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Human activities in the drainage basin of the river Kyrönjoki, Western Finland, have greatly influenced the hydrology and sediment load of the river. The main factors have been agriculture, forestry, peat mining and watercourse works. Also sewage from towns and small-scale industry has increased the nutrient transport to the delta of the river. The aim of this study was to assess factors influencing the sedimentary conditions, sediment accumulation rates and sediment quality in the delta of the river. The sediment studies were carried out in 1983-1988 in the delta. The drainage basin of the river Kyrönjoki covers 5030 km^2 in the middle boreal vegetation zone. The river channel has been cleared many times since the 1600s to prevent floods and to allow agriculture on the adjoining land. Extensive cultivation of the paludified Litorina clay plains along the river has also continued for centuries. Forestry drainage of mires covered almost all the mires of the basin in 1960s and 1970s. Since 1963, four reservoirs and four hydroelectric power stations with daily regulation of water have been built. The estuary of the river was echo sounded, and on the basis of the results the delta was delimited, and areas of accumulation and erosion were separated. Samples of the sediment surface from 65 sites and long cores from 8 sites in the delta of the river Kyrönjoki were analysed for water content, organic content, C, N, P, Ca, Fe, Mn, Pb, Cu, Zn, Cd and Hg. The sediment from Nabbviken Bay in the delta was dated on the basis of annual laminae. The chemical analyses showed that the organic matter and heavy metal content have increased during recent decades. The heavy metal content was clearly lower than in areas polluted by industrial works. The phosphorus content of the sediment was very high. The sedimentation rate in the delta increased from the 1930s to the 1950s, due to increased land reclamation for agriculture and forestry drainage, and then decreased in the beginning of the 1970s below the level of 1930s, due to the construction of water reservoirs. On the basis of the chemical analyses of the sediment surface the delta was divided into two parts according to the sedimentary conditions. In the inner part with acid river water dominating, the conditions were reducing. The Fe/Mn ratio of the sediment was high, and the heavy metal content usually low. In the outer part of the delta, where weakly basic brackish water dominates, the sedimentary conditions were mostly oxidizing. The Fe/Mn ratio was low, and the heavy metal content usually high in the accumulation areas. This is because the fine-grained allochthonous material, which has a high heavy metal content, flocculates and precipitates when it reaches the brackish water of the Gulf of Bothnia, and the salinity and pH get higher. Due to land uplift and accumulation of the sediment, which together are approximately 2 cm a year, the delta gradually moves towards the sea. The present-day shallow bays will be filled and the deeper ones are formed into lakes.

Keywords: drainage basin processes, land use, river delta, sedimentation, sedimentological conditions, sediment quality, heavy metals

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1. Introduction

1.1 Factors influencing on sedimentation

Raindrops and water flowing on the earth surface move soil particles, and transport them along the current dissolved and suspended in the water, or as bedload on the bottom of a stream. This is a fully natural process taking place continuously or periodically. The transport capacity of water depends on the velocity of the current: the higher the velocity the larger particles the water can transport (Hjulström 1935). When the current slows down the transported suspended solids and bedload are deposited. The most coarse and heavy particles are deposited first, and the most fine-grained and light-weighted particles last. Thus they are transported with water the longest distance. The diluted matter can be deposited when chemical conditions, e.g. acidity, change. Sedimentation occurs in streams in places with slow current, and when the stream ends in a lake or sea, deposition forms a delta.

The intensity of erosion depends on the cumulative influence of many factors: climate, relief, soil, vegetation and human influence. The influence of the different elements on erosion is very complex. One element may influence many other elements, which in turn, affect erosion, increasing or decreasing it (Jansson 1982, 124).

The amount of sediments transported by water and deposited depends on the intensity of erosion and the width of the drainage basin as well as the current of the water. The formation of a delta depends on the amount of deposited matter, shore processes, waves, currents, tide and changes of water level (Wright 1978, 6). On the Finnish coast an important factor is land uplift, which makes deltas to rise above the sea level, and gradually to move towards the sea.

At present, in most regions human activities are increasingly affecting sediment transport and delta formation. People dam rivers, control floods and natural erosion, change the drainage, clear new fields, clearcut forests, use the water for irrigation etc.

In Finland the most important human activities affecting the hydrological cycle are draining for agriculture and forestry, and watercourse works with regulation of discharge in water systems. In this study watercourse works are defined as clearing of streams, and building of embankments, reservoirs and channels.

The main purpose of watercourse works is to decrease the seasonal hydrological changes to prevent floods and to increase the production of hydroelectric power. The daily regulation causes short-term changes in discharge nearby power stations, upstream and downstream. In daytime, when the consumption of electricity is high, a lot of water flows through the power station, while in the night the flow is decreased. Daily regulation causes a continuous erosion in the channel. Watercourse works increase erosion during the dredging, especially if it is conducted below the water level. On the other hand, reservoirs act as sediment traps, and decrease the amount of suspended solids transported to the delta (Sundborg 1992).

Land reclamation for agriculture, forestry drainage of mires and amelioration for peat extraction increase peak flows. Sub-drainage of arable fields has a controversial influence (e.g. Hyvärinen and Vehviläinen 1981, Seuna and Kauppi 1981, Bilaletdin 1983, 115, Sallantaus 1984). Forestry drainage also increases total discharges from ditched areas (Mustonen and Seuna 1971, 33, Seuna 1982). Land reclamation and forestry drainage increase erosion considerably especially during the ditching and immediately after it (e.g. Heikurainen *et al.* 1978, Kenttämies 1981, Heikkinen and Knuutinen 1989). In areas with erosion sensitive soil, the erosion may continue during decades (Virkanen and Tikkanen 1998, Vuori *et al.* 1998). Also forest clearcutting and soil scarification increase both the inorganic and organic load to watercourses (Ahtiainen 1992, Rask *et al.* 1998, Turkia *et al.* 1998). A lot of organic matter is leached from peat extraction areas as long as the works continue (e.g. Sevola 1981, Heikkinen and Visuri 1988, Sallantaus 1988, Marja-aho and Koskinen 1989). Sewage from densely populated areas and industry increase especially the amount of dissolved matter transported by the water but agriculture nowadays causes by far the largest nutrient load in the rivers (Savea-Nukala *et al.* 1997, Tikkanen *et al.* 1997).

1.2 Previous studies on the deltas in the Gulf of Bothnia

Only a few studies on river deltas have been made in Finland. Rosberg (1895) studied the deltas of 30 rivers flowing into the Gulf of Bothnia surveying their width and structure. He divided the deltas into four morphological categories: (1) Archipelago delta, (2) Submarine delta with topmost supramarine parts, (3) Purely submarine delta, and (4) A modified delta with wide alluvial plains. The delta of the river Kyrönjoki represented type 4. Rosberg also understood the possibilities to use deltas to study the influence of land use in the drainage basin on the river.

Säntti (1954) was the first to study recent sedimentation in river deltas. He estimated the sedimentation rates in the delta of the river Kokemäenjoki in southwestern Finland. Somppi (1983) and Heikkilä (1985, 1986a, 1986b, 1986c, 1991) have studied sedimentation and accumulation of trace metals in the delta of the river Kyrönjoki. Saaristo (1984) studied the structure, topography and land use in the delta of the rivers Temmesjoki and Liminganjoki. Tikkanen *et al.* (1985) studied material transport and accumulation in the deltas of two little streams in southern Finland. Pitkänen (1986, 1994) has studied the nutrient load from Finnish rivers and the eutrophication in the deltas.

On the Swedish western coast of the Gulf of Bothnia several studies of sedimentation in river deltas have been carried out recently by Brydsten *et al.* (1990), Brydsten (1992), Forsgren and Jansson (1992) and Malmgren and Brydsten (1992) in the Öre estuary and Widerlund and Roos (1994) in the Kalix river estuary. They found out that regulation for the exploitation of hydroelectric power reduced the transport of particulate matter, total phosphorus, iron and silica by 10-50%. They also revealed a strong estuarine filter effect due to increasing salinity and pH, and proved that the major part of the river input of suspended solids was deposited near the river mouth.

The recent sediments and sedimentation outside the coast in the Baltic Sea have been studied intensively during recent decades, especially for geochemistry, origin and transport of sediments (e.g. Ignatius and Niemistö 1971, Tulkki 1977, Boström *et al.* 1978, Niemistö *et al.* 1978, Hallberg 1979, 1991, Heino 1979, Niemistö and Voipio 1981, Mäkelä 1986, Jonsson *et al.* 1990, Brydsten 1993, Lax *et al.* 1993, Leivuori and Niemistö 1993, Müller 1996). Even though most of the suspended sediment input from the rivers is deposited in the deltas, the above mentioned studies show that especially during spring floods a lot of matter transported by the rivers accumulates in the deep basins of the Baltic, where the human impacts on water ecosystems can be revealed in the sediment stratigraphy.

There are a number of earlier studies on the river Kyrönjoki, its drainage basin and delta. Erviö (1975) studied the agriculture on sulphide-bearing clay plains along the river. Alasaarela (1981, 1982, 1985) has studied the connections between watercourse works and acidity as well as changes in water quality. Lilja (1982) studied the transport of fine-grained material in the river Kyrönjoki and sedimentation in floodplains. Bilaletdin (1983) studied the influence of land reclamation on the hydrology of the river Kyrönjoki. Storberg (1983) compiled information on the quality of water. Koskenniemi (1987, 1995) has studied water quality, macrophyte vegetation and zoobenthos in reservoirs constructed in the Kyrönjoki basin.

Salo *et al.* (1985) studied erosion in the upper reaches of the river in Hyypänjoki, which is a tributary of the river Kyrönjoki (Fig. 1). Mansikkaniemi (1985) has studied material balance in the floodplain in Ilmajoki and Seinäjoki. Meriläinen (1984a, 1984b, 1985, 1986, 1989) made studies on the zoobenthos, macrophyte vegetation, spreading of the river water and loads of nutrients, organic matter and suspended solids in the delta. Turunen (1985) compiled a comprehensive study of the history of the use of rivers in Southern Ostrobothnia on the western coast of Finland. Jones (1987) studied thoroughly the land use history with special reference to land uplift in Maxmo in the delta of the river Kyrönjoki. Hudd *et al.* (1984, 1986, 1993) and Ranta (1985) have studied fish populations in the river Kyrönjoki and its delta and human influence on them, especially acidification problems. Hildén and Rapport (1993) compiled a review of human impact on the river Kyrönjoki and its estuary, especially paying attention to biological characteristics.

1.3 The aims of the study

The aim of this study was to survey the recent sedimentation in the delta of the river Kyrönjoki and human impact on it. The main emphasis was on a survey of the sedimentation rates and sediment chemistry, especially trace metals in the delta, and to find explanations for these features by analysing the land use in the drainage basin and watercourse works in the river.

The main aspects of the study were:
- Analysis of the drainage basin and water construction works of the river Kyrönjoki
- Analysis of the width and structure of the delta of the river Kyrönjoki
- Human influence on
- sedimentary conditions
- sedimentation rates
- quality of sediment (organic content, nutrients, heavy metals)
- Future development of the delta

2 Study area

2.1 Description of the Kyrönjoki drainage basin

2.1.1 Topography

The Kyrönjoki drainage basin covering 5030 km^2 is situated in western Finland, and the river flows into the Gulf of Bothnia 30 km northeast of the town Vaasa (Fig. 1). The length of the river sys-

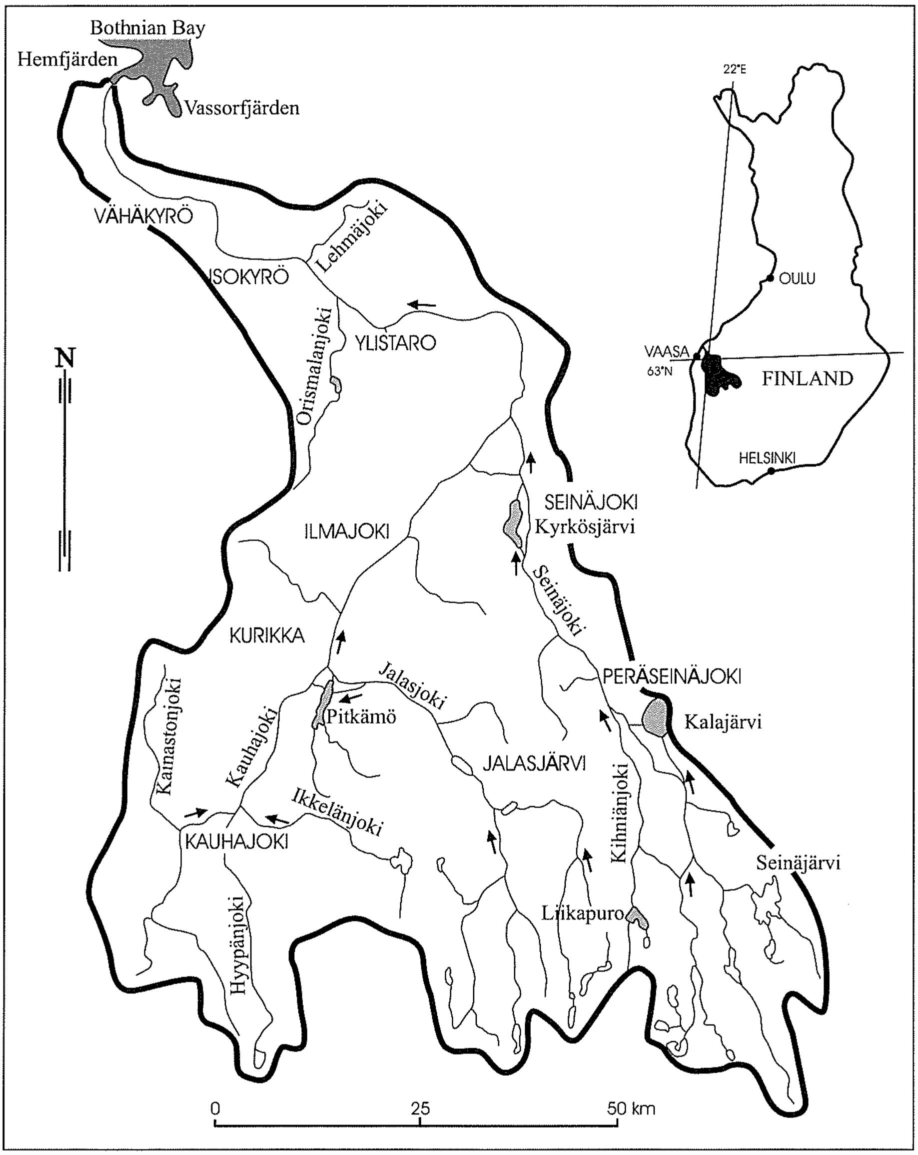


Fig. 1. Location of the drainage basin of the river Kyrönjoki and the most important names of places and watercourses in the drainage basin.

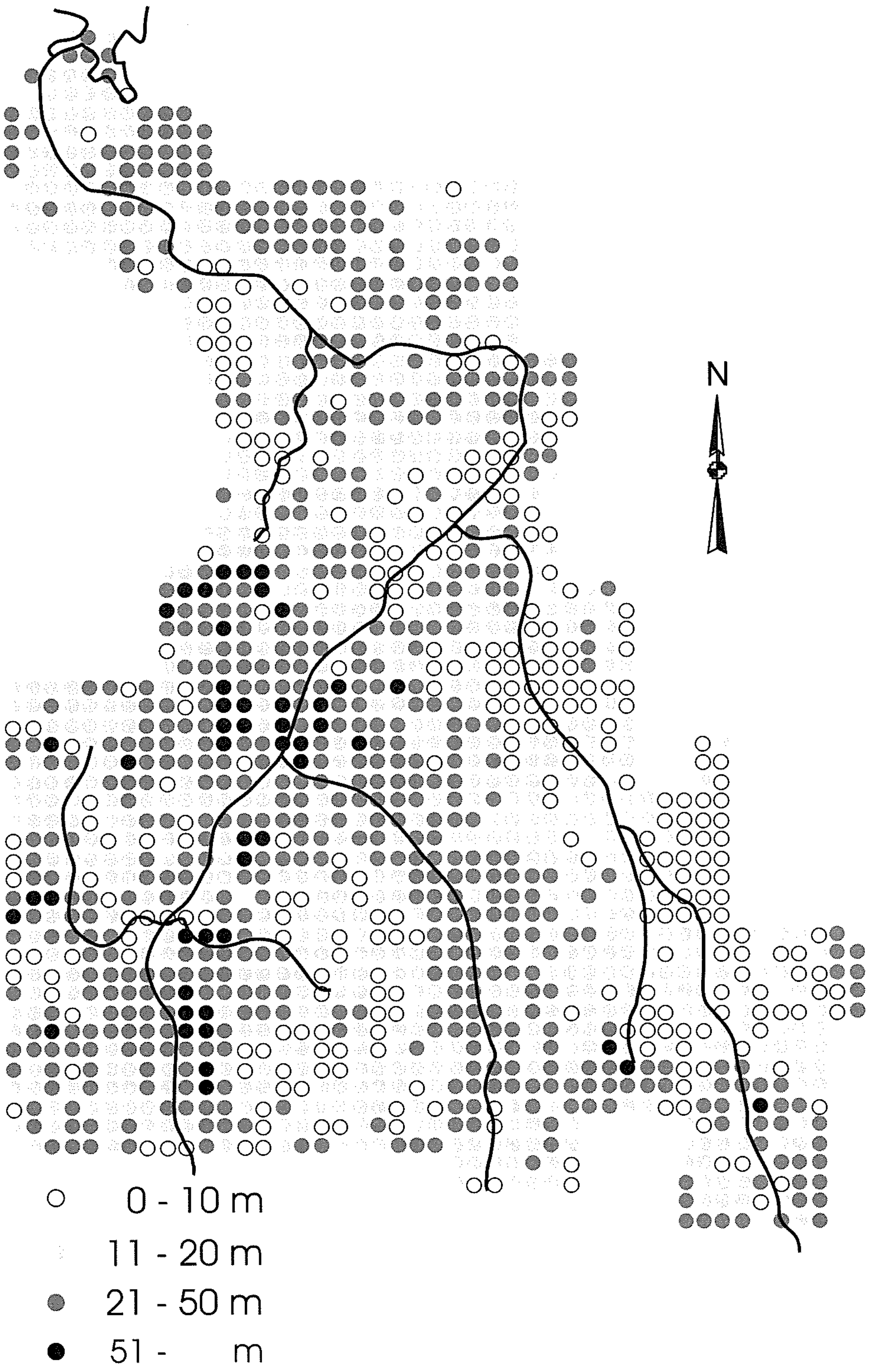


Fig. 2. Altitude differences in a 2 x 2 km grid in the drainage basin of the river Kyrönjoki.

tem of the Kyrönjoki, measured from the springs of the river Seinäjoki to the sea, is about 200 km. The main branch, the river Kyrönjoki itself, from the confluence of the tributaries Kauhajoki and Jalasjoki to the sea, is 124 km long. The highest point of the drainage basin is Vähä Nummikangas, which reaches a height of 196 m a.s.l. It is located 8 km east of the middle course of Hyypänjoki in Kauhajoki municipality (Fig. 1, cf. Mansikkaniemi 1985, 158).

