Historic sediment accumulation rates in Karlskärsviken, a bay of Lake Mälaren, Sweden

Gull Olli

ABSTRACT

Historic sediment accumulation rate development was investigated in Karlskärsviken, a bay of Lake Mälaren, by dating of sediments in cores taken from the bay. The Lake Mälaren transition period from brackish water to freshwater was determined by diatom analysis and for modern times by fly-ash (SCP) and caesium isotope Cs-137 analyses. Results show that in the long period from medieval times to about 1950, the sediment accumulation rate increased to about double in the outer section of the bay, but only by about 33% in the near shore. After that, new farmland was drained by a ditch dug in 1951 with its outlet in Karlskärsviken, which enlarged the bay catchment area by 100%, and a marina and a public beach were constructed in 1953. These catchment system changes increased considerably the inflow of particles to Karlskärsviken and the sediment accumulation in the bay, directly and mostly in the near shore, but also with some and longer term effects further out in the bay. In later times, as the ditch became overgrown by reeds and bushes, the sedimentation rate decreased again in the near shore, while it continued to increase further out in the bay. These results indicate that even relatively small and common catchment enterprises may considerably affect sediment transport to recipient bay waters.

Key words | erosion, eutrophication, sediment accumulation, sediment transport

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INTRODUCTION

No soil phenomenon is more destructive worldwide than soil erosion. It involves losing not only water and plant nutrients but ultimately the soil itself. The soil finds its way into streams, rivers, and lakes and pollutes those resources and bodies (Brady 1990). In northern countries, which have been cleaned by glacial covers again and again, the soil layers are often very thin, which increases erosion problems. Spring thaws also bring loads of soil from well-drained fields to lakes. Regular monitoring of eutrophication and sediment accumulation has been carried out in the basins of Lake Mälaren, west of Stockholm (Figure 1), since 1965 (Östlund *et al.* 1998; Lännergren 1998; Persson 2001). The development of both the littoral and near shore pelagic zones is less investigated but more important to the surrounding people for recreation and from an aesthetical point of view.

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The aim of this study is to estimate sediment accumulation rate development within a near shore pelagic zone over the last thousand years, with particular focus on the influences of known human activity changes in the bay catchment in the last century. The study investigates in particular whether and in what way sediment accumulation rates may have been affected by the dredging of a ditch in 1951, which became a main surface water outlet into the bay, and the construction of a marina and a public beach in 1953. This ditch was earlier very shallow but its 1951 dredging drained new farmland and enlarged the catchment area by about 100%. In general, it may be of interest to understand and quantify how relatively small and common catchment enterprises may affect sediment transport to recipient bay waters.

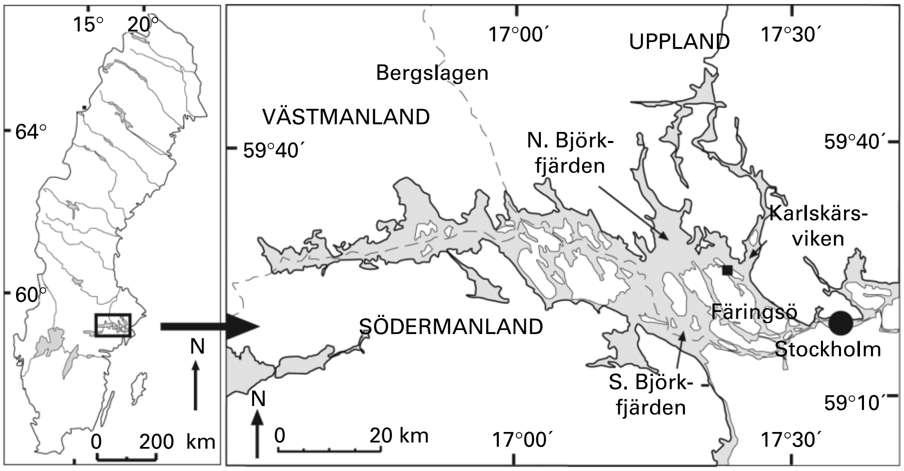

Figure 1 | Lake Mälaren, west of Stockholm, is the third largest lake in Sweden. Karlskärsviken to the north of Färingsö (map by Sven Karlsson).

