment and associated nutrient accumulation rate is taken into account, which still remains at the high 4.4 mg BSi cm<sup>-2</sup> yr<sup>-1</sup> on average for the bay since about 40 years (Fig. 5).

However, in the inner section of the bay, here represented by core 3, the P concentration has diminished, even when regarding the P accumulation rate increase. This particular P



**Fig. 5.** Average BSi accumulation rate (mg BSi cm<sup>-2</sup> yr<sup>-1</sup>) in Karlskärsviken since the Middle Ages. The accumulation rate increased until the 1960s and has thereafter been the same, despite the efforts to diminish the nutrient loads.



concentration decrease may be the result of a greedy macrophyte zone in the discharging ditch, which has not been maintained during the last decades. The reeds take advantage of the nutrient rich water and the diatoms downstream in the bay have no chance to profit on it. Si deficit may also cause the BSi decrease. A shallow bay has a very short hydraulic residence time, which makes the Si reservoir insufficient in a spring with low precipitation, when the diatom growth explodes. Si concentrations in water have at the lowest been measured to be 5–10  $\mu\text{g L}^{-1}$  in May in basins of Lake Mälaren (Lännergren, 1998) and may even have been lower in the bay, limiting diatom production.

#### 4.3 Climate influence

It is mentioned above in this paper (Sect. 3.2.) that climate change may have influenced the diatom production during the 1930s and the World War II. In analogy, also the B Si oscillation after the 1950s may be due to temperature fluctuations. From the warmer years in the 1930s to the colder conditions during World War II, the temperature difference was about 1.5°C, which probably is responsible for the BSi-P decrease from 25 to 23  $\mu\text{g TPL}^{-1}$  (Table 2). Thereafter, there is a temperature difference from the late 1960s to the late 1990s of about +0.7°C, which may mask a TP concentration decrease of about 1  $\mu\text{g TPL}^{-1}$ . On the other hand, the years 1971 to 1975 were as warm as the late 1990s. Besides that, a difference of 1  $\mu\text{g TPL}^{-1}$  is within the margin of error in this study, which focuses on main trends and approximate values.

#### 4.4 Si deficit

The above mentioned P water concentrations are yearly average values. The bio available P concentration is reduced when the diatoms make use of it in spring. When the diatoms do not consume all P in water due to Si deficit, there is P left for another spring or summer blooming with flagellating alga and green alga (Schelske et al., 1983). This second blooming, which frequently occurs in Lake Mälaren, is often taken as a proof of increased P loading from the tributaries, even when it depends on silica deficit in spring. The P level at such occasions may then be the same as in previous years without this secondary blooming. A strong eutrophication effects, with a large biomass in the water column, is not considered to appear until the P concentration is above 25–30  $\mu\text{g TPL}^{-1}$  (SEPA, 1993). As the present nutrient trophy is about 25  $\mu\text{g TPL}^{-1}$ , P should not cause these secondary algal blooms, if Si concentrations were sufficient in spring and the diatoms could consume the P in water. It is rather the timing of P and Si loading that does not seem to be favourable for the diatoms, and therefore the P level of about 25  $\mu\text{g TPL}^{-1}$  causes visible eutrophication effects with flagellating and green algae.

Climate influences, Si supply and sediment accumulation rates indicate that the BSi concentrations alone are not sufficient for interpreting past times P water concentrations in this bay of Lake Mälaren. Climate and Si deficit have to be taken into account. Climate is known and deficit of Si or other requirements are probable when there is enough supply of BAP in the sediments, when the BSi concentration decreases. There is always an uncertainty when reconstructing past times values, but in Lake Mälaren there are measuring in the monitored program (SEPA, 2006) during the last decades from other sites, which indicates reliability in this study. Certainly, the oscillations of P concentrations may be a few  $\mu\text{g L}^{-1}$  larger or smaller but of less dignity than the studies based on diatom species from other ecosystems and the increasing and decreasing trends are surely reliable.

#### 4.5 Background P concentration

When estimating the relevant background trophy, the P concentration at about 1850 may be a more realistic reference value than the medieval P concentrations in the deeper water column that existed at that time. This is also suggested by Willén (2001). From about 1850 until today, the pelagic P concentrations have increased from about 20–22  $\mu\text{g BSi-TPL}^{-1}$  to 25–26  $\mu\text{g BSi-TPL}^{-1}$  (Fig. 3), which is 25% increase. The background TP concentration in Lake Mälaren has earlier been estimated to 6–15  $\mu\text{g PL}^{-1}$  by Persson et al. (1990) and to 15–30  $\mu\text{g PL}^{-1}$  by Renberg (1999) and Renberg et al. (2001). Shallow bays were not studied in these previous investigations, but the latter investigation results conform to the presently estimated BSi-TP concentrations. Considering the warmer climate during the last decades compared to the cold middle of the nineteenth century the background BSi-P concentration, 20–22  $\mu\text{g TPL}^{-1}$ , may possibly be put higher. According to the differences between the warmer thirties and the colder forties the temperature influence on the BSi concentration is about 2–3 mg BSi (g DM) $^{-1}$ , and the background P concentration may be put about 1–2  $\mu\text{g TPL}^{-1}$  higher.

### 5 Conclusions

In Karlskärsviken, the shallow inner section of the bay, where water quality is dominated by the outflows from the catchment area, is less nutritious than the section further out, which is influenced by the main streams from the western part of Lake Mälaren. The pelagic P concentration in the inner section was measured 1998–2000 and found to be about 25  $\mu\text{g TPL}^{-1}$ , which possibly is 4–5  $\mu\text{g TPL}^{-1}$  higher than it was during the middle of the nineteenth century. The BSi concentration in the sediments is used as an indicator of P concentration in the pelagic zone, but other circumstances have also to be considered, such as climate, Si supplies to the water column and, above all, the sediment accumulation

rates. These factors together indicate that the P loading to Karlskärsviken has not changed durable since the 1960s and 1970s.

The background BSi-P water concentration is here estimated to be 20–22  $\mu\text{g TPL}^{-1}$ . This conforms to previous results by Renberg (1999) and Renberg et al. (2001), who estimated a background P concentration of about 15–30  $\mu\text{g TPL}^{-1}$  in the basins of Lake Mälaren.

In the inner section of the bay, represented by core 1, former analysis of fly-ash, carbon and lead carried out by the author, showed anomalies at the levels dated 1951–1953. Corresponding anomalies are also recorded in the BSi and P stratigraphies. During this period, both the discharging ditch and its catchment area were enlarged and also water enterprises were in progress.

Coinciding peaks in BSi concentrations and in the ratios BSi-P  $\text{TP}^{-1}$  and BSi-P  $\text{BAP}^{-1}$  followed by BSi concentrations indicate that Si depletion sometimes occurs in the bay water column, which brakes the diatom production. The secondary bloom of green alga, which is recurrent in Lake Mälaren, is possibly an effect of silica deficit in the water column, which reduces the diatom mass. The available P is not consumed by the diatoms in spring and at such occasions visible eutrophication effects with flagellating and green algae appear later in summer.

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