The topography of the drainage basin of the river Kyrönjoki was studied by determining the heights of the highest and lowest points, and the height of the middle point of a 2 by 2 km grid in the basic topographic maps on a scale of 1 : 20 000 (Mansikkaniemi and Heino 1971). An isopleth map of the maximum height differences in the grid was compiled (Fig. 2).

The topography of the drainage basin is gently sloping. Local height differences in a 2 by 2 km grid system are mostly less than 20 m. Only in a few places are the differences as much as 87 m (Kurikka, Juonenvuori hill) and 77 m (Ilmajoki, Santavuori hill) (Figs. 1, 2). The river course is located between hills, and in its upper reaches it has formed a valley, which is at its deepest more than 60 m below the surrounding plains in Hyypänjoki (see also Salo *et al.* 1985). In the downstream area from Ilmajoki to the sea there is a very flat alluvial plain along the river. Its width varies from 1 km to 6 km (Fig. 2).

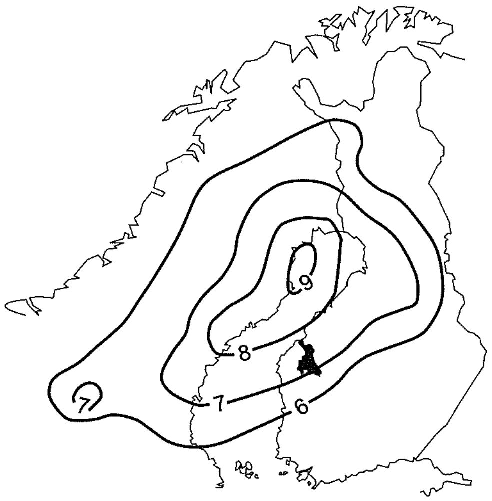


Fig. 3. Recent land uplift (mma^{-1}) in Fennoscandia. The drainage basin of the river Kyrönjoki in black. Redrawn after Kakkuri (1990).

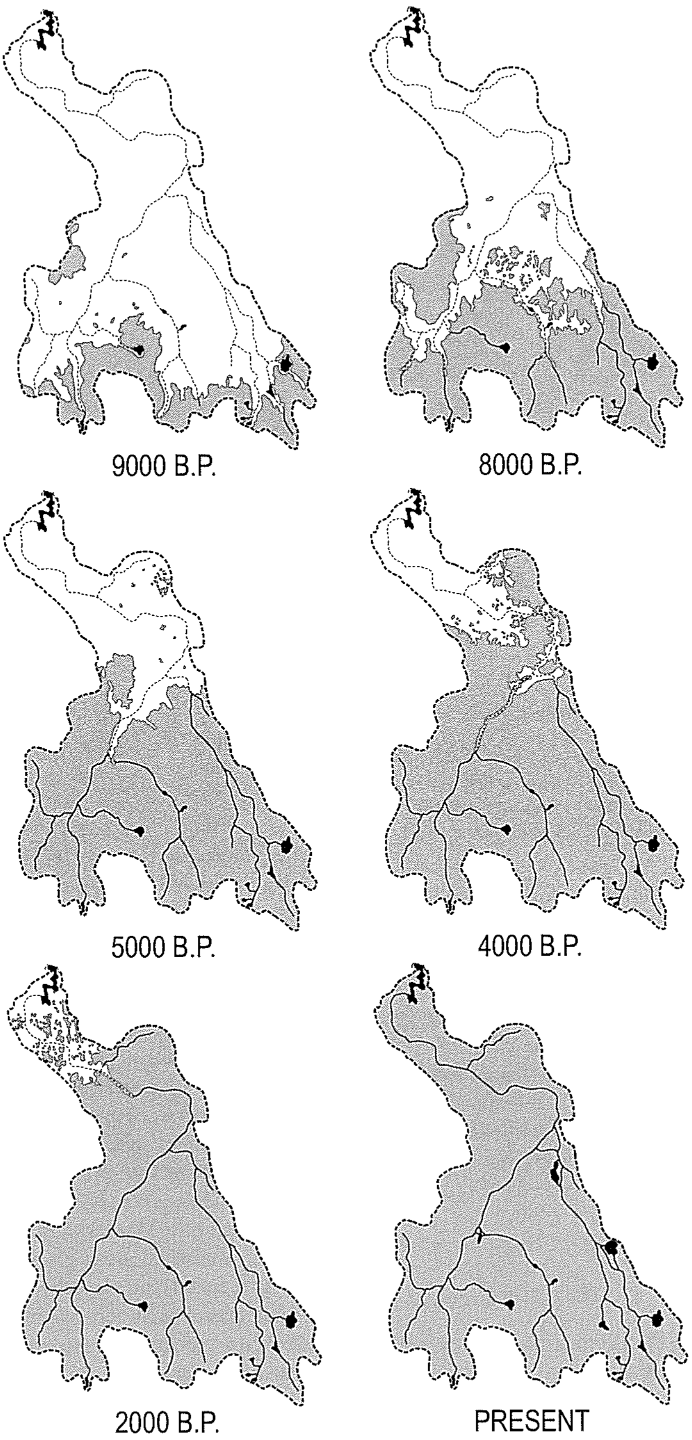
In the course above Ilmajoki the mean gradient of the river Kyrönjoki is rather steep, about 1.5 mkm^{-1}. In the Ilmajoki flood basin the gradient of the river is very shallow, only 0.04 mkm^{-1} over a stretch of 34 km. Downstream of the flood basin there is a number of rapids with a height difference of a few metres each, and the gradient in the lowest 70 km of the river is 0.5 mkm^{-1} (Mansikkaniemi 1985, 158). The gradient gradually gets more gentle due to the annual land uplift, which is approximately 8 mm at the delta of the river Kyrönjoki, and about 7 mm in the upper course of the river (Fig. 3, Kakkuri 1990).

2.1.2 The development of the river Kyrönjoki

The development of the river Kyrönjoki started after the land had risen from the Ancylus lake stage of the Baltic Sea (see Donner and Eronen 1981). The whole drainage basin was below the water level for a short time, but due to the rapid uplift of the land, the drainage basin and the river system started to form. About 9000 years ago only the highest areas of the present southern watershed of the drainage basin were dry land (Fig. 4) The upper reaches of the tributary Seinäjoki already existed. 8000 years B.P. Hyypänjoki, Ikkelänjoki, Jalasjoki, Kihniänjoki and Seinäjoki were still separate small rivers (Fig. 4). About 5000 years B.P. Kauhajoki and Jalasjoki formed a joint delta in Kurikka, and Seinäjoki flowed into the Litorina Sea near the present town of Seinäjoki (Fig. 4). The formation of Kyrönjoki proper started approximately 4000 years ago, when the rivers Ilmajoki and Seinäjoki had a joint delta between the present towns. The present extensive floodplains were formed then (Fig. 4). 2000 years ago the delta of the river Kyrönjoki was in Isokyrö, and there was a large archipelago off the coast.

2.1.3 Bedrock

The bedrock of the river Kyrönjoki drainage basin consists mainly of acidic Precambrian granites, granodiorites and gneisses (Laitakari 1942, Fig. 5). Quartzite forms a little area in the northern part of Ilmajoki. Basic rocks, amphibolites and basic schists are of minor importance. Marble



9000 B.P.

8000 B.P.

5000 B.P.

4000 B.P.

2000 B.P.

PRESENT

Fig. 4. The Holocene development of the Kyrönjoki river system and the drainage basin. Shaded area is dry land at different times. Datings after Salomaa (1982).

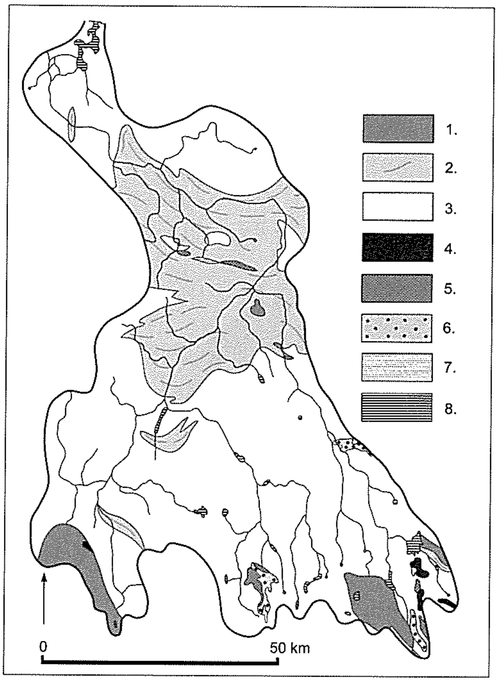


Fig. 5. The bedrock in the drainage basin of the river Kyrönjoki. 1. Granite, 2. Granite veins in migmatitic gneiss, 3. Granodiorite and quartz diorite, 4. Gabbro, anorthosite and peridotite, 5. Metabasalt, greenstone and amphibolite, 6. Quartz-feldspar schist and gneiss, 7. Quartzite. Redrawn after Simonen (1987).

Fig. 6. Bedrock outcrops (shaded) in the drainage basin of the river Kyrönjoki. Redrawn after Kujansuu & Niemelä (1987).

has been found only in two very little areas in Kurikka and Isokyrö and graphite in a limited area in Seinäjoki (Eskola *et al.* 1919, Laitakari 1942). The bedrock consists of rock species which are not easily soluble. Bedrock outcrops, rising tens of metres from the clay plain are common along the river from Kurikka and Seinäjoki down to the delta of the river. In the upper course of the tributaries Jalasjoki and Seinäjoki there are also numerous low rocky outcrops, but in the upper course in Kauhajoki they are rare (Fig. 6).

2.1.4 Soils

In the river valleys the dominating surface soils are clay and silt. In the plains along the lower course of the river clays predominate (Fig. 7). Most of the clays have deposited on the bottom of the Litorina Sea some 7000 - 2500 years B.P., covering older clays from the Ancylus lake period of the Baltic Sea (Donner and Eronen 1981, 28-31). The river has a channel 10-15 m deep in the Litorina clay, stretching down to the Ancylus clays only at the upper limit of Litorina clays about 95 m a.s.l. The Litorina clays contain a lot of sulphates, which are easily leached, when the plains are cultivated (Erviö 1975). This causes the acidity of the water in the lower course of the river Kyrönjoki (Alasaarela 1982). In the upper course of the river, above the Ilmajoki flood basin silt and fine sand predominate along the rivers, especially along the tributaries Kauhajoki and Jalasjoki, and the river Kyrönjoki in Ilmajoki and Kurikka (see also Mansikkaniemi 1985).

In the watershed areas glacial till covers wide areas. It is widely overlain by peat. Glaciofluvial sand and gravel exist only in limited areas near the watersheds, especially in the south-western part of the catchment in Kauhajoki, and in Ilmajoki in the Koskenkorva interlobate formation (Punkari 1980, Fig. 7). The thickest glaciofluvial deposits (135 m) are in Karhukangas, the southwestern corner of the catchment (Niemelä and Raikamo 1983). Most of

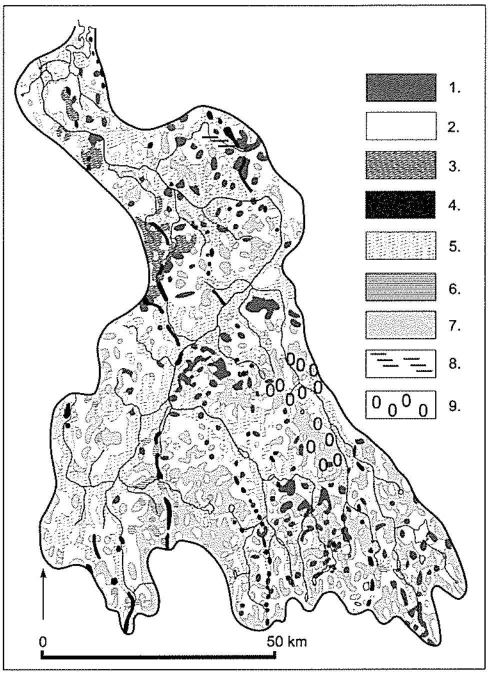


Fig. 7. Quaternary deposits and formations in the drainage basin of the river Kyrönjoki. 1. Bedrock terrain (superficial deposits less than 1 m thick), 2. Ground moraine, 3. Hummocky moraine/ablation moraine, **4.** Esker, delta, ice-marginal and interlobate formation, 5. Marine and lacustrine deposit (silt and clay), 6. Littoral deposit (gravel and sand), 7. Peat deposit, 8. End moraines (mainly de Geer moraines), 9. Drumlins. Redrawn after Kujansuu & Niemelä (1987).

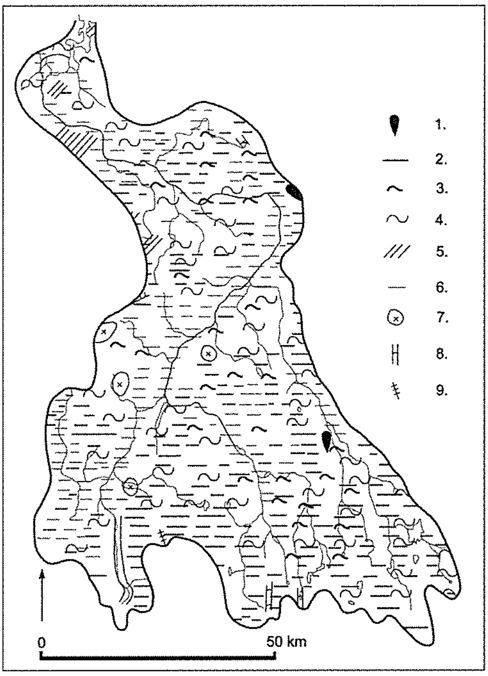


Fig. 8. Geomorphological formations in the drainage basin of the river Kyrönjoki. 1. Drumlin field, 2. Peatland, 3. Roches moutonées, 4. Undulating ground moraine cover, 5. De Geer moraines, **6.** Fine-sediment plain, 7. Monadnocks and similar residual landforms, 8. Structurally controlled valley, 9. Esker. Redrawn after Fogelberg & Seppälä (1986).

the glaciofluvial deposits have been used for the construction of roads and buildings. Only in Kauhajoki most of the formations are intact.

2.1.5 Geomorphology

During the last glaciation the study area was covered with a thick layer of ice, which moved from northwest to southeast. As well as during earlier glaciations it smoothed the forms of the bedrock, drifted the superficial deposits and deposited a basal till layer covering most of the bedrock. Some eskers formed during earlier glaciations were preserved in Kauhajoki, but also covered by till (Gibbard *et al.* 1989). Deglaciation took place between 9500 - 9000 years B.P (Aartolahti 1972, Donner and Eronen 1981). During the deglaciation glaciofluvial formations, eskers and deltas, were formed in Kauhajoki, Ilmajoki and Isokyrö (Fig. 8). After deglaciation the whole study area was for a short time below the surface of the Ancylus Lake stage of the Baltic (Salomaa 1982).

The present catchment has risen gradually from the Baltic Sea. The first large estuary was in Kauhajoki about 6000 years ago (Palomäki 1991). Four thousand years ago the delta was in the present Ilmajoki flood basin. While the land rose from the Baltic Sea, winds blew sand from the glaciofluvial deposits and formed a large aeolian sand field, and a number of dunes to the east of Kauhajoki on both sides of the tributary Ikkelänjoki. Afterwards, a great deal of the sand was covered by a thin layer of peat, and brooks flowing into the river Ikkelänjoki carved little valleys in the easily erodible sand.