BACKGROUND

Dating

The stage "Lake Mälaren" dates back to the he 12th century, making it reasonable to start the sediment dating study at that time (See also paragraph *Diatoms* under methods). During past times, many catchment and water undertakings around and in Lake Mälaren have been well documented (piers, poles etc.). Land disposal at Färingsö is also fairly well known since the fifteenth century (starts with "Karl VIII's Jordabok" from the middle of that century). During the Middle Ages all transactions, in which the church or the king were involved, were documented. Therefore we know which farms belonged to "taxing farmers". The catchment area to Karlskärsviken has all the time been registered as "taxing farms" and no main catchment and water undertaking is documented or known to local people. It is unlikely that any large such undertaking should have been performed by an individual farmer and without any additional detailed dating source it is impossible to capture a short anthropogenic event in the sediment dating before 1850. After that time the spheroidal carbonaceous particles (SCPs) provide dating information.

SCPs, which have been the usual term for fly-ash particles from fossil fuel combustion (Rose 2001), have been used for indirect dating of sediment cores and to assess sediment distribution patterns within lake basins (Griffin & Goldberg 1975, 1979; Rose 1990; Wik 1992; Wik & Renberg 1996; Rose *et al.* 1999). SCPs start to appear in sediments deposited about 1850. They increase slowly until the World War I, when a decrease can be recorded. A peak of SCPs is frequent in sediments accumulated in the 1930s. Since World War II the use of fossil fuel has rapidly increased and polluted sediments and soils. The peak of SCPs is dated 1973, just before the oil crisis. It is assumed that an increase or a decrease of SCPs in lake sediments occurs homogeneously and simultaneously within a lake (Rose *et al.* 1995, 1999).

Caesium analyses often detect a peak in the isotope Cs-137, associated with the Chernobyl accident in 1986. When the Chernobyl accident occurred and during the hours thereafter the winds were from E to WNW and spread the radioactive fallout in a tail-like zone over The Baltic Sea towards the southeast of Sweden up to Gävlebukten (Map by SMHI in SSI Report 2002). This resulted in a higher content of Cs-137 in the sediments and soil in this area than the earlier peaks in 1952 and 1963–64 from nuclear weapon tests fallout, verified in cores from The Baltic Sea (Uppsala Universitet 1998).

Site description

The studied area, Karlskärsviken, a typical bay of Lake Mälaren, is located 20 km west of Stockholm (Figure 1) at the northern part of the island of Färingsö. The western shore of Karlskärsviken has a broad transition zone overgrown by reeds and other macrophytes between the open water and the low lying shore meadows. The main surface water inlet, i.e. the already mentioned ditch which was dredged in 1951, was overgrown by reeds in the 1990s, a situation which causes substantial deposition of both organic and inorganic particles (Benoy & Kalff 1999) in the littoral zone. The eastern shore is rocky and steep. The sediments consist of clay and gyttja clay in the uppermost layers. The Karlskärsviken bay (Figure 2) covers about 20 ha and has an average depth of about 3 m and its catchment area is about 560 ha. Since 1953 there has been a public beach and a marina on the west side of the bay.

Site history

Before the Middle Ages, Lake Mälaren was not a lake but a bay of the Baltic Sea (Granlund 1928; Åse 1980; Miller & Hedin 1988). Between the tenth and the twelfth century AD isostatic uplift turned the bay into a lake. The Karlskärsviken bay was located in a stream from northwest to southeast in Lake Mälaren. Over the years that stream turned into a brook but was not definitely cut off until 1951. Until World War II the surrounding area was dominated by arable land and grazing cattle, but after the war the grazing cattle were reduced. No industries are established in the area but some commercial green houses are located there.

METHODS

Field work

Sediment cores were taken in the bay in a transect from the ditch outlet to the outer end of the bay (Figure 2). The core locations are outside the macrophyte zone. In the macrophyte zone the sediments have been dredged, and no historical information is archived for the area. An additional core was taken closer to a public beach. A 1 m long Russian peat corer was used for cores 1, 2, 4 and 5, all taken in winter when the bay was covered by thick ice. A turbidity-meter was used to measure the water depth and to know where to start the coring. Cores 1, 4 and 5 were two metres long and core 2 one metre. The upper 5 centimetres of core 1 were empty. The cores 3 and 6 were taken with a freeze corer. The length of core 3 was 48 cm and core 6 was 65 cm in length.

Laboratory work

All cores were sectioned into 1 or 2 cm slices, and these slices were freeze-dried and prepared for further analyses. The slices were weighed before and after drying to estimate the sediment dry mass content. Then they were dated from late

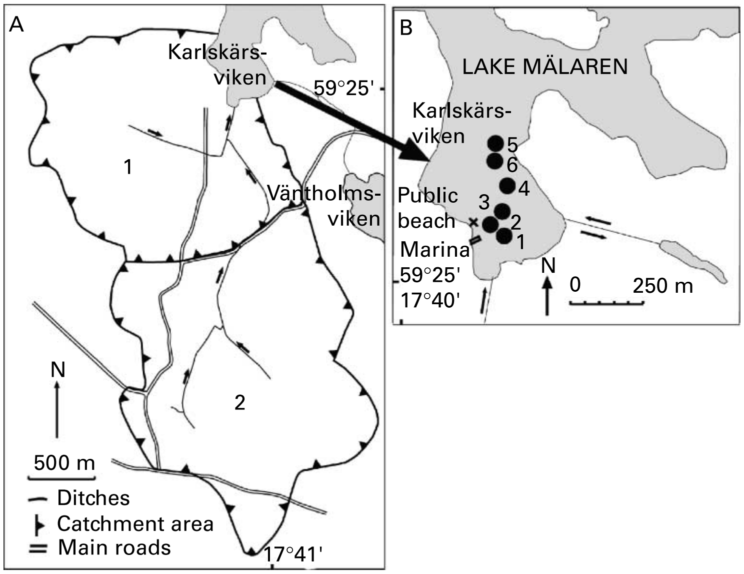

Figure 2 | (A) Catchment area to Karlskärsviken. 1) The original catchment area. 2) The enlarged catchment area since 1951. (B) Karlskärviken with the locations of the sampling points. The ditch with arrows in both directions is the rest of the former strait between Karlskärsviken and Väntholmsviken (maps by Sven Karlsson).

Viking age, about 950 AD until present. The chronological control is based on indirect dating of medieval times by diatom analyses and of modern times by the occurrence of black spheroidal carbonaceous particles (SCPs), fly-ash in everyday speech and the Cs-137-peak associated with the Chernobyl accident in 1986. The knowledge of the local activities during the second half of the twentieth century has also been useful for chronological control. Organic carbon content was analysed by combustion at 550° in a carbon analyzer.

The upper part of core 3 was analysed for the isotope Cs-137 at the Studsvik Nuclear laboratory. The downward migration of Cs-137 has been estimated to be 0.05 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ (Owens *et al.* 1999), which is too slow to be detected in increments of 1 cm.

Knowing the weight and chronology of the sediments, the sediment mass accumulation rate per unit cross-sectional area is estimated as $S = \rho_d \times V_d/A_c$, where V_d is the rate of dry sediment volume increase in the core, A_c is the cross sectional core area and the dry density is presumed to be $\rho_d = 2.65$ kg/l.