Landslides were mapped using aerial photographs and topographic maps along the river channel between Koskenkorva and Ilmajoki where

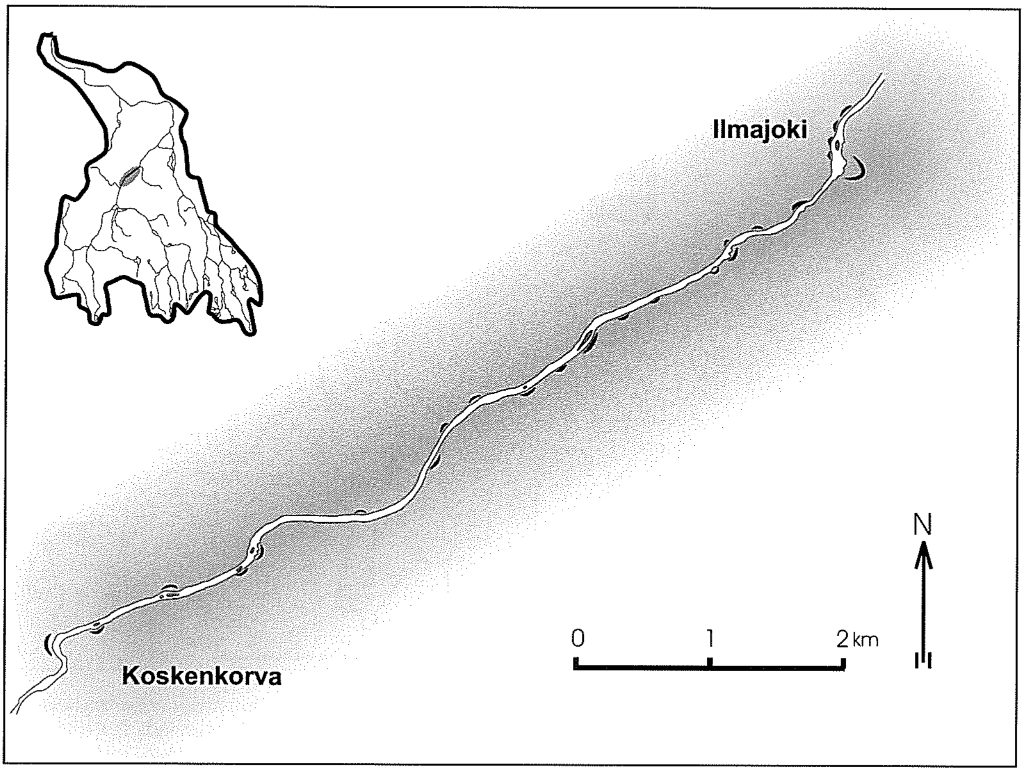


Fig. 9. Landslides along the river Kyrönjoki between Koskenkorva and Ilmajoki.

landslides are common and have a strong influence on sediment transport and river channel formation (Fig. 9). In connection with the landslides the bottom typically rises in the middle of the river forming small islands which are eroded during flood periods.

In the lower course of the river plain marine clay deposits dominate in the riversides. Wave washed bedrock outcrops rise 20 - 80 metres from the plain on both sides of the river.

2.1.6 Climate

The mean annual temperature in the Kyrönjoki drainage basin over the period 1931-60 is +3.5°C. The mean temperature of the warmest month, July, is +16°C and that of the coldest month, February, -8°C. The mean thermal summer lasts 110 days and thermal winter 150 days. The mean length of the growing season is 160 days. The mean effective temperature sum during the growing season is 1100°C (Helminen 1988). The mean annual precipitation is about 600 mm, and mean annual evaporation 350 mm. Thus, the macroclimate is clearly humid. The mean greatest snow depth of the winter in forests varies between 35 and 50 cm in the different parts of the drainage basin. The average duration of snow cover on open ground is 130 days, and the mean maximum soil frost penetration in till ground at sites cleared of snow 145 cm (Solantie 1988a, 1988b).

2.1.7 Vegetation

The drainage basin of the river Kyrönjoki is situated in the boundary zone between south and middle boreal vegetation zones (Ahti *et al.* 1968). The watershed areas in the south and east belong to the middle boreal and the lowlands along the downstream course of the river belong to the south boreal zone.

The mineral soil in the Kyrönjoki drainage basin is covered by coniferous forests, dominated by Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karsten). Deciduous trees are of minor importance. The dominating forest site types are Vaccinium type dominated by lingonberry (*Vaccinium vitis-idaea* L.) in the field layer and Myrtillus type dominated by bilberry (*Vaccinium myrtillus* L.) in the field layer (for the site types see Cajander 1949). Close to the delta there are primary herb-rich forests dominated by black alder (*Alnus glutinosa* (L.) Gaertner) as narrow strips along the shores, in the ground lately risen from the sea (Schwanck 1981). In other parts of the drainage basin fertile herb-rich forests are very rare. In the watershed areas dry heath forests with heather (*Calluna vulgaris* (L.) Hull) dominating in the field layer, cover considerable areas. At present all the forests are effectively managed, and they are in various successional stages from clearcut areas to approximately 100 years old secondary forests. There are about 10 000 owners of small strips of the forests, who have so far managed their forests independently. Nowadays most of the landowners make joint management plans for the forests. No pristine or old-growth forests, developed naturally after selective cuttings of earlier periods, are left in the drainage basin (Väre 1998).

The mires of the Kyrönjoki catchment belong mostly to the zone of concentric raised bogs. The southeastern part of the catchment belongs to the zone of eccentric bogs. There are also a number of aapamires in the study area (Ruuhijärvi and Hosiaisluoma 1988). The dominating mire site types are ombrotrophic *Sphagnum fuscum* pine bogs and dwarf shrub pine bogs. In the margins of the mires there are also minerotrophic fens and spruce mires. In the aapamires there are open oligotrophic *Sphagnum papillosum* fens. Mesotrophic and eutrophic fens are very rare (Heikkilä 1987, Heikkilä 1990).

2.1.8 Hydrology and man's influence on it

Daily mean discharges of the river Kyrönjoki in Skatila near the outlet (F = 4805 km^2) were given by the Hydrological Office of the National Board of Waters and Environment (At present the Finnish Environment Institute). The discharge of the river Kyrönjoki fluctuates over a wide range (NQ : MQ : HQ = 1 : 43 :528 m^{3}s^{-1}). Spring, summer and autumn floods are frequent. The difference between the highest and lowest observed water level at the Munakka gauging station in the Ilmajoki flood basin is 6.5 metres, which was the

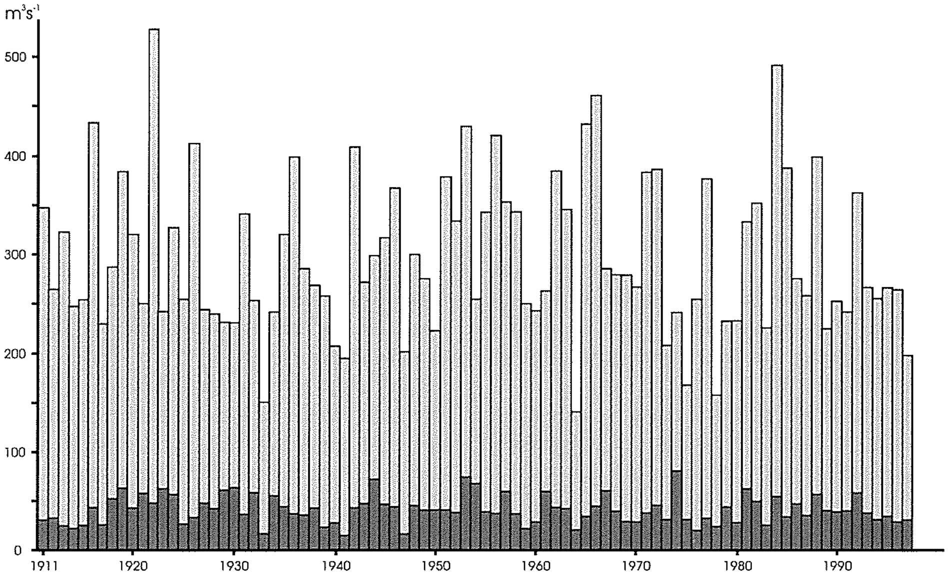


Fig. 10. Annual mean and maximum discharges in Skatila in 1911-1997.

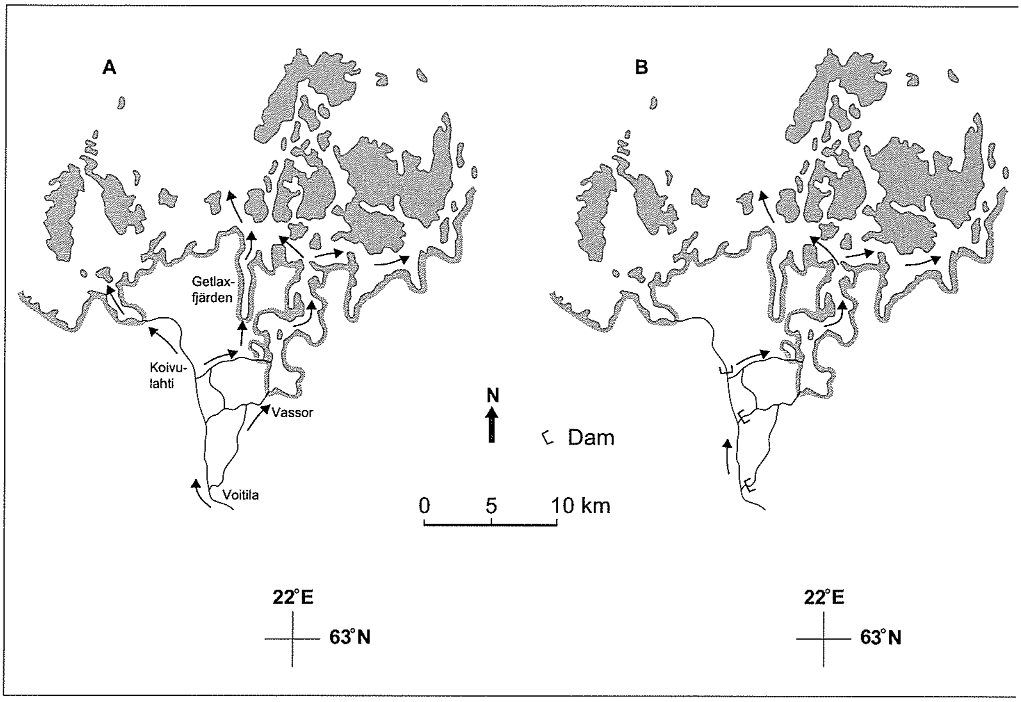


Fig. 11. Main directions of water flow in the delta of the river Kyrönjoki before (A) and after (B) the regulation of the lower reaches of the river in the late 1950s.

greatest difference observed in Finland over the period 1961-70 (Bilaletdin 1983, 10). The annual variation of discharges, especially the highest ones, is also great (Fig. 10).

The river channel has been dredged many times since the 1600s to prevent floods and to make the use of the riversides for agriculture possible. To get more arable land, many lakes have been drained from the 1850s to 1930s especially in Peräseinäjoki, Jalasjärvi and Kauhajoki. In earlier times the river was very important for the transport of the products of the catchment region, especially timber and tar, to the harbour of Vaasa. Therefore some clearings were made to improve the traffic in the river (Turunen 1985).

Since the 1950s artificial embankments have been built in the downstream area between Koivulahti and Vassor to prevent floods there (Fig. 11). After the construction of a dam in Getlaxfjärden in 1957 all the water of the river Kyrönjoki flows to the sea through Vassor Bay (Fig. 11). In the 1980s embankments have been built in the Ilmajoki flood basin, too. Since 1963, four relatively large reservoirs, Liikapuro, Pitkämö, Kalajärvi and Kyrkösjärvi, have been built (Fig. 12). In connection with the reservoirs, four hydroelectric power plants have been built. The power plants use daily regulation, which causes continuous fluctuation in the water level in the river several kilometres below the power stations. During the periods of low discharge the water level fluctuates daily with an interval of 50 cm in Ilmajoki 30 km below the Pitkämö power station (Fig. 1). Very many other minor dredgings and other works along the water course have been done, almost continuously especially during this century (Table 1).

The river system has changed dramatically from the 1850s. Especially in the upstream area numerous small lakes have been dried to obtain arable land or meadows. The lakes thus do not act as sediment traps as they used to. Most of the floods have been prevented as well, and the floodplains where earlier a lot of suspended solids were deposited are now dry land. On the other hand, reservoirs in the mid-reaches of the river now collect

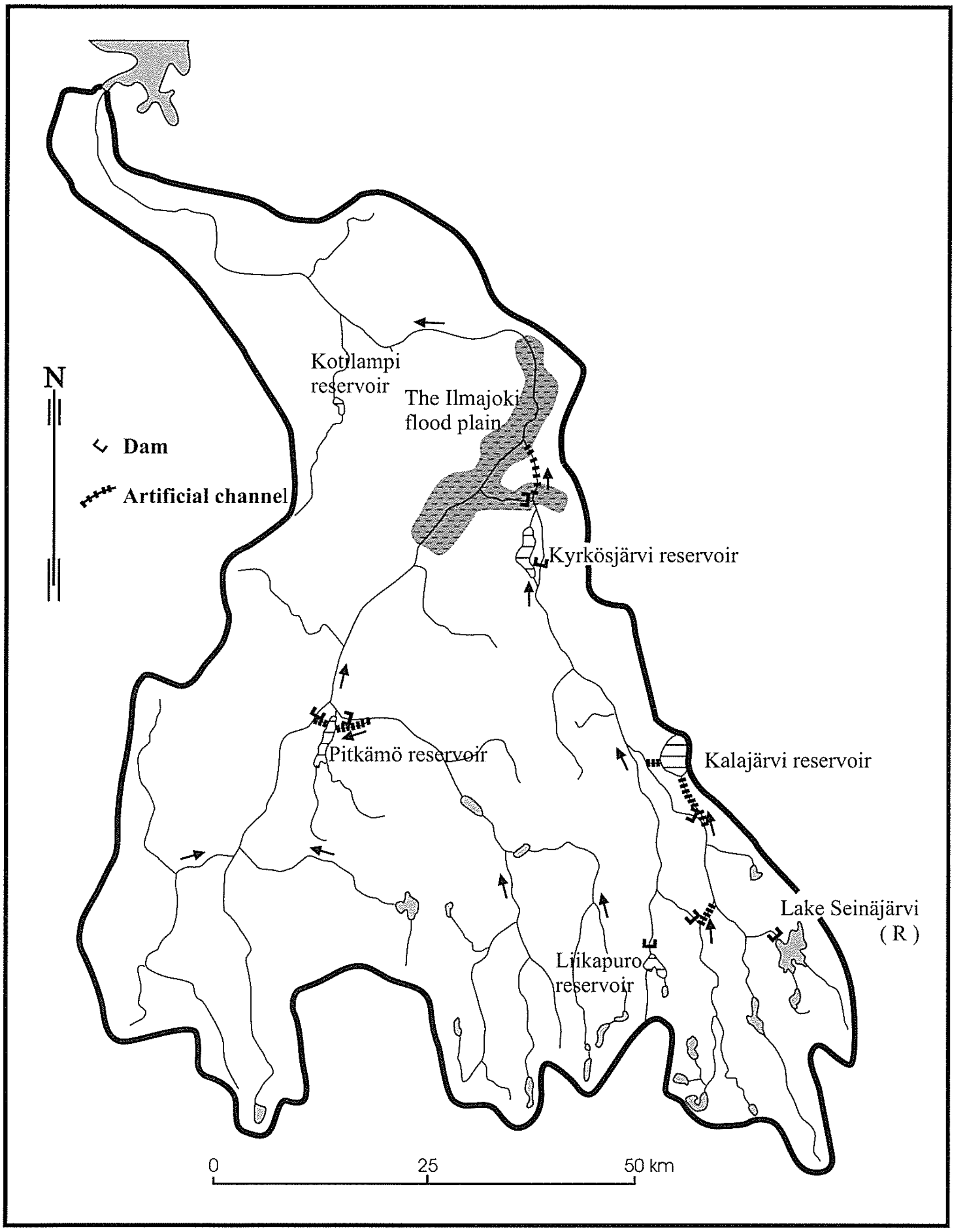


Fig. 12. Main watercourse works in the river Kyrönjoki. Reservoirs are hatched and regulated lakes marked with R.

Table 1. The main watercourse works in the river Kyrönjoki system (Mainly after Turunen 1985).

Year	Watercourse work	Excavated land masses m^3		Distance from delta km
		Below water	Above water	
1753-1767	Clearing of rapids in Hanhikoski Napuenkoski and Voitilankoski	total c. 3000		10
1779-1781	Clearing of the lower course of the river for timber floating			10
1817-1819	Clearing of rapids in Hanhikoski and Voitilankoski			10
1820-1850	Dredging of channels in the delta			0
1868-1874	Clearing of rapids in Hanhikoski			60
1876-1880	Clearing of the river Jalasjoki			130
1890-1892	Clearing of the river in Koivulahti			5
1895-1899	Clearing of the river Lehmäjoki			40
1899-1904	Clearing of the lower and middle course of the river Kyrönjoki	total c. 200 000		30
1903-1904	Clearing of the river Orismalanjoki			50
1929-1933	Clearing in the lower course and delta of the river Kyrönjoki	total c. 950 000		0
1930-1939	Clearing of the upper course of the river Kyrönjoki	total c. 275 000		60
1939-1952	Clearing of the river Kihniänjoki			110
1952-1968	Clearing of the river Jalasjoki			130
1959-1970	Clearing of the river Kainastonjoki			150
1967	The reservoir of Liikapuro			160
1953	The embankments in Vassorfjärd	9 000	4 000	0
1954	The embankments in Vassorfjärd	9 000	3 000	0
1955	The embankments in Hemfjärd	33 600	22 400	0
1956	The emb. in Hemfjärd and Vassor	52 200	32 800	0
1957	The emb. in Hemfjärd and Vassor	58 200	39 800	0
1958	The emb. in Hemfjärd and Vassor	18 000	12 000	0
1959	The emb. in Hemfjärd and Vassor	16 000	10 000	0
1963	Embankments in Vassorfjärden	6 000	3 000	0
1965	Embankments in Vassorfjärden	3 000	1 000	0
1966	Embankments in Vassorfjärden	4 000	2 000	0
1967	Clearing of the river Seinäjoki	total 82 600		90
1968	Clearing of the river Seinäjoki	total 56 100		90
	Regulation in Voitila	66 000	80 100	10
1969	Regulation in Voitila	117 000	116 400	10
1970	Regulation in Voitila	65 000	63 900	10
	Pitkämö reservoir	2 800		125
1971	Regulation in Voitila	25 000	32 100	10
	Embankments in Hemfjärden	6 000	4 000	0
	Pitkämö reservoir	11 000		125
	Kalajärvi reservoir	30 000		100
1972	Regulation in Voitila	27 000	30 200	10
1973	Clearing of the river Lehmäjoki	8 500		40
	Regulation in Voitila	14 100	21 100	10
	Kalajärvi reservoir	35 000		100
1974	Regulation in Voitila	12 800	19300	10
	Clearing of the river Lehmäjoki	43 600		40
1975	Clearing of the river Lehmäjoki	29 500		40
	Regulation in Voitila	20 300	30 500	10
1976	Regulation in Voitila	56 800	38 000	10
1977	Regulation in Voitila	27 400	18 300	10
	Kalajärvi reservoir	9 200		100

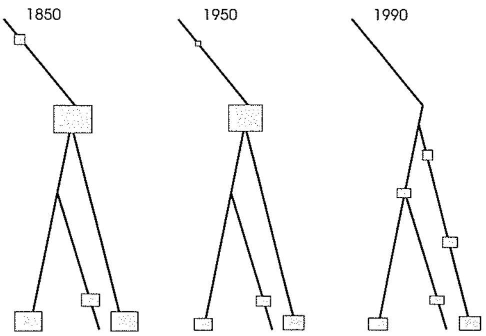


Fig. 13. A simplified model of the Kyrönjoki river system. Main sediment sinks at different times (see text).

most of the suspended solids eroded from the upstream area (Fig. 13).