Diatoms

The shift in aquatic environment, from brackish water to freshwater, is reflected in the composition of the diatom assemblages in the sediments and is used for approximate dating of the transition period for Lake Mälaren, which occurred from about 800 to about 1200 AD (Miller & Robertsson 1982; Risberg & Miller 1997; Risberg *et al.* 2002). The final freshwater stage occurred at the end of the 10th century AD, established by C-14 analyses (Risberg & Miller 1997; Risberg *et al.* 2002). To identify this period, prepared slides from the whole cores were examined and those from the transition period were studied according to the following method.

The preparation of diatom slides for analysis followed methods described by Battarbee (1986). The diatom floras of Krammer & Lange-Bertalot (1991) and Snoeijs (1993) were used for identification of freshwater diatom taxa and for information on ecology. All diatoms and freshwater diatoms were counted. Between 500 and 700 diatom frustules were counted from each slice at the levels associated with the period.

SCPs

For SCP counting the sediment samples were prepared according to Rose (2001). Rose improved the method elaborated by Griffin & Goldberg (1975). Spheroidal particles and particle fragments greater than half a sphere were counted at × 400 enlargement using a light-microscope. The results are compared to those by Wik (1992), Rose (1990) and Rose *et al.* (1999) and to lead graphs analysed on the same cores (Olli & Destouni 2008) and to Brännvall *et al.* (2001).

RESULTS AND DISCUSSION

Organic carbon

At the lowest levels in the cores the organic carbon content is less than 2% but increases upwards (Figure 3). In the most recent sediments carbon reaches almost 4%. This upwards increase is expected even if there is no change in

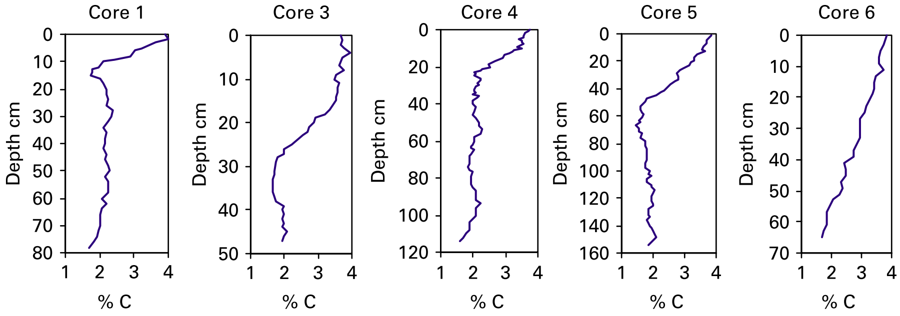

Figure 3 | Organic carbon contents in the cores 1, 3, 4, 5 and 6 from Karlskärsviken. The decrease of org. C in core 1 at 15 cm corresponds to the construction period 1951–1953.

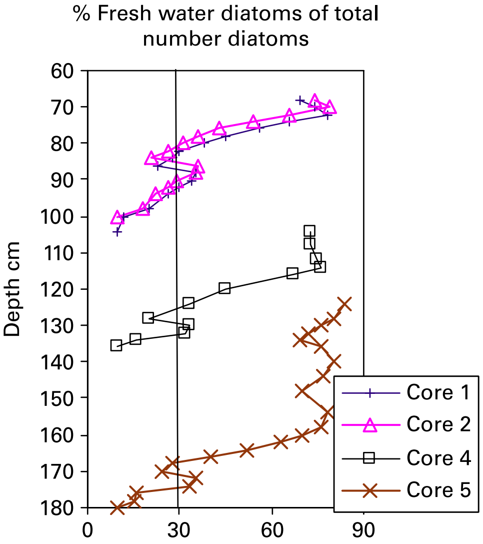

Figure 4 | The percentage of fresh water diatomtaxa counted on total number of diatom frustules in the cores 1, 2, 4 and 5 at the levels associated with the transition period. At about 1,000 the fresh water diatoms were increasing and had a percentage of about 30%.

sedimentation sources, as carbon oxidizes in the sediments over time and is released as carbon dioxide. Between the depths 11–15 cm in the near shore core (core 1) the organic carbon content decreases below 2% but increases first slightly and then more rapidly and reaches 4% at the top. This anomaly shows a heavier inorganic impact probably related to the ditch dredging and the construction of the marina and public beach.