2.1.9 Land use

The land use elements in the drainage basin have been studied upstream of the Ilmajoki flood basin by Mansikkaniemi (1985). The information was completed for the downstream area by studying 100 grid sampling points in each km^2 square in the basic maps (cf. Mansikkaniemi and Heino 1971). The catchment was divided into five elements: forests, mires, arable fields, built-up areas and waters (Fig. 14). All paludified forests were regarded as mires, because their treatment is rather uniform in forestry: most mires and paludified forests have been ditched to improve the growth of timber. In that respect paludified forests differ from forests on mineral ground. Only densely inhabited areas were counted as built-up areas. Single houses or roads were not counted, because in the map the houses are presented as being much larger and roads much broader than they really are. This causes some underestimation of the proportion of built-up areas. On the other hand, to count them as they are presented in the map obviously would result in an overestimation of their proportion (cf. Mansikkaniemi 1985).

The riversides are relatively densely populated, and agriculture is intensive along the river. Approximately 100 000 people live in the drainage basin (about 20 inhabitants/km^2) (Savea-Nukala *et al.* 1997), and the largest towns are Seinäjoki (25000 inhabitants), Ilmajoki, Kurikka and Kauhajoki (about 5000 inhabitants each) (Fig. 15). Approximately half of the population is rural.

There is only small-scale industry in the Kyrönjoki basin. The largest industrial units are the Koskenkorva alcohol distillery, and the dairy of Normilk Ltd. in Seinäjoki. There is no mining of metals or large-scale metal industry. Small handicraft works are the most typical form of industry in the study area, located especially in Kauhajoki, Kurikka, Seinäjoki and Vähäkyrö.

The basin covers 5030 km^2 according to Mansikkaniemi (1985, 160) for the upstream area, and the present measurements for the downstream area. It can be divided into different elements as follows: built-up areas and roads 4.3%, arable fields 24.8%, forests 38.4%, paludified forests and mires 28.4%, and lakes and rivers 4.1% (Fig.14). The figures differ significantly from those given by the National Board of Waters (at present the Finnish Environment Institute), determined in the 1960s (see e.g. Heikkilä 1986c), especially for forests, built-up areas and watercourses. The differences are partly due to different methods in determining the proportions. Some paludified forests have been counted as forests, and only natural lakes have been taken into account in the calculations of the National Board of Waters. The proportion of roads has increased due to recent road construction, but it also seems that their proportion has been overestimated in the upstream area by Mansikkaniemi (1985). On the other hand, their proportion has evidently been underestimated in the downstream area. The differences in the accuracy of available maps in different times possibly explain the other differences.

2.1.10 Drainage works

The extent of mire ditching was studied using the statistics compiled by the local forestry authorities in Seinäjoki. Only ditching supported by the state could be taken into account, because no data is available about the ditching the land owners have made without the support of the state. Such ditching covers about 30% of the ditched area in the Kyrönjoki drainage basin. They are evidently not distributed in the same pattern as the ditching about which statistics are available. Therefore, no correction can be made. Thus, the figures given about forestry drainage in this study are too low. A map including all forestry drainage was compiled on the basis of new topographic maps on a scale of 1 : 20 000 (Fig.14).

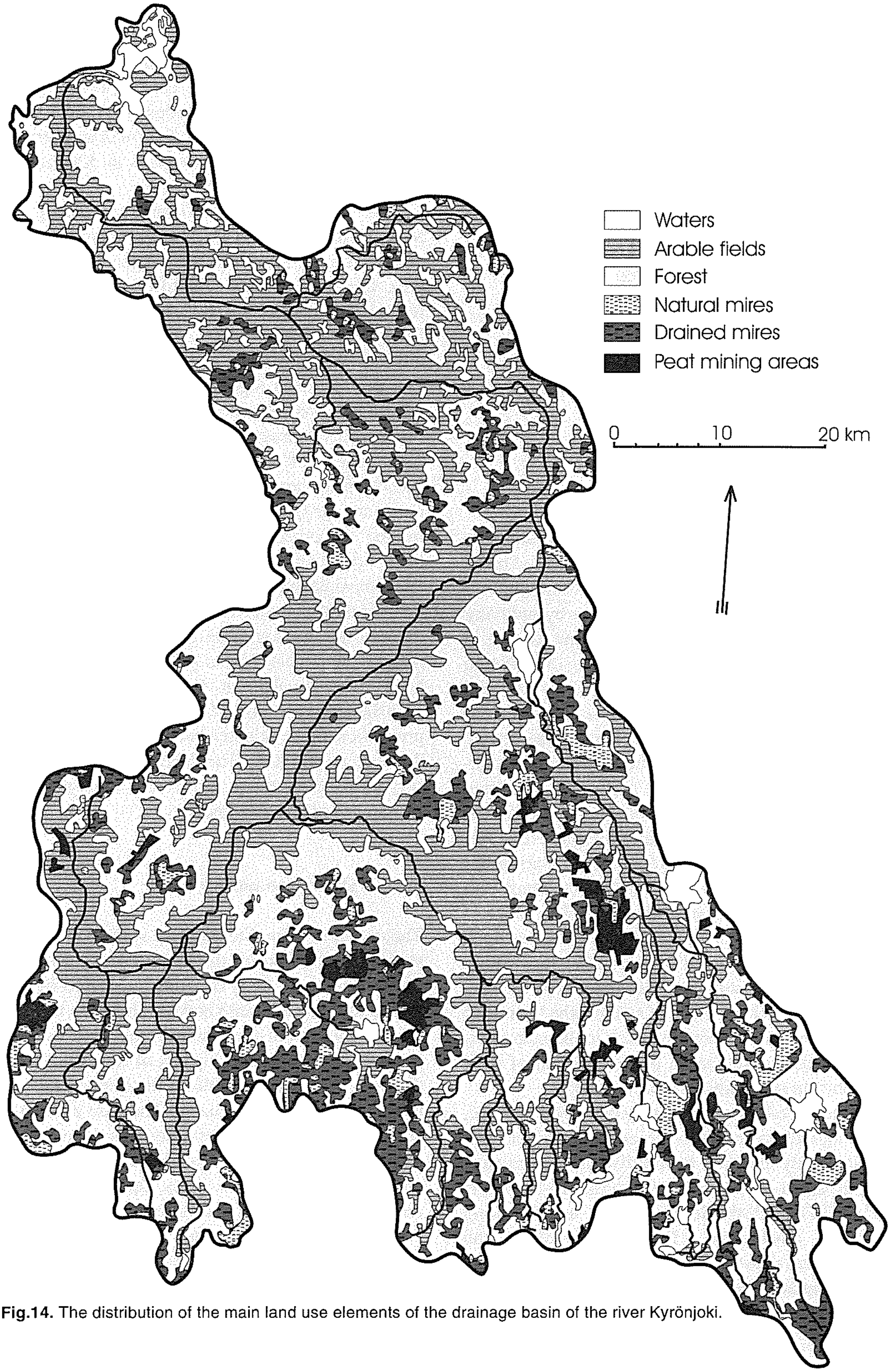


Fig.14. The distribution of the main land use elements of the drainage basin of the river Kyrönjoki.

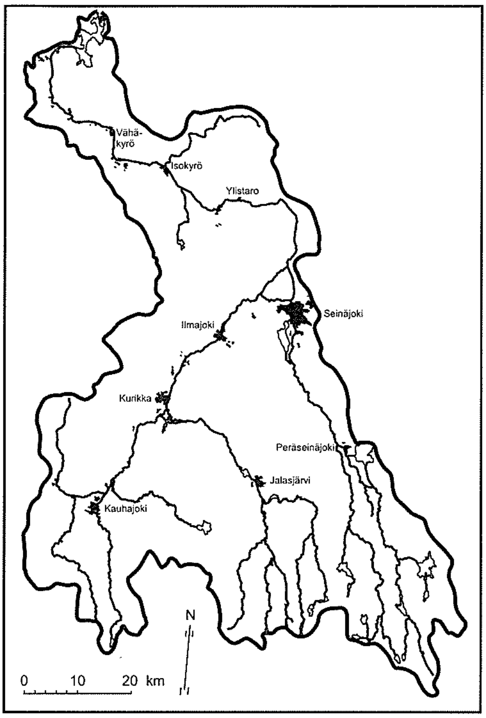


Fig. 15. The location of dense population in the drainage basin of the river Kyrönjoki.

On the basis of the statistics compiled by the provincial forestry authorities in Seinäjoki, 845 km^2 of mires and paludified forests have been drained for forestry with financial support from the state in the catchment of the river Kyrönjoki since 1950, i.e. 60% of the area of mires and paludified forests in the basin. It covers 16.8% of the whole basin. If the ditching made with the support of the state in the 1930s and privately over the whole period, which cover about 30% of the drained area, are taken into account, the figures rise to 80% and 22%, respectively. The drainage is intensive especially in the downstream area below the Ilmajoki flood basin. Practically all mires and paludified forests have been ditched there. The coverage of mires in that area is, however, significantly smaller than in the upstream area, being only 15%. In some parts of the upstream area, especially in the basin of the river Seinäjoki, peat covers about 40% of the territory (Fig.14). Also in the upstream area ditching has been very intensive (Fig. 16).

A great deal of the drained mires are very poor, and e.g. in Kauhajoki approximately 30% of the mires drained with state support have not met the criteria of economically profitable ditching (Heikkilä 1984, Fig. 17). Since the study the criteria of profitable ditching have changed, and it can be roughly estimated that 50% of the ditching has been unprofitable in the Kyrönjoki catchment. Very few new areas will be drained, but in the old ditched areas there is a need to clear the ditches or in some cases to make additional ditches. The effects of the clearing of the ditches on the watercourses is similar to ditching the mires for the first time: during the ditching and a period of a few years after that a lot of humic substances and nutrients are leached to the watercourses (Ahtiainen 1988, Manninen 1998). Also in the catchment of the river Kauhajoki extensive erosion of sand in connection with the ditching of mires with a thin peat layer has occurred (Fig. 18). It is probable that there erosion due to ditching is continuous (see Virkanen and Tikkanen 1998). Data from the adjacent Isojoki river basin shows that drainage increases the concentrations of aluminium and suspended solids in stream waters and thus significantly contributes to the deterioration of water quality (Vuori *et al.* 1998).

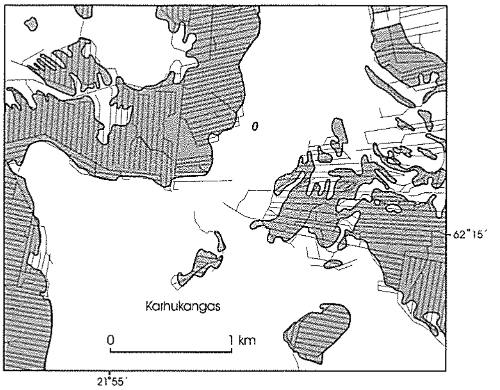


Fig. 16. An example of the drainage of mires (shaded) in the Karhukangas area in Kauhajoki.

In the Kyrönjoki catchment the influence of forestry drainage was at its greatest between the years 1965 and 1980. Drainage in the upper course increases peak flows, but the drainage in the lower course decreases them (Mustonen and Seuna 1971, 42). Therefore, when estimating the influence of drainage at different times, the annual drained area below the Ilmajoki flood basin subtracted from the drained area above it has been used (Fig. 19). The influence of the drainage in the lower course has been estimated to be as great as the influence of the

Fig. 17. An ombrotrophic mire Karhujärvenneva drained for forestry in 1977 without any timber growth response. The mire is located nearby the eastern end of the scale bar in Fig. 16. Photo Raimo Heikkilä July 1983.

Fig. 18. A little brook in Kauhajoki flowing from the south into the middle course of the river Ikkelänjoki (see Fig. 1), filled with sand eroded from ditches in a drained mire with a thin peat layer on fine-grained sand. Photo Raimo Heikkilä June 1982.

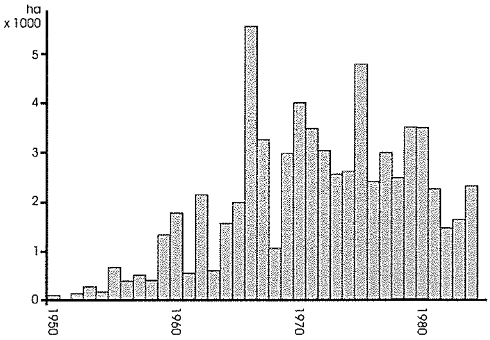


Fig. 19. The annual forestry drainage area in 1950-1989 in the drainage basin of the river Kyrönjoki influencing the hydrology of the river mouth.

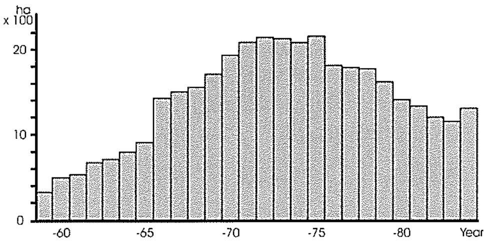


Fig. 20. Floating sums of forestry drainage in the drainage basin of the river Kyrönjoki in decades over the period 1950-1984. The figure under each bar shows the last year of each decade.

drainage in the upper course, but in the opposite direction. It is a rather coarse assumption, but this kind of calculation gives a more realistic view of the total influence of drainage than total drainage amounts of the whole catchment. Forestry drainage of mires increases the discharge in water courses after the drainage, but the influence of drainage gradually decreases when the tree cover of mires becomes more dense and evapotranspiration increases (Seuna 1982). Therefore, a floating sum of the drained area over a period of 10 years has been calculated (Fig. 20). It is based on the hypothesis that the change in the hydrology of the drained mires disappears in 10 years. Because a great deal of the drainage in the Kyrönjoki catchment has not increased the tree growth significantly (Heikkilä 1984), it is probable that the duration of the hydrological changes is much longer.

Bilaletdin (1983, 115) states that each drained percent of the Kyrönjoki basin has increased peak flows by 0.4%, and each percent of agricultural reclamation has had a 1.3% effect. Thus, drainage for agriculture and forestry has increased peak flows considerably in the river Kyrönjoki (Tables 2 and 3). On the basis of Bilaletdin's formula the increase until the year 1980 is 24%, but due to the reversibility of the hydrological change in drained mires the influence on peak flows is somewhat smaller.

On the other hand, the aim of the watercourse

Table 2. Agricultural land reclamation (km^2) and its percentage in the Kyrönjoki drainage basin (Bilaletdin 1983, 21).

Period	Area of reclamation		Cumulative area of reclamation	
	km^2	%	km^2	%
1921-30	28.57	0.6	28.57	0.6
1931-40	85.40	1.8	113.97	2.4
1941-50	94.77	2.0	208.74	4.3
1951-60	215.40	4.5	424.14	8.8
1961-70	182.33	3.8	606.47	12.6
1971-80	95.63	2.0	702.10	14.6

Table 3. Forestry drainage (km^2) and its percentage in the Kyrönjoki drainage basin (Bilaletdin 1983, 23)

Period	Area of drainage		Cumulative area of drainage	
	km^2	%	km^2	%
1931-40	59.55	1.2	59.55	1.2
1941-50	-	-	59.55	1.2
1951-60	53.94	1.1	113.49	2.4
1961-70	208.58	4.3	322.07	6.7
1971-80	284.89	5.9	606.96	12.6

works has been the decrease of peak flows, and therefore their increase has been theoretical. Without the watercourse works peak flows would evidently have risen significantly, especially in the snow melting period.

2.1.11 Peat mining and mire conservation

Data about peat mining was obtained from VAPO Ltd., which is responsible for almost all peat mining in the Kyrönjoki drainage basin.

Peat mining is intensive in the Kyrönjoki drainage basin. Altogether 41 mire areas covering about 7000 ha have been reserved for peat mining by VAPO Ltd., and about 3000 ha is already in use to produce fuel for the power stations at Seinäjoki and Tampere (Fig. 21). There are 10 established mire reserves in the drainage basin, covering about 2300 ha, and 10 more mires planned to be protected, covering about 2700 ha (Maa- ja metsätalousministeriö 1981, Heikkilä 1996).

Peat mining causes very severe summer peak flows from the mires (Sallantaus 1984). Because the peat mining areas cover only 1.5% of the Kyrönjoki catchment, or 8% of the area drained for forestry, their influence on the discharge is locally great in the tributaries, but not significant in the delta of the river. The leaching of humic substances from peat mining areas is great (e.g. Sallantaus 1988), and both dissolved and solid organic matter is transported to the delta of the river. Forestry drainage of mires also has an influence on water quality increasing the amount of humic substances and nutrients, especially during and right after ditching (Ahtiainen 1988).

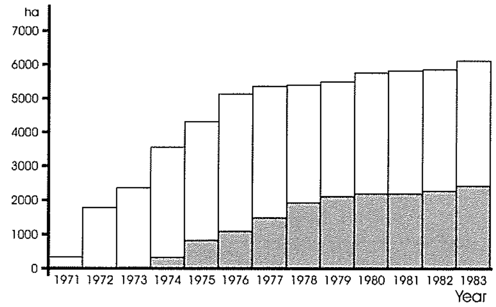


Fig. 21. Mire area drained for peat mining (whole bar) and area used for peat mining (shaded part of the bar) in the drainage basin of the river Kyrönjoki.

2.1.12 Agriculture

The riversides have been taken into agricultural use since the 1300s in the downstream area in Isokyrö and Vähäkyrö, and gradually also in the upstream area. To use the peatlands for agricultural purposes, extensive ditching of the large mires in the river valley in the Ilmajoki flood basin was started in 1783 (Turunen 1985, Toivonen 1997). During the 1800s and up to the 1960s land reclamation for agriculture was very intensive. Along the lower course, from Ilmajoki and Seinäjoki towards the delta, most of the fields are on clay plains. In the upper course most of the fields are gently sloping towards the river. In the valleys of Hyypänjoki and the upper course of Jalasjoki there are relatively steep cultivated valleysides.

The ditching of the plains in the river valley, where the soil is sulphide-bearing Litorina clay, caused an acidic discharge to the river. The first problems with the acidity were recorded in 1834, when all the fish in the lower course of the river died, and the normally dark brown water, containing a lot of humic substances, turned clear for a period of a few days (Sevola 1979). Since then acidity problems have been recorded several times, and almost every year in the 1970s, the worst year being 1972 (Storberg 1983, Alasaarela 1985).

On the basis of geological maps approximately 70% of the arable fields in the drainage basin of the river Kyrönjoki are located on mineral soil, and 30% of them were originally mires with peat soil (Fig. 22). The cultivated mires are mainly located near the watersheds, and in the Ilmajoki flood basin nearby Seinäjoki. On the basis of field observations at least 50% of the fields have been ploughed in mires. Due to the originally thin peat layer of many cultivated mires, and decomposition and erosion of peat over centuries of cultivation, in many cultivated mires the thickness of peat is less than 30 cm, which is the minimum for geological peatlands. Therefore, in many cultivated mires the ditches have reached the mineral soil below the peat. Along the lower courses of the river, where the mineral soil in large areas is sulphide-bearing clay, cultivation has caused extensive leaching of acidic compounds to the river.

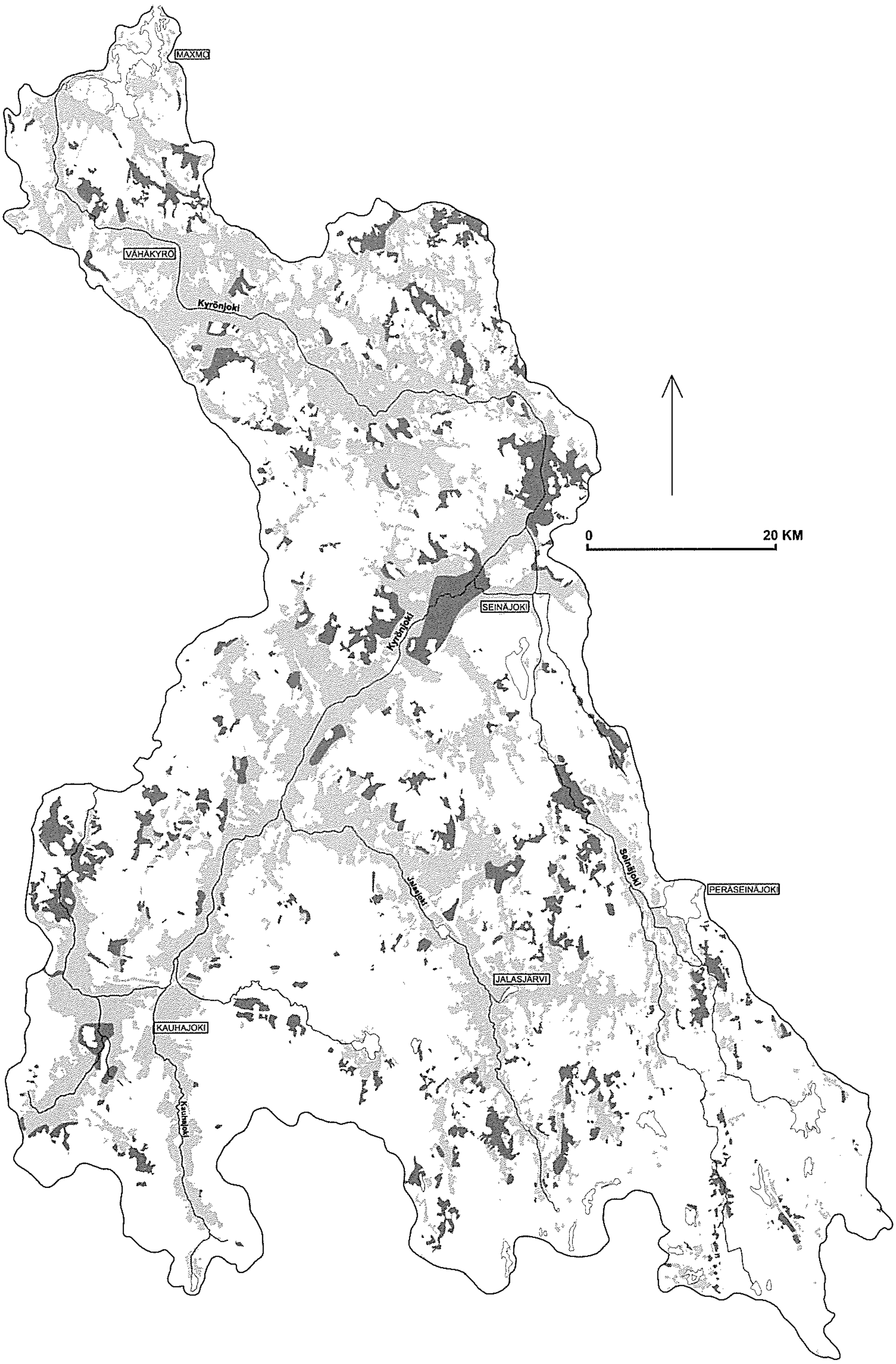


Fig. 22. Arable fields in the drainage basin of the river Kyrönjoki. Mineral soil fields are light grey and peat fields dark grey.

2.2 The delta of the river Kyrönjoki

Approximately 4000 years ago the delta of the river Kyrönjoki was located between the towns of Ilmajoki and Seinäjoki. Because of land uplift it has gradually moved northwest, about 15 metres a year. At present, the river carves its channel in the deltaic sediments of earlier periods, and transports the sediments to the present delta.

Rosberg (1895) studied the morphology of the deltas of the rivers flowing into the Gulf of Bothnia, and described the contemporary delta of the river Kyrönjoki as modified, with wide alluvial plains. Due to the building of artificial embankments in the downstream area from the 1950s on, the delta is now almost purely submarine. The river now has only one outlet through Vassor instead of the previous two, the main outlet through Vassor and the minor outlet through Getlaxfjärden. There are only narrow strips of alluvial meadows left in Mälsor (Fig. 23). Most of the delta is very shallow. Only in the northwestern part of Pudimofjärd, in Östra Gloppet and in a small area in Peuskofjärden does the depth exceed 10 metres (Fig. 23). The present delta covers approximately 7000 hectares, about 4600 hectares of which belong to accumulation areas.

In this study, areas with topset and foreset layers have been included in the delta of the river Kyrönjoki (e.g. Morisawa 1985, 133). Also adjacent areas with erosion and transport due to waves or the flow of river water belong to the delta. In front of the delta there is still a wide area where material transported by the river Kyrönjoki is deposited as bottomset layers during high floods (Mäkelä 1986).

3 Materials and methods

3.1 Bathymetry, bottom quality and dynamics

The delta of the river Kyrönjoki was echo sounded in June, 1984 using Atlas Echograph 450 and Atlas Monograph 58 echo sounders. The sound frequency was 30 kHz. A total of 100 km of echo sounding lines were analysed (Fig. 24).

A bathymetric map of the delta was compiled on the basis of the echo sounding diagrams. The delta

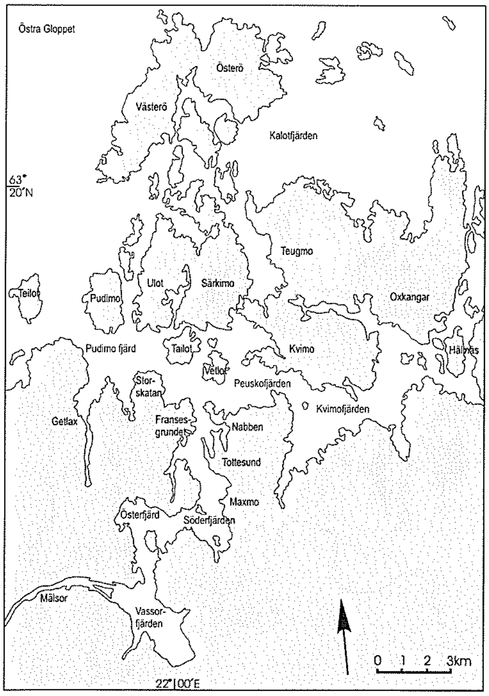


Fig. 23. Names of places in the delta of the river Kyrönjoki.

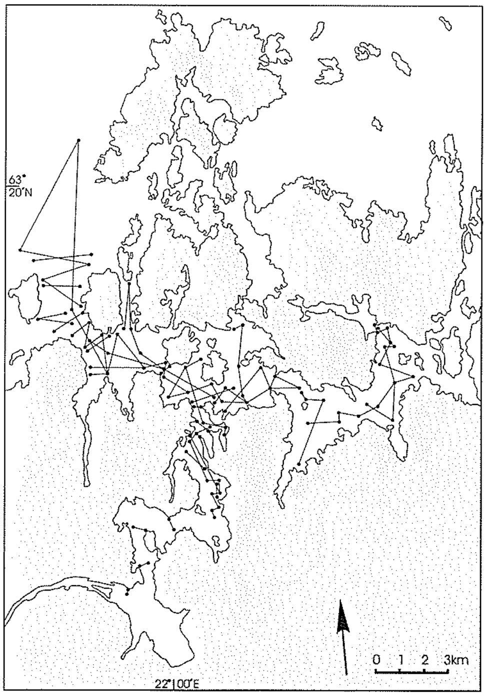


Fig. 24. Echo sounding lines in the delta of the river Kyrönjoki.

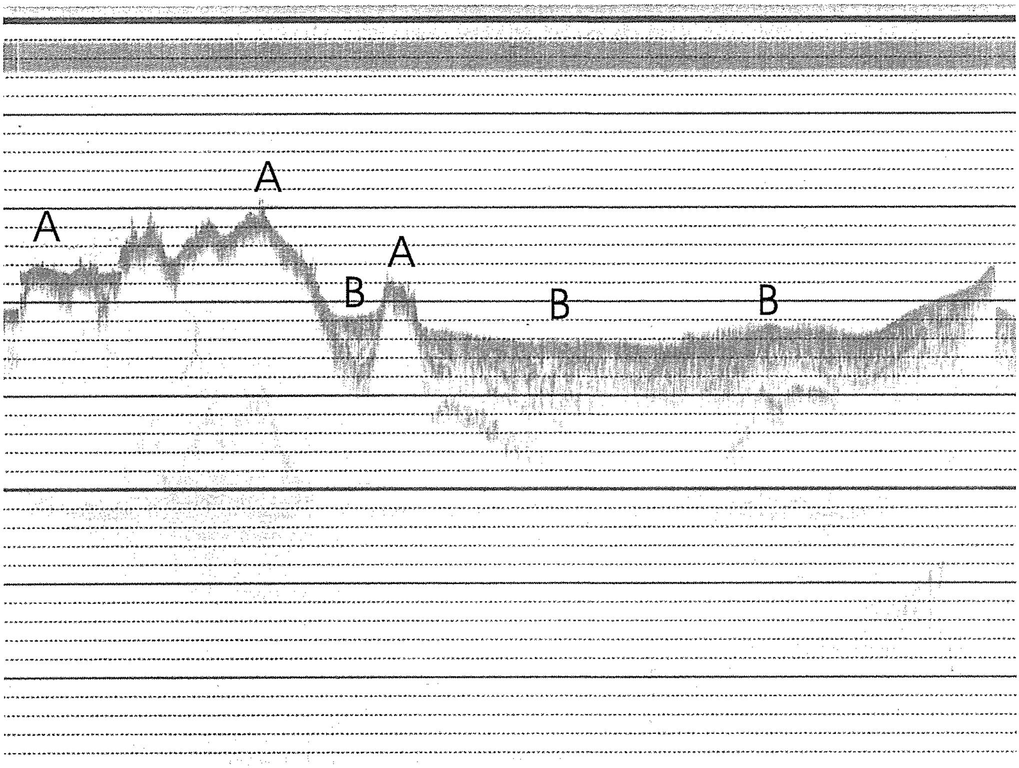


Fig. 25. An example of an echo sounding graph in the southern part of Östra Gloppet. A shows erosion areas and B accumulation areas.

was delimited, and it was divided into erosion and accumulation areas using the echo graphs. The plain bottoms where, in addition to the echo of the surface layer, there was another echo showing the hard moraine layer were taken to be accumulation areas. Bottoms with only one echo, or in some cases a repeated echo at double depth, were taken to be erosion areas (Fig. 25). The results of echo soundings were confirmed by sampling the uppermost layer of the sediment surface in 65 sites (Fig. 26).

On the basis of echo soundings it was not possible to distinguish between accumulation and transportation areas. Attempts were made to separate them using the water content of the sediment surface: bottoms with a water content of 75% or higher in the uppermost 2 cm layer of sediment were designated accumulation areas, and bottoms with content between 50% and 75% transportation areas. In erosion areas the water content was less than 50% (Håkanson *et al.* 1984: 109).

3.2 Sediment sampling

To survey the temporal and spatial differences in sediment quality and sedimentation, sediment samples of the topmost 2 cm layer were cored in September 1983 and in June and July 1984 in 61 sites in the estuary of the river Kyrönjoki, and in 4 sites outside the delta in sea area (Fig. 26), using a modified Kajak sampler (Hakala 1971).

The topmost 30-70 cm of the sediment layer were cored at 15 sites in September 1983 using the core freezing technique which uses a metal corer filled with dry ice and ethanol (Saarnisto 1975). The corer was lowered to the bottom with a wire, and in about 10 minutes a 1.5 cm thick sediment layer froze on the surface of the corer. A wedge-shaped corer (Renberg 1981) was found to be easy and rapid to use, and it did not seem to sink into the sediment during freezing. A cylinder corer (Saarnisto 1975) was also used, and it was possible

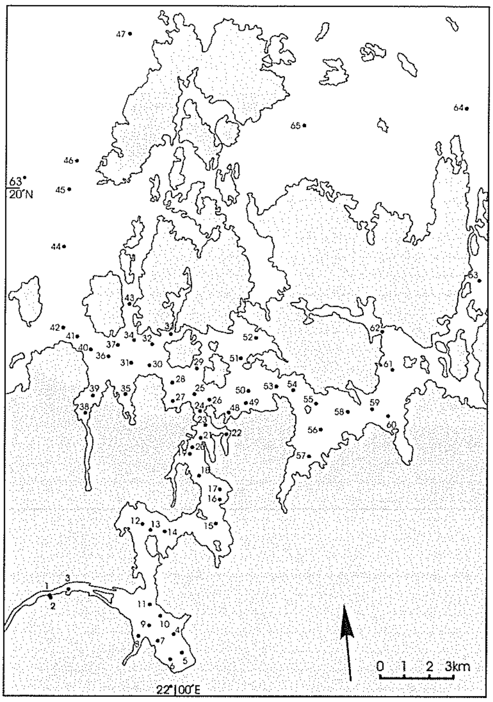


Fig. 26. Sediment sampling sites in the delta of the river Kyrönjoki.

to get long cores (down to 150 cm) with it, but it was rather difficult to use, especially from a boat. It was also very difficult to remove the cores from the corer without breaking them. In Nabbviken (site 22, Fig. 26) a new core was taken in October 1988.

In the frozen sample of the sediment, layers stayed undisturbed, and the laminae could be seen when it was smoothed with a knife without special preparation on the surface of the samples. Drying the samples for a couple of days in a freezer with air circulation made the laminae even more visible. Tape peel preparates were made of the smoothened and dried sample surface to examine the diatoms and for scanning electron microscope (SEM) analyses (see Simola 1977).

Two samples of the surface sediment (30 cm) were taken in October 1983 in a flooded meadow along the river in Mälsor (sites 1 and 2, Fig. 26) by forcing a plastic tube into the sediment. Six sites (numbers 21, 22, 23, 30, 38 and 48, Fig. 26) were cored in March and April 1984, and April 1985 using a piston corer (0-190 cm). The piston corer was pushed down into the sediment using 2 m long plastic tubes, which were plugged together. The samples were contained in a 2 m long plexiglass tube. The deeper sediment layers were cored in Nabbviken (140-440 cm) and from a transect in Pudimo Fjärd (70 cm) in February and March, 1988 using a large Russian peat sampler (Tolonen 1967).

The sampling sites for long cores were chosen on the basis of bathymetric maps and echo soundings in accumulation areas: deep sites in the inner curves of the river channel and sheltered bays. In the outer parts of the delta where an actual river channel does not exist, sampling was made in deep sites, and sites in which the echo sounding showed the bottom to be soft. To control the echo soundings sampling was also attempted in some sites where the bottom seemed to be hard. The failure of sampling due to the hardness of the bottom confirmed the results of echo sounding.

The samples taken with a piston corer were subsampled into 2 cm slices in the field, and the long cores taken with the Russian peat sampler were sliced at 10 cm intervals. The samples taken using the core freezing technique in Nabbviken were subsampled according to the visible laminae. The other frozen samples were sliced at 2 cm intervals. The subsamples were stored in a freezer until they were transported to the laboratory.

3.3 Sediment analyses

The sediment samples were dried to constant weight in small open plastic bags at +50°C. The low drying temperature was used to prevent the evaporation of mercury from the samples. The water content of the samples was determined as the ratio of the weight of the evaporated water and the fresh weight of the samples (Håkanson and Jansson 1983, 73).

The grain size distribution of three cores were determined using dry samples weighing 4 g, by the pipette method (Elonen 1971, 83) at the Seinäjoki laboratory of the Vaasa district of the National Board of Waters and Environment. Organic matter was removed from the samples with hydrogen peroxide.