Diatoms

Using diatom taxa, the shift in aquatic environment, from brackish water to freshwater, is detected in the cores 1, 2, 4 and 5 (Figure 4 and Table 1). The changes in diatom taxa in the brackish water transgression in the tenth century and the beginning of the final freshwater stage at the end of that century are clear in these cores. Following a time period of halophilous diatom taxa (e.g. *Amphora ovalis* v. *pediculus* and *Epithemia* spp.), the abundance of freshwater species (e.g. *Aulacoseira islandica, Aulacoseira ambigua* and *Stephanodiscus neoastraea)* increase, which indicate the end of the brackish water period. Also the next slight brackish water inflow into Lake Mälaren, concurrently with a temperature rise, is detected (Figure 4). This event is estimated to have occurred in 1200 by Moberg *et al.* (2005) and Briffa (2000). Some medieval glimpses of the lake level are found in the Erikskrönika (Erikskrönikan 1400s; Hallström 1969), which conform to the estimated chronology. In the final fresh water stage after the transition period the diatom assembly shows several periods with inflow of brackish water into Lake Mälaren. In fact, the final hydrological isolation of Lake Mälaren from the Baltic Sea, when brackish water ceased to enter Lake Mälaren, occurred in the 1960s, when the floodgate was improved at the lock in Stockholm. During medieval times Karlskärsviken was located in a strait and is compared to the Björkö strait.

In Karlskärsviken the first increase of brackish water diatom taxa after the onset of the final freshwater stage is noticed at level 148 cm in core 5 and at level 68 cm in core 1 (Table 1). The increment between the peak dominated by brackish water diatom taxa and the following peak of fresh water, the final end of the brackish water period, diatoms measure 14 cm (Table 1) in core 1, 0.03 g DM/cm^2/yr, and 16 cm in core 5, 0.05 g DM/cm^2/yr. Thus, during the

Table 1 | Diatom development during the transgression period. The percentages are the estimated percentages of freshwater diatoms relative to the total number diatom frustules. Brackish water is abbreviated b.w. and fresh water f.w. Deeper down in the sediments than column 1 indicates, the f.w. diatoms are < 10%. The first b.w. (transgression) peak corresponds to the dating of the Björkö strait. The second b.w. peak (transgression) is estimated to have occurred at the beginning of the thirteenth century. After the last b.w. peak until today, the f.w. diatoms oscillate but are never less than 80% of the total number of diatoms

	Depths				
Core	**<10% f.w. diatoms**	**b.w. peak**	**>30% f.w. diatoms**	**f.w. peak**	**b.w. peak**
1.	102 cm	86 cm	82 cm	72 cm	68 cm
2.	100 cm	84 cm	80 cm	70 cm	66 cm
4.	138 cm	128 cm	126 cm	114 cm	108 cm
5.	182 cm	170 cm	167 cm	154 cm	148 cm

transition period, when the whole of Karlskärsviken was located in the strait, sediment accumulation rates were higher further out from the shore, the slightly deeper part of the strait, than closer to the shore, the shallower section.

SCPs & Cs-137

SCPs are in low concentrations, when they start to appear in the sediments (Figure 5A). They increase first slowly but then suddenly reach a maximum before a decrease in the upper sediments. A clear decrease of SCPs, which corresponds to the World War II era, is detected in all the cores and so is the peak associated with 1973 (Figure 5A and Table 2). An earlier decrease, which can be associated with World War I, is pronounced in core 5 (Figure 5B). The peak of the isotope Cs-137 occurs between 11 and 12 cm in core 3 (Figure 6), which is dated 1986 due to the Chernobyl accident. The years are not exact as each increment covers several years (Table 3).