Dried and homogenized samples (1-3 g) were ignited at +550°C for 3 hours. The content of organic matter was determined as loss-on-ignition. The ignited samples were extracted at +150°C using 37% HCl, and filtered through Whatman 40 filters. Distilled water was added to the filtered extract to a volume of 50 ml. HCl extracts were analysed for iron (Fe), manganese (Mn), lead (Pb), copper (Cu), zinc (Zn), cadmium (Cd) and calcium (Ca) with a Varian Techtron 1200 atomic absorption spectrophotometer (AAS) at the ecological laboratory of the Department of Botany, University of Helsinki. A few samples were also analysed for aluminium (Al). Total phosphorus (P) was determined for the HCl-extracts with a Datex Akea spectrophotometer using the molybdenum blue method at Lammi Biological Station. Mercury (Hg) was analysed with a Perkin Elmer 50 B AAS with the flameless method at the Department of Environmental Protection, University of Helsinki. Total carbon (C) and (N) were determined with an HP 185B CHN analyzer at the Department of Limnology, University of Helsinki. The pH and redox potential of the sediment surface was measured in fresh Kajak samples in the field with a portable Mettler pH and redox meter.

3.4 Dating methods

The samples from the flooded meadow in Mälsor (sites 1 and 2, Fig. 26) were dated according to the annual growth rate of *Carex acuta* L.. The growth rates were determined on the basis of the height differences between the initial points of annual growth for different years, covered with sediment (for the method see Seppälä 1974: 215-217). It was assumed, that each year the plants, after the spring flood, start a new growth just above the sediment layer deposited since previous spring. The samples from the flooded meadow were subsampled for the topmost parts on the basis of the layers determined using the annual growth of plants in the meadow. The lower parts of those samples were sliced at 1 cm intervals.

The sediment of Nabbviken (site 22, Fig. 26) was dated on the basis of the laminae visible in the frozen samples. On the basis of the seasonal succession of diatoms observed in tape peel preparates, the laminae were found to be annual varves (Simola 1977). The dating on the basis of the laminae reached back to 1931. On the basis of the extrapolation of the mean thickness of the varves formed in the 1930s and 1940s the age of the sediment was roughly estimated down to the depth of 440 cm from the sediment surface.

Attempts were made to obtain ^{210}Pb and ^{137}Cs datings for the sediment of Fransesgrundet (site 21, Fig. 26) (see e.g. Appleby *et al.* 1979, Oldfield 1981, 312-315, Jaakkola ym. 1983). No satisfactory results were obtained, obviously due to the variation of sedimentation rates between years, and bioturbation, evidence of which could be seen in frozen samples. In addition, the mobility of ^{137}Cs in the sediment makes the results unreliable (Davis *et al.* 1984).

In the sediment of Getlaxfjärden (site 38, Fig. 26), which was dammed in 1957, dating for the mentioned year was done on the basis of a severe change in the stratigraphy of the sediment. When the flow of the acid river water was prevented by damming, the sedimentary conditions changed drastically and caused a change in the sediment in the content of some elements which are sensitive for redox conditions, e.g. manganese (Brümmer 1974).

Attempts were made to find trace layers on the basis of sediment chemistry in the stratigraphy of different sites. Single elements, especially lead, due to its immobility in sediment (Förstner 1982, 281, Moore and Ramamoorthy 1984, 107), were studied. A multivariate analysis was also attempted. The multivariate method used in this study was detrended correspondence analysis (DCA), which was run on the Burroughs 7800 computer of the Computer Centre of the University of Helsinki, using the program DECORANA (Hill 1979, Gauch 1982, 152-160). DCA was also used to find out the similarities and differences between different elements in their behaviour in the deposition processes.

3.5 Rates of sedimentation

The sedimentation rates for the dated profiles were calculated on the basis of the thickness of sediment deposited in a year and the bulk density of the sediment. The bulk density of fresh sediment (x) was calculated on the basis of water content and organic content (Axelsson and Håkanson 1971, 12):

$$x = \frac{100y}{100+(w+o)(y-1)}$$

where w is the water content of sediment, o the organic content as % of fresh weight and y the density of mineral material. The value used for the density of mineral material in the calculations was 2.5 gcm^{-3}. The density of mineral material is of minor importance, when the water content of the sediment is higher than 75% (Håkanson and Jansson 1983, 81).

3.6 Diatom analysis

The seasonal succession of diatoms was studied in the tape peel preparates of the frozen sample of the sediment core from Nabbviken (Simola 1977). The method gives only qualitative results. A quantitative study was made in a 15 cm long portion of the Nabbviken core covering a period of 7.5 years in 1970-1977. The sample was subsampled so that each varve couplet was divided into two parts: the light layer deposited in the spring and the dark layer deposited in the autumn and winter. Thus, 15 subsamples were studied. Preparates were made using standard methods (Battarbee 1986). 200 diatoms were counted in each subsample. A diagram was compiled on the basis of the percentage of each species.

3.7 Scanning electron microscope analysis

The distribution of elements in the annual laminae of the Nabbviken core were analysed in tape peel preparates (cf. Alapieti and Saarnisto 1981) with an energy dispersive micro analyzer (EDS), which was connected to a scanning electron microscope (SEM) at the Laboratory of Electron Microscopy, University of Helsinki (see e.g. Smart and Tovey 1982, 161). The area of the preparate studied at one time was 4 by 6 mm. The distribution of 15 elements was photographed in each area. The aim of the method was to survey the seasonal changes in the deposition of different elements. Because each area studied covered only a few months, several areas were studied side by side in the vertical direction. The distribution pattern of the elements was studied using systematic strip sampling from the photographs.

3.8 The study of the spreading of the river water using aerial photos and satellite images

The spreading of the water of the river Kyrönjoki in the estuary, the estuary currents and changes in the vegetation were studied using aerial photos from different times (20 July,1947, 3 August, 1961, 26 April, 1984 and 22 May, 1984), and material produced by Landsat 1 satellite 30 August, 1972. The pixel size of the satellite image was 80 by 80 m. The satellite image was studied at the Laboratory of Land Use at the State Technological Research Centre, Espoo, Finland, using numerical analysis of digital information with the support of vegetation, forest cover and land use data obtained in the field. The results were printed as a coloured choropletic map on a scale of 1:50 000 (Kuittinen 1984).

4 Results of sediment studies

4.1 Delimitation of the delta

The outer limit of the delta was determined as the outer limit of foreset layers in the deep sea areas. They could be vaguely seen in the echographs at the beginning of the deep hollows when echo sounded from the river mouth outwards. In such places soft bottoms were also sloping towards the sea. Bottomset layers exist even much further out, at least 30 km to the north from the NW parts of the delta (Mäkelä 1986). During high flood periods the water from the river Kyrönjoki can be seen to flow as a brownish area up to 30 km out from the outer limit of the delta. The suspended load colours the water brown, and the freshwater from the river flows on the surface of the slightly saline (about 3.5 per mille) brackish water because of its slightly lower density (Meriläinen 1984a).

On the basis of aerial photographs, Landsat MSS satellite image analysis and field observations, most of the water from the river Kyrönjoki flows to Östra Gloppet through Pudimo Fjärd during flood periods. A minor part of the water flows between Getlax and Teilot, between Pudimo and Ulot, between Särkimo and Kvimo, and through Kvimofjärden (Figs. 23, 27 and 28). During mean discharge the river water mixes with brackish water in the western part of Peuskofjärden. When the discharge is low during winter and middle summer, brackish water may stretch up to Vassorfjärden in the estuary.

Plain or gently sloping soft bottoms were determined to be areas of accumulation, and hard bottoms areas of erosion. Areas of transportation were mostly included in the areas of accumulation, because in many cases it was impossible to distinguish between them using the water content of the sediment surface as an indicator. According to Håkanson (1981, 34) the water content in accumulation areas is 75% or higher. In the delta of the river Kyrönjoki the content in very many cases

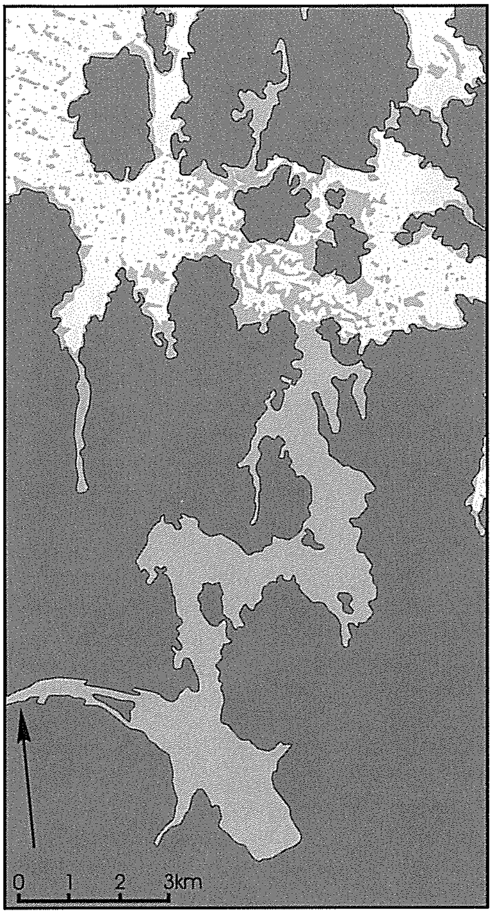


Fig. 27. Landsat MSS interpretation of the flow of the river water (dark grey) in the delta of the river Kyrönjoki and mixing with brackish water (light grey).

varied between 70% and 80%, and due to the inaccuracy of the determination of the water content, it would be rather daring to make a strict limit in the accuracy of 1% as an indicator of the sedimentation dynamics (Fig. 29).

In the shallow areas, where wave erosion is weak due to the sheltering islands, only the middle of the river channel is an erosion area due to the fast flow of the water, while the bays and shallowest shore areas are areas of accumulation. In the deeper NW parts of the delta, which are open to winds from the NW and W, the shallow areas near the shores are eroded by waves, and the deepest points (depth 6-30 m), are usually areas of accumulation (Figs. 29, 30, see Brydsten 1985, 1992).

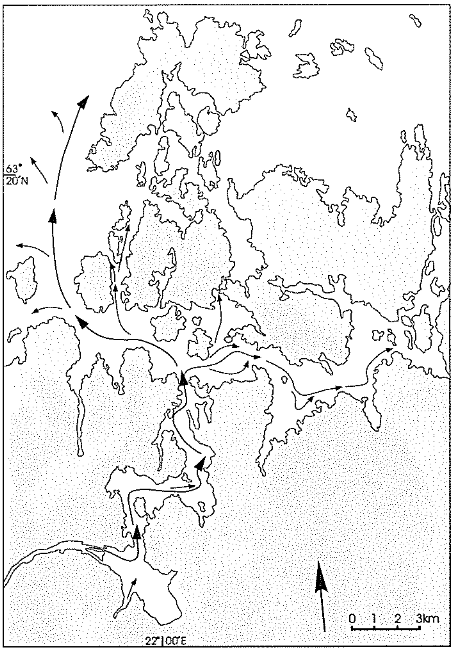


Fig. 28. Main directions of the flow of river water in the delta of the river Kyrönjoki on the basis of aerial photos and satellite image interpretation, and erosion channels on the bottom.

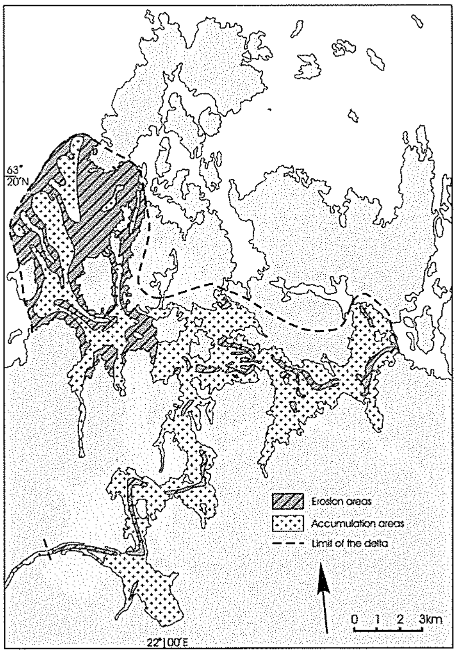


Fig. 29. Delimitation of the delta and its subdivision into erosion and accumulation areas.

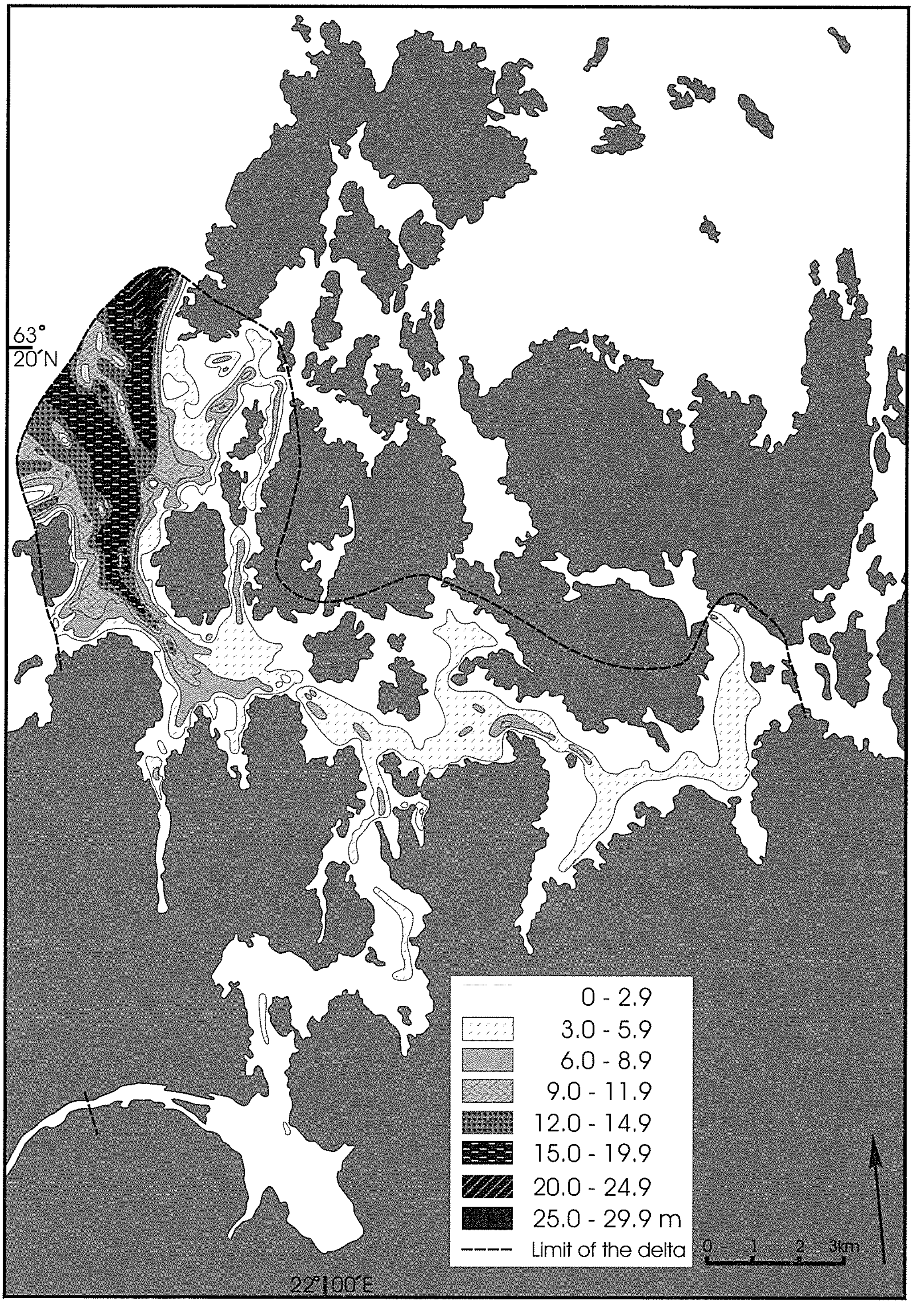


Fig. 30. Bathymetric map of the delta of the river Kyrönjoki.

4.2 Spatial characteristics of the chemistry of the surface sediments

The analyses of the surface sediments (2.0 cm) at 65 sites in the delta of the river Kyrönjoki and adjacent coastal areas revealed features of spatial differentation in the sedimentary conditions in the delta. The redox conditions, mainly dependent on the differences of the type of the prevailing water in sediment-water interface, made it possible to distinguish between areas dominated by acid fresh water from the river and those with neutral or basic brackish water (Heikkilä 1986a).

In Vassor Bay very acid water (pH about 3.0) is pumped from a dammed field area of about 200 hectares on Litorina clay, about 1 m below the sea level. There, in addition to Hg, the content of Cd, Cu and Zn is relatively high (Figs. 31-34). The lead content varies irregularly over the whole delta, and no clear trend could be found (Fig. 35). In the inner part the mean organic content in the sediment surface is slightly lower than in the outer part of the delta, but high values also occur in the inner part in areas where the accumulation is continuous without erosion during the flood periods (Fig. 36). On the basis of the C/N ratio the maxima of allochthonous sedimentation exist in the inner part of the delta where the values are highest, showing a greater proportion of acid humic substances transported by the river when compared with the outer part where the organic matter consists more of autochthonous material of planktonic origin (Fig. 37, see Hansen 1961, Müller 1997).

The phosphorus content of the sediment surface seems to vary rather irregularly in different parts of the delta, while the mean Ca content is clearly lower in the inner part than in the outer part of the delta (Figs. 38 and 39). In the area dominated by the water from the river the pH of the sediment surface is clearly lower than in the outer part of the delta, dominated by brackish water, ranging from 5.7 to 6.8. The only exception was Nabbviken (Site 22, Fig. 40), where the hypolimnion is permanently saline. The mean redox potential of the sediment surface is clearly lower in the inner than in the outer part indicating reducing conditions in the sediment surface in the inner part dominated by the acid river water, and oxidizing conditions in the outer part dominated by brackish water (Fig. 41, see Brümmer 1974, Hallberg 1974).

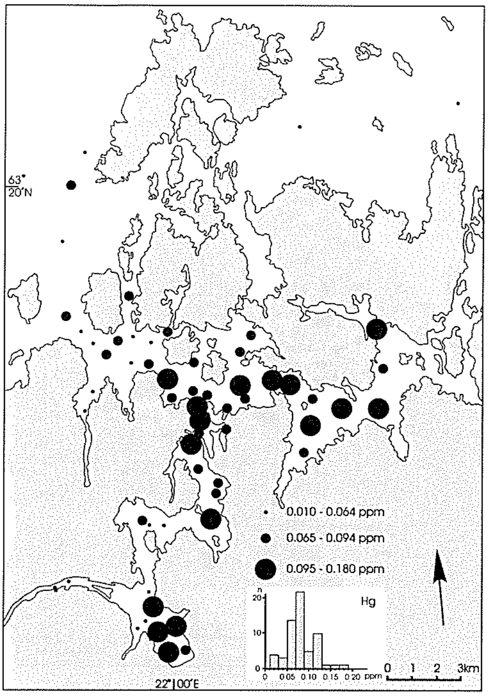


Fig. 31. Hg content of the surface sediment in the delta of the river Kyrönjoki.

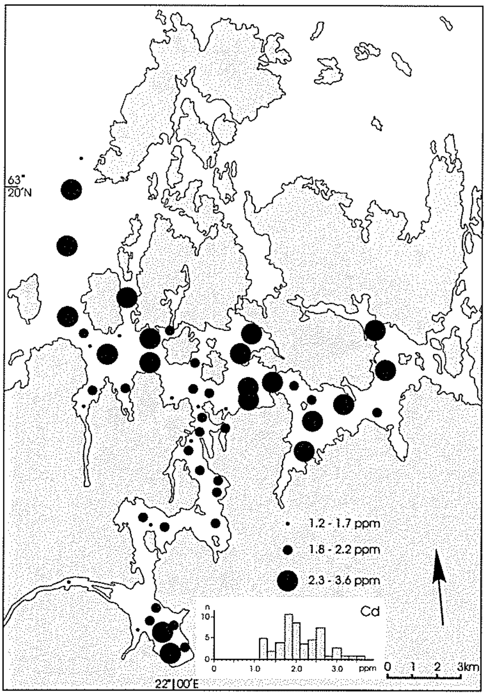


Fig. 32. Cd content of the surface sediment in the delta of the river Kyrönjoki.

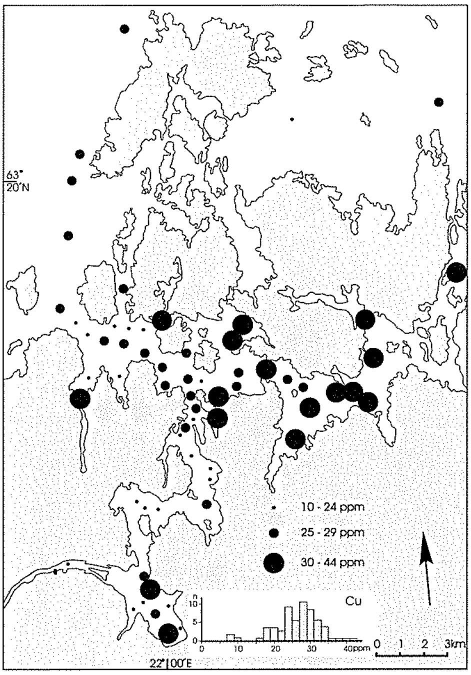


Fig. 33. Cu content of the surface sediment in the delta of the river Kyrönjoki.

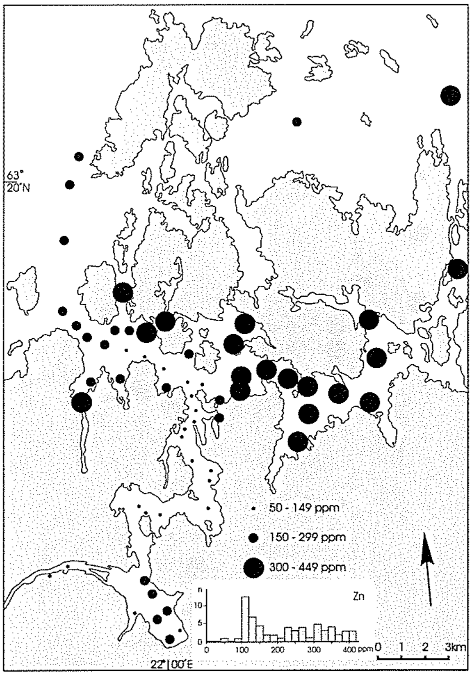


Fig. 34. Zn content of the surface sediment in the delta of the river Kyrönjoki.

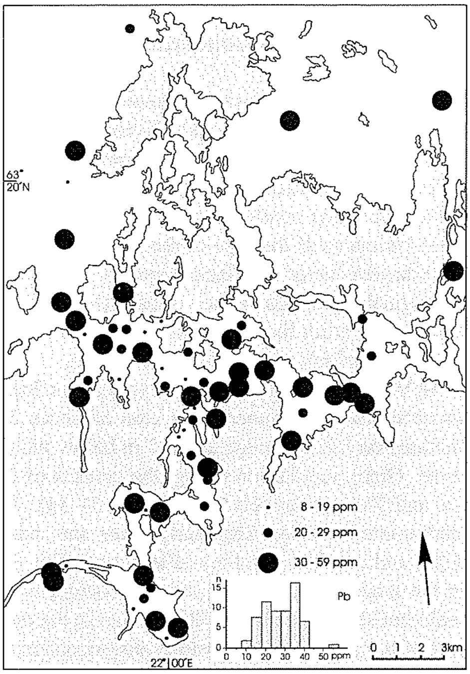


Fig. 35. Pb content of the surface sediment in the delta of the river Kyrönjoki.

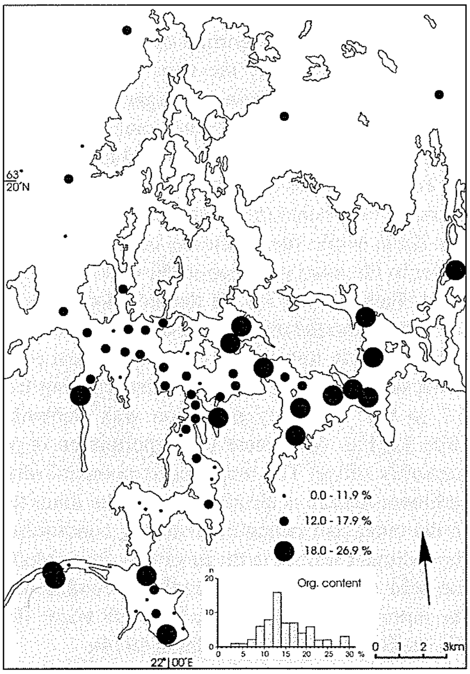


Fig. 36. Organic content of the surface sediment in the delta of the river Kyrönjoki.

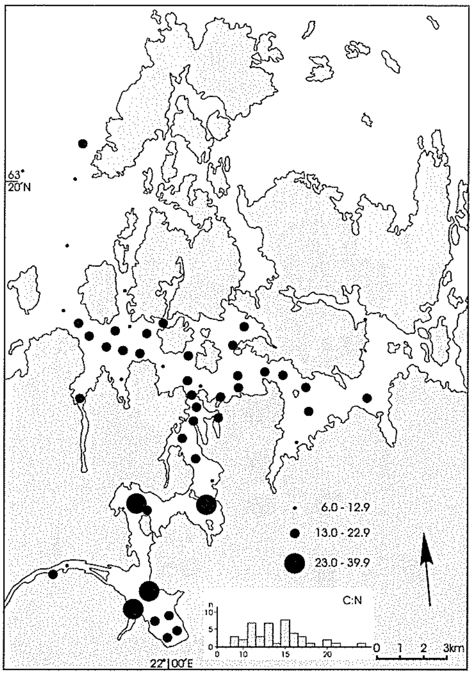


Fig. 37. C/N ratio of the surface sediment in the delta of the river Kyrönjoki.

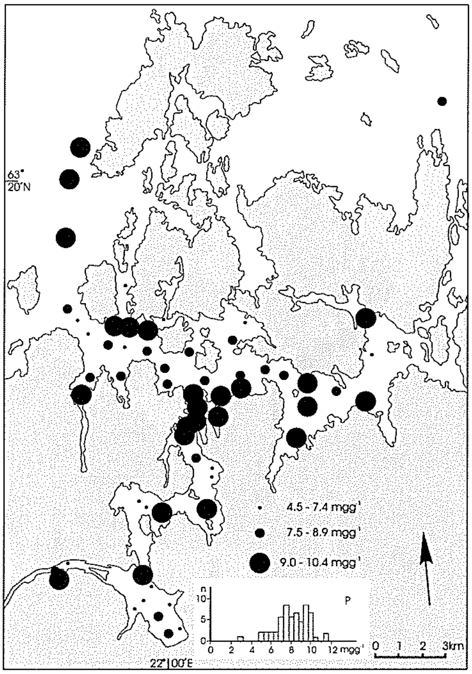


Fig. 38. P content of the surface sediment in the delta of the river Kyrönjoki.

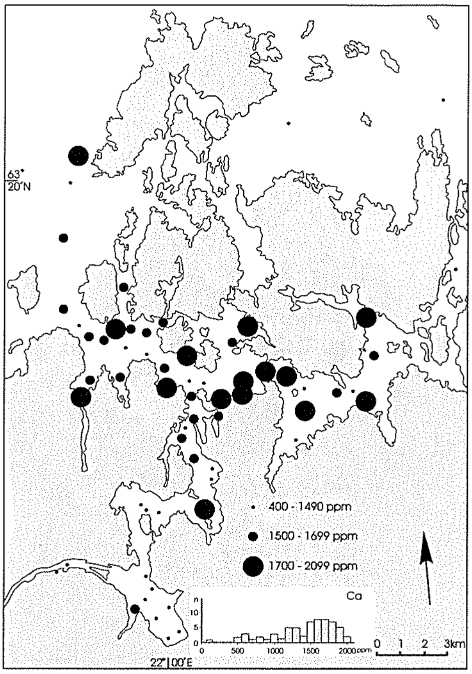


Fig. 39. Ca content of the surface sediment in the delta of the river Kyrönjoki.

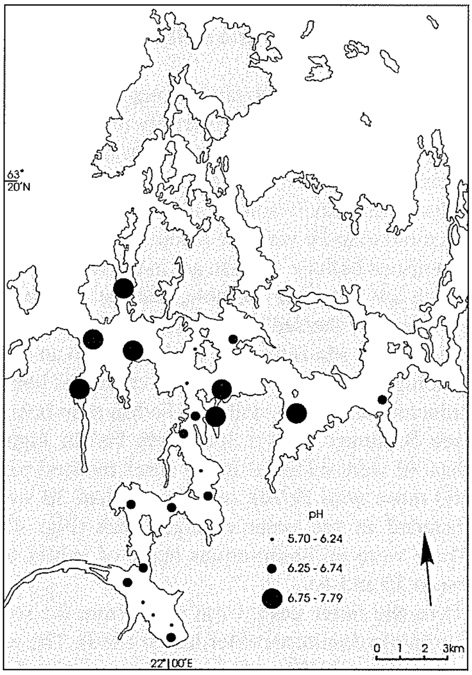


Fig. 40. pH of the surface sediment in the delta of the river Kyrönjoki.

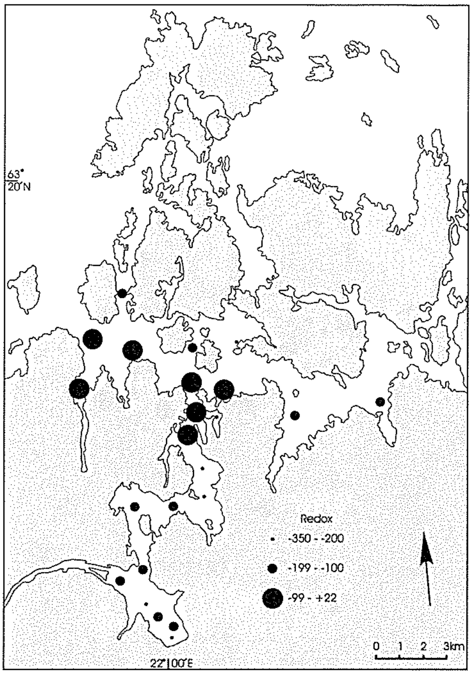


Fig. 41. Redox potential of the surface sediment in the delta of the river Kyrönjoki.

4.3 Subdivision of the delta

The delta was divided into two parts according to its sediment chemistry, especially the redox conditions determined using the Fe/Mn ratio as an indicator. In the oxidation-reduction gradient Mn is reduced into easily soluble ions at a higher redox potential than Fe with the result that in oxidizing conditions both Fe and Mn are in the form of ions which are not easily soluble, and the content of both ions in the sediment is high, and thus their ratio is low. Mn is the first to change into an easily soluble form, and therefore its content is low in reducing conditions, and then Fe/Mn ratio is high (see Brümmer 1974). Sites with Fe/Mn higher than 40 were included in the inner reduced part, and those with Fe/Mn ratio lower than 30 were included in the outer oxidized part (Fig. 42). There were no observations made of values between 30 and 40.

(I) In the inner part, fresh water from the river Kyrönjoki dominates (Meriläinen 1985). The water is quite acid. The pH is usually approximately 5.5, except in late summer when it may rise to 6.5. On the other hand, during high flood periods it

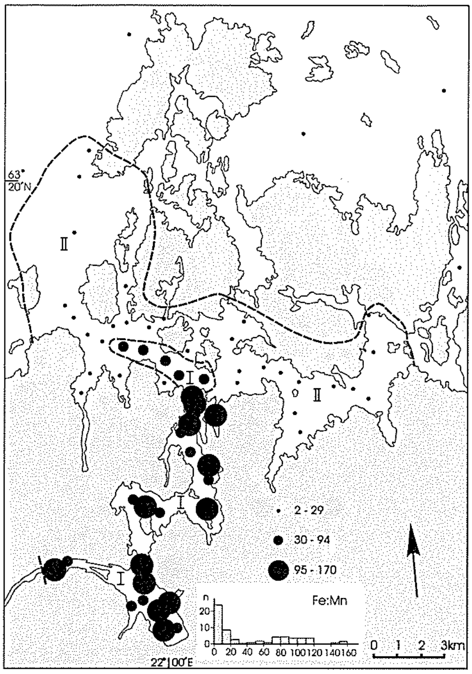


Fig. 42. Delimitation of the delta and its subdivision into inner (I) and outer (II) part on the basis of the Fe/Mn ratio in the surface sediment in the delta of the river Kyrönjoki.

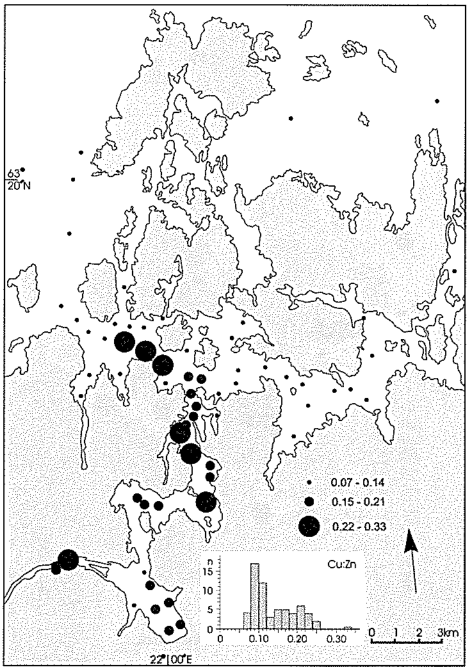


Fig. 43. Cu/Zn ratio of the surface sediment in the delta of the river Kyrönjoki.

may sink as low as 4.0 (Meriläinen 1984b). Due to the acidity, the sedimentary conditions are reducing (see Brümmer 1974), as indicated by the high Fe/Mn ratios (44-170) and Cu/Zn ratios (0.14-0.33) in the sediment surface. The Cu/Zn ratio behaves in a similar way to Fe/Mn ratio in the oxidation-reduction gradient, but the differences are not as sharp (e.g. Hallberg 1974; Vuorinen 1978; Simola 1983b; Fig. 42, 43). The heavy metal content in the sediment surface is in most cases low, and except for Hg it does usually not differ significantly from the natural background.

The organic content of the sediment surface is correlated with different elements as well as the elements with each other (Table 4). Ca, Fe and Mn, however, seem to be independent of the other elements and the organic content.

(II) In the outer part of the delta, brackish water of neutral pH usually dominates (Meriläinen 1985). Sedimentary conditions are mainly oxidizing, as indicated by low Fe/Mn ratios (2-29) and low Cu/Zn ratios (0.007-0.14) (Fig. 42, 43). The heavy metal content of the sediment surface in general is higher than the natural background. Moreover, the mean organic content of the sediment is higher than in the inner part of the delta.

Like in the inner part, also in the outer part different elements and organic content are rather strongly correlated (Table 5) because most of the analysed elements are rather strongly bound with the organic sediment (Sholkowitz 1976). Due to the different redox conditions, however, the relationships differ from those in the inner part. In the outer part P, Ca, Pb and Cd seem to be independent of the other variables measured.

The DCA ordination of the variables measured from the sediment surface samples gave almost the same result as Fe/Mn ratio for the subdivision of

Table 4. Statistically significant correlations between organic content and different elements in the surface sediment of the inner part of the delta of the river Kyrönjoki.