Sediment accumulation rates

From about 950 to 1950 sediment accumulated on average from 0.03 to 0.04 g DM/cm^2/yr near the shore of the bay. Further out (cores 5 and 6), the corresponding sediment accumulation was from about 0.05 to 0.1 g DM/cm^2/yr. The heavier sediment load in the outer and deeper part of the bay is expected, as many particles first settle in the shallower section, where after they resuspend and contribute to the sediment accumulation in the deeper parts of a bay/lake (Håkanson & Jansson 1983).

In the near shore of the bay (core 1) the increment from 10 to 15 cm shows anomalies (Figures 3 and 5A); the carbon content decreases instead of increases and SCPs do not show the expected increase after World War II. Three events, construction of the ditch in 1951, and of the marina and of the public beach in 1953, provided new sediments, mainly clay, which resulted in a high sediment mass accumulation rate of about 0.49 g DM/cm^2/yr from 0.04 g DM/cm^2/yr in the previous period and which explain the anomalies (Figures 3, 5A and 7). About 100 m further out, core 3, the SCPs do not

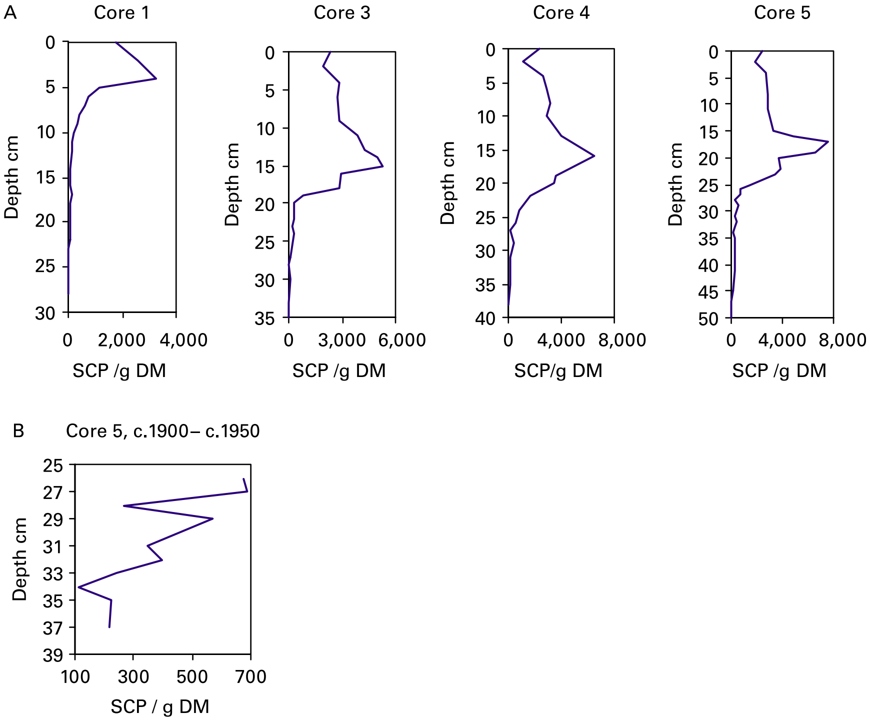

Figure 5 | Number of SCP/g DM from fossil fuel combustion. (A) From the start about 1850 and (B) core 5 between about 1900 and 1950. With the scale used in (B) the SCP decreases during the World Wars are evident. The small decrease of SCP at 31 cm may be a result of the economic crisis about 1930.

Table 2 | Year corresponding to depth in cm according to the number of SCP in the sediments. About 1973, there was a peak for SCP. 1953 is dated according to the number of SCP and the other elements, which show a clear decrease, corresponding to the years of known human water undertakings. 1945 and 1918 were boundaries between war years with low SCP fall-outs followed by years of progressing industries. 1850 marks the time when the SCP appear in the sediments

	Depth cm				
Year	**Core 1**	**Core 3**	**Core 4**	**Core 5**	**Core 6**
1973	4	15	16	17	18
1953	9	20			
1945	16	23	27	31	32
1918				38	40
1850	25	33	38	49	51

Table 3 | Average number of years covered by 1 cm sediment. Table 2 shows the dating of the sediments. Between each date is an increment corresponding to a certain number of years. The number of years, which are deposited in 1 cm sediment, indicates how exact or inexact the dating is

	No. of years				
Periods	**Core 1**	**Core 3**	**Core 4**	**Core 5**	**Core 6**
1953–1973	4	4			
1945–1973			2,7	2	2
1850–1945	11	10	9		
1918–1945				4	3,5
1850–1918				6,8	5,8
1150–1950	11–15,5		7,5–9	4–7,5	

increase as expected between 20–22 cm (Figure 5A) if the sediment accumulation rate had been even, which signals an impact from the construction works into that site as well, about 0.21 g/cm^2/yr. Still further out, the cores 4–6, the sedimentation accumulation rate increases after the construction period, in core 4 from 0.05 to 0.11 g/cm^2/yr and in the cores 5 and 6 from 0.1 to 0.22 g/cm^2/yr, and these new rates seem to continue. Cores 5 and 6 are close to each other and show similar sediment mass accumulation rates.

In core 3 (Figure 7), which is dated by Cs-137 analyses (Figure 6), a sediment accumulation rate decrease is detected during the two last decades, from 0.07 to 0.06 g DM/cm^2/yr. Before 1950 the rate was 0.04 g DM/cm^2/yr. It is likely that a larger decrease has also occurred closer to the ditch outlet, core 1, but 5–6 cm is missed from this core. The upper 5 cm in the corer was empty and an additional cm might have been lost as the sediment was unconsolidated. Measuring the depth with a turbidity-meter, the upper layers are seldom missed as often happens with an echo-sound, but the border between sediment and water is sometimes diffuse. If nothing was missed, the sediment accumulation rate would have decreased from 0.06 to 0.02 g DM/cm^2/yr in the last decades, which is less than the rate in the Middle Ages of 0.03 g DM/cm^2/yr and therefore not likely. On the other hand, if the sediment accumulation rate has not decreased and continued to be 0.06 g DM/cm^2/yr, about 11 cm would have been missed, which is not likely either, as only 5 cm was missed in the corer. Therefore an accumulation rate decrease must have occurred due to the new vegetation in the ditch, which resulted in a sediment mass accumulation decrease in both cores 1 and 3. During the last decades the ditch was not maintained but overgrown by reeds and bushes and some of the particles from the fields upstream certainly settled in the ditch before reaching the outlet (Benoy & Kalff 1999).

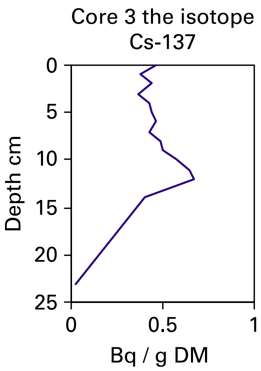

Figure 6 | The Cs-137 in core 3. The Chernobyl accident in 1986 is dated between 11 and 12 cm.

The upper levels are disturbed in the core close to the former strait/outflow from Karlskärsviken, core 4. That former strait, now a ditch without connection with Väntholmsviken (Figures 1 and 2), has been dredged in some parts during 1995 and that may have influenced this section of the bay (Figures 2 and 7) and explain the recent high sediment accumulation.

The results above may also have general applicability for near shore waters with low bathymetric slope gradient. In Karlskärsviken, the slope gradient is $< 1\%$, which is a common situation in the western part of Lake Mälaren. About 74% of the shoreline in Lake Mälaren is gently

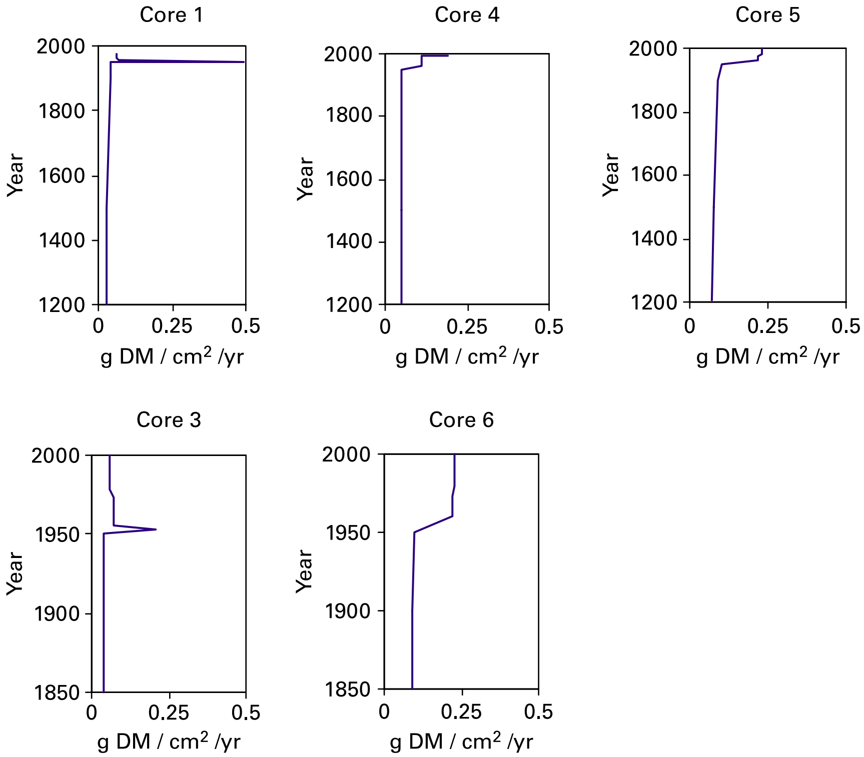

Figure 7 | Sediment mass accumulation rates in the cores 1, 3, 4 and 5. The dates are estimated by SCP analysis, in core 3 the sediment accumulation has decreased during the last decades. A larger decrease has certainly occurred in core 1, but is not measured due to the lack of sediments. The upper part of core 4 is shown separately to demonstrate the late increase.

sloping with $<$ 4% slopes (Andersson 2001). Ditches, dredging and other water activities occur generally at gently sloping shore stretches of most low lying eutrophic lakes, as the cultivated fields and the settlements are located there and not on rocky shores.

If one studies only deep basins, the effects of near shore activities may be missed, but these effects may be important for the environmental quality and people in the area. At smaller mean depths, the relative increases in biomass or production is also greater than the relative change in the mean depth (Ahl 1979) and biomass increase is often a main deterioration problem in lakes.

CONCLUSIONS

In the long period from medieval times to about 1950, the sediment accumulation rate in the studied bay increased to about double in the middle of the bay, but only by about 33% in the near shore section. After the ditch dredging in 1951 and marina and public beach construction in 1953, the sediment accumulation rate increased in the whole bay, very quickly in the near shore section and later also further out in the bay. In the last decades, the ditch has been overgrown by reeds and bushes, enabling much of the eroded particles to settle within the ditch. This resulted in a lower sediment accumulation rate in a wide bay section close to the ditch outlet.

The 1951 change from a shallow ditch into a deeper and broader one increased the sediment accumulation in the bay considerably, but the results indicate that this effect occurred mostly around the dredged area and less so out in the deeper parts of the bay. Nevertheless, increased sediment accumulation lowers the mean lake depth and a shallower lake is more at risk of eutrophication than a deeper one (Ahl 1979). The results of this study indicate therefore that relatively common and small-scale catchment enterprises may have important sediment accumulation impacts and associated ecosystem effects in recipient bay waters.

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