	Org.	C	N	P	Ca	Fe	Mn	Pb	Cu	Zn	Cd
C	0.94***										
N	0.63**	0.60**									
P	0.69***	0.69***	0.62**								
Ca	-	-	-	0.37*							
Fe	-	-	-	0.49**	-						
Mn	-0.40*	-	-	-	-	0.40*					
Pb	0.41*	-	-	-	-	-	-				
Cu	0.48**	0.72***	0.46*	0.58***	-	-	-	-			
Zn	0.51**	0.60**	-	0.40*	-	0.37*	-	0.37*	0.67***		
Cd	0.56**	0.63**	0.45*	0.42*	-	-	-	0.59**	0.59**	0.66***	
Hg	0.60***	0.60**	-	-	-	-	-	-	0.67***	0.38*	-

Table 5. Statistically significant correlations between organic content and different elements in the surface sediment of the outer part of the delta of the river Kyrönjoki.

	Org.	C	N	P	Ca	Fe	Mn	Pb	Cu	Zn	Cd
C	0.97***										
N	0.90***	0.88***									
P	-	-	-								
Ca	-	-	-	-							
Fe	0.36*	0.57**	0.61**	-	0.47**						
Mn	0.54**	-	0.53**	-	-	-					
Pb	0.33*	-	-	-	-	-	-				
Cu	0.87***	0.86***	0.78***	-	-	-	0.43**	0.46**			
Zn	0.79***	0.72***	0.82***	-	-	0.48**	0.57***	-	0.77***		
Cd	-	-	-	-	-	-	0.54**	-	-	0.50**	
Hg	0.56**	0.56**	-	-	-	0.42*	-	-	0.40*	0.37*	-

the delta. Only two points (sites 3 and 14, Fig. 26) in the erosion area of the actual river channel were placed in a different group when compared with the results of Fe/Mn ratio (Fig. 44). In those sites also the Fe/Mn ratio was clearly lower than in the surrounding sites, being however high, when compared with the values of the outer part. In axis 1 of the DCA ordination a rather clear salinity gradient, increasing downwards, can be seen.

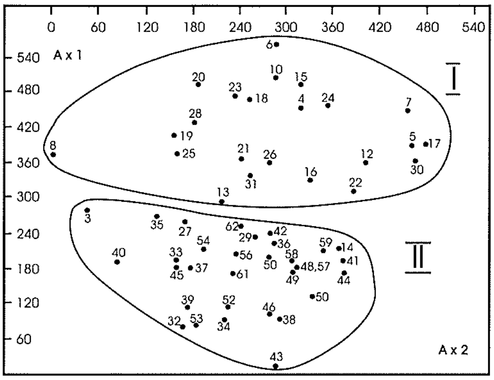


Fig. 44. DCA ordination of the characteristics of the surface sediments. Group I corresponds to the inner part and Group II to the outer part of the delta.

4.4 Datings

In the flooded meadow of Mälsor the dating results from different plant individuals differed slightly, but the deviation of the datings was relatively small (Fig. 45). In the deeper layers datings could be made only of a few plant individuals. Thus the results of the early stages of the dated periods are not as reliable as the results of the latest years (Fig. 45).

In the depression of Nabbviken Bay there is a permanent anoxic layer of brackish water in the bottom with a thickness of about 1.5 m. The 5.5 m thick surface layer is normally fresh water from the river Kyrönjoki. In the depression there is a deposit of at least a 440 cm thick layer of mud, which is black when fresh, and regularly varved, which is uncommon in shallow coastal areas in brackish water. The mean thickness of the varve couplets was about 1 cm. On the basis of the seasonal succession of diatoms the layers were determined to be annual laminae (see Simola 1983a, 8). The varves are clearly visible in frozen samples: the layers deposited during spring are light, those deposited in summer and autumn a little darker and the layers deposited in winter are almost black (Fig. 46). Inside the annual laminae one can see

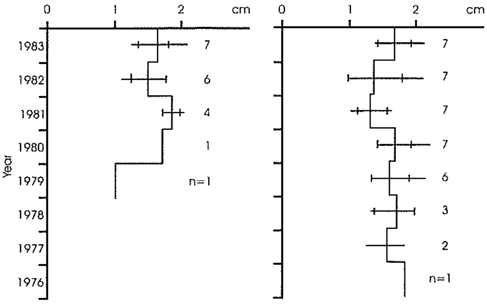


Fig. 45. Mean annual accumulation of sediment in the flooded meadow of Mälsor (sites 1 and 2, Fig. 28) measured on the basis of the annual growth of *Carex acuta* L.. The horizontal line shows the range of the measurements, and vertical lines across the range show the standard deviation of the measurements.

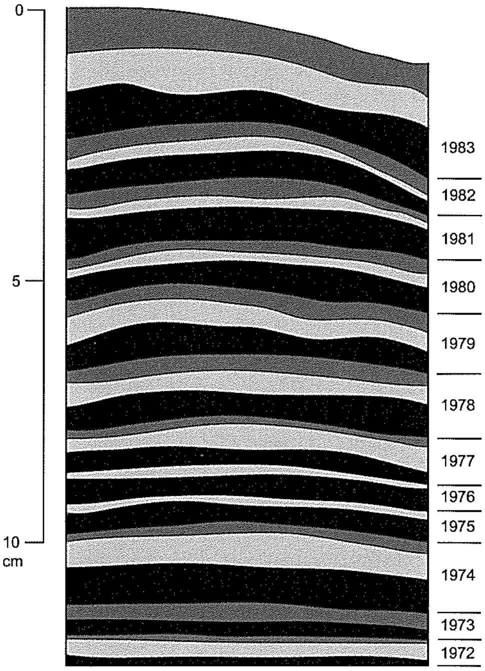


Fig. 46. The structure of the surface part of the varved sediment in Nabbviken Bay (site 22, Fig. 28). White = spring layer, grey = summer layer, black = autumn and winter layer.

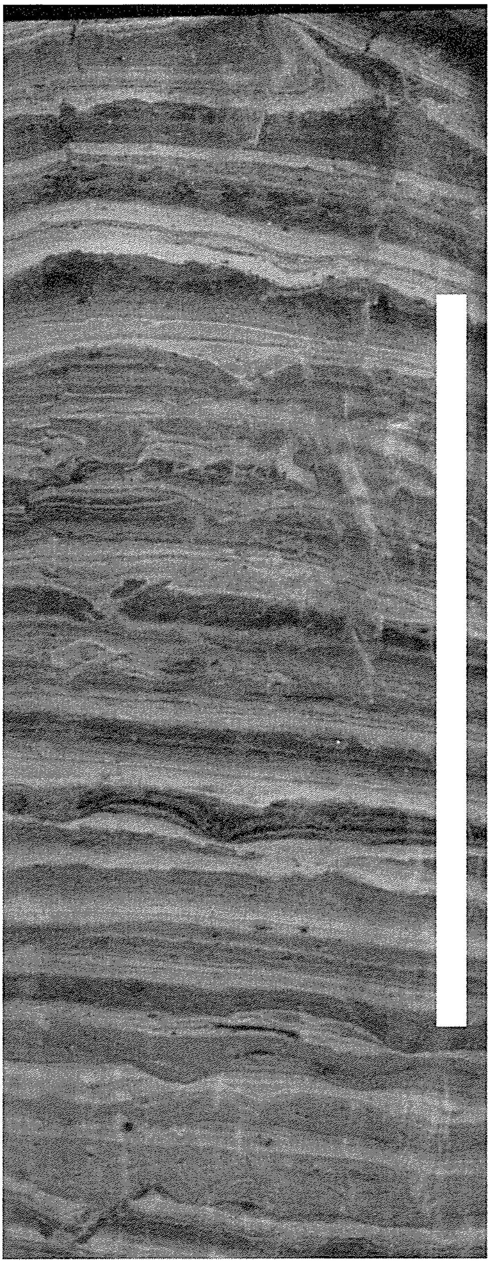


Fig. 47. Annually laminated sediment from Nabbviken Bay (site 22, Fig. 28). The length of the vertical scale bar is 10 cm. Photo Raimo Heikkilä October 1988.

thin layers deposited during short periods, possibly even diurnally (cf. Simola and Tolonen 1981).

The depression was sampled twice, in 1983 and 1988, and on the basis of the counting of the easily recognizable laminae and the measurements of the thicknesses of the varves it could be confirmed that the layers are annual laminae (Fig. 47)

The sediment column in Getlaxfjärden was dated on the basis of a change in the chemical stratigraphy of the sediment. The change is due to the damming of the Bay in 1957. Before that some of the water from the river Kyrönjoki flowed to the sea through Getlaxfjärden, and fresh water dominated there. Therefore, the sedimentary conditions were reducing, and Fe/Mn ratios high. After damming brackish waters are most prevalent in the Bay, and the sedimentary conditions are oxidizing, with low Fe/Mn ratios. In 1985 the change in the sediment chemistry occurred at a depth of 30 cm. Thus the sediment accumulation in Getlaxfjärden had been about 1 cm/year.

4.5 Sedimentation rates and accumulation of sediment

On the basis of the datings and the dry bulk density of the sediment, 9000 ± 2500 $gm^{-2}a^{-1}$ of dry matter has been deposited during the period 1979-1983 in the flooded meadow on the river bank (site 1, Fig. 26). Twenty-five metres from the shore the dry matter accumulation has been 9400 ± 2300 $gm^{-2}a^{-1}$ during the period 1976-1983.

In the varved sediment of Nabbviken (site 22, Fig. 26) the thickness of the annually deposited sediment during the period 1931-1983 was 0.6 - 2.4 cm. The mean thickness of varves was 1.2 ± 0.3 cm. The varves deeper in the sediment tend to be thinner than those on the surface, which is mainly caused by the consolidation of the sediment. The accumulation rates of dry matter give more comparable information between years, because the influence of consolidation on dry matter accumulation is not as significant as on the thickness of varves, even though matter diluted in the interstitial water is transported upwards in the sediment during the consolidation process. On the basis of the thickness of the varves and dry matter density the mean annual accumulation of dry matter has been 2500 ± 800 $gm^{-2}a^{-1}$ (Fig. 48). The dry matter accumulation has earlier been clearly higher than during the 1970s and 1980s. The annual variation was also earlier much greater than in the 1980s. On the other hand, the accumulation of organic matter has been fairly stable over the whole study period.

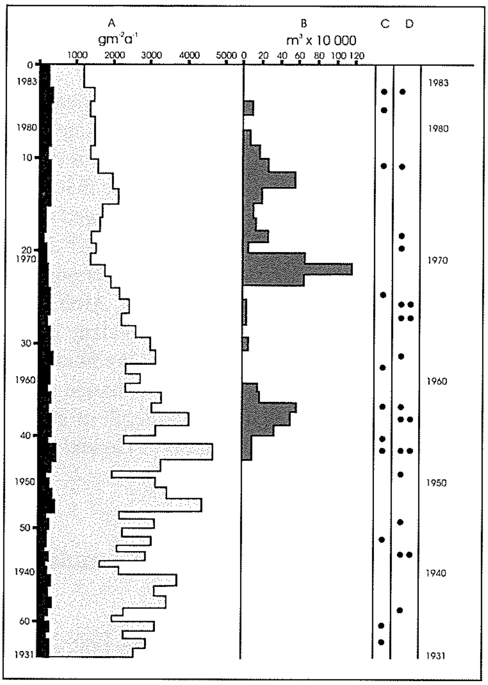


Fig. 48. Sediment accumulation in Nabbviken Bay (site 22, Fig. 28). A = Accumulation of organic matter (black) and total dry matter accumulation in 1931-1983, B = Dredging in the river below the water surface. There is no information for dredging for the 1930s, because exact annual information was not available, C = years with high mean discharge (>50 m^3s^{-1}), D = Flood years: one dot means 350 m^3s^{-1} > HQ > 400 m^3s^{-1} and two dots mean HQ > 400 m^3s^{-1}.

The sediment accumulation was at its highest in the 1950s, when land reclamation for agriculture was very intensive (Table 2). In the 1960s accumulation decreased evidently due to increased land drains instead of open ditches. At about 1970 the sediment accumulation decreased constantly on a clearly lower level than earlier (Fig. 48). The probable cause was the construction of the Pitkämö reservoir, which effectively collects the sediments of Kauhajoki and Jalasjoki. After 1970, the annual variation in sediment accumulation rates has been much reduced when compared with the earlier situation when there was no significant regulation in the watercourse. Despite the decrease of total sediment accumulation, the accumulation of organic matter has been fairly stable over the period 1931-1983. This is probably due to increased leaching of organic matter from areas drained for forestry and peat mining. The slight currents in the reservoirs are able to transport some of the organic suspended solids through the reservoirs whilst most of the inorganic suspended solids are deposited in them.

The accumulation rates are much higher in the innermost part of the delta on the riverside than in the inner part closer to the boundary of the inner and outer parts, in Fransesgrundet (sites 21 and 23, Fig. 26) and Nabbviken (site 22, Fig. 26). On the river bank silt with low organic content is deposited on a meadow where the dense vegetation catches the suspended solids. If Nabbviken (site 22, Fig. 26), which is situated in the middle of the delta, is estimated to represent the mean accumulation rate in the delta, and the mean rate is multiplied by the determined accumulation area of the delta, the mean total accumulation rate of dry matter in the delta is 110 000 tons a year. The accumulation rates in Getlaxfjärden (site 38, Fig. 26) are of the same order as in Nabbviken.

The mean sedimentation rate is clearly higher than estimated for the load of suspended solids in the estuary (Meriläinen 1986). The difference is explained by inaccuracy in both estimates. In the estimation of the load of suspended solids, bottom transport is not taken into account. Also the estimation of the load is strongly dependent on sampling frequency. Infrequent sampling may cause a considerable underestimation of the load (Walling and Webb 1985, Tikkanen 1990).With pH rising outwards in the delta, part of the diluted matter is deposited. There is also autoctonic sedimentation in the delta. In the results measured for the sediments, also diluted matter in the interstitial water is included. My estimate of the accumulation area of the delta may possibly be too high, as some of transport bottoms have been taken as accumulation areas. Obviously, there is also a lot of spatial variation in the sedimentation rates in the accumulation areas in the outer part of the delta depending on the directions and velocity of currents of the river water.

4.6 Stratigraphy of the sediments

4.6.1 Grain size distribution

Three sample series, from the flooded meadow of Mälsor (site 1), Vassor Bay (site 11) and Fransesgrundet depression (site 21, Fig. 26), were analysed for grain size distribution. According to Soveri (1964, 334) the surface samples of Mälsor were clay, and below the depth of 10 cm fine-grained silt. In Vassor, the samples were silt excluding two clay layers near the surface. The proportion of coarse sediment tends to increase towards the surface. In Fransesgrundet, the whole series of samples was silt, but the proportion of fine-grain classes tends to increase towards the sediment surface (Fig. 49).

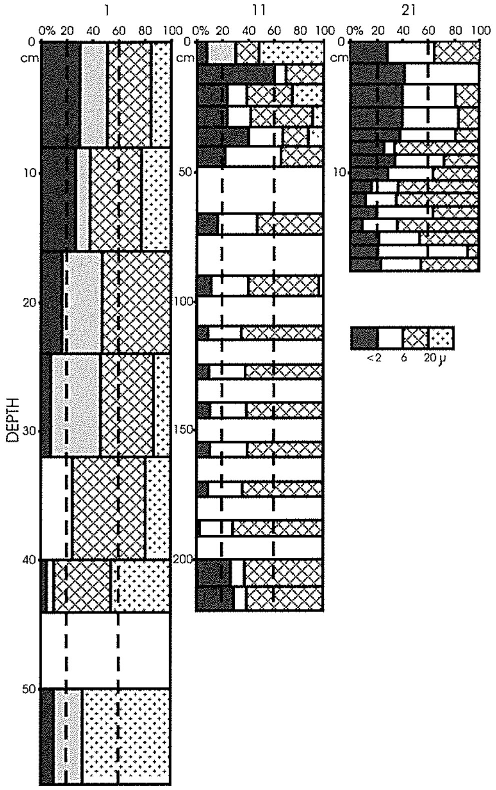


Fig. 49. Vertical grain size distribution of sediment in Mälsor (site 1), Vassor (site 11) and Fransesgrundet (site 21).

On the basis of the vertical grain size distribution the sedimentary conditions seem to have been relatively stable in Fransesgrundet. In Vassor and Mälsor there is more irregular variation than in the outer part of the delta. Thus, the sedimentary conditions seem to be more varying in the area where the river water constantly dominates (see Cato 1977, 20).

4.6.2 Diatoms

In the quantitatively analysed sample series there are both fresh water and brackish water diatoms (ecology after Hustedt 1930, Mölder and Tynni 1967, 1969 and Cholnoky 1968). During the study period 1970-1977 the proportion of brackish water species has increased and that of fresh water species decreased (Fig. 50). In the whole series there are abundantly brackish water species living on the bottom (especially in the genera *Navicula* and *Nitzschia*) which indicates that the hypolimnion in Nabbviken (site 22, Fig. 26) is constantly brackish water. The quantitative diatom diagram shows an indication for seasonal rhythmical variation for a few species, e.g. *Grammatophora marina, Hyalodiscus scoticus, Navicula halophila* and *Nitzschia punctata* of the brackish water species, and *Amphora coffeaeformis, Diploneis smithii, Eunotia exigua, Gomphonema acuminatum* and *Stauroneis parvula* var. *prominula* of the fresh water species (Fig. 50). For most species, however, the rhythm is vague, probably due to inaccurate slicing of the sample. Also the rate of redeposition of diatoms eroded from older delta sediments upstream is unknown. However, in the tape peel preparates a qualitative seasonal variation of species could be clearly seen.

4.7 Content of organic matter and different elements in the sediment cores

4.7.1 Organic content

Loss-on-ignition is fairly accurately the same as organic content in the sediment, even though some crystalline water is evaporated from the clay minerals during the ignition (Håkanson and Jansson 1983, 76). In this material the lowest observed value for loss-on-ignition was 0.5%. Thus, the proportion of crystalline water of the loss-on-ignition is not significant.

In the studied sediment columns loss-on-ignition was in most cases high, varying between 5 and 30% of dry weight. In the postglacial clays of the lower parts of sample series from sites 21 and 23 (Fig. 26) loss-on-ignition was low, between 0.5 and 3% (Figs. 51-56).

The organic content in the sediment surface is clearly higher than deeper in the sediment column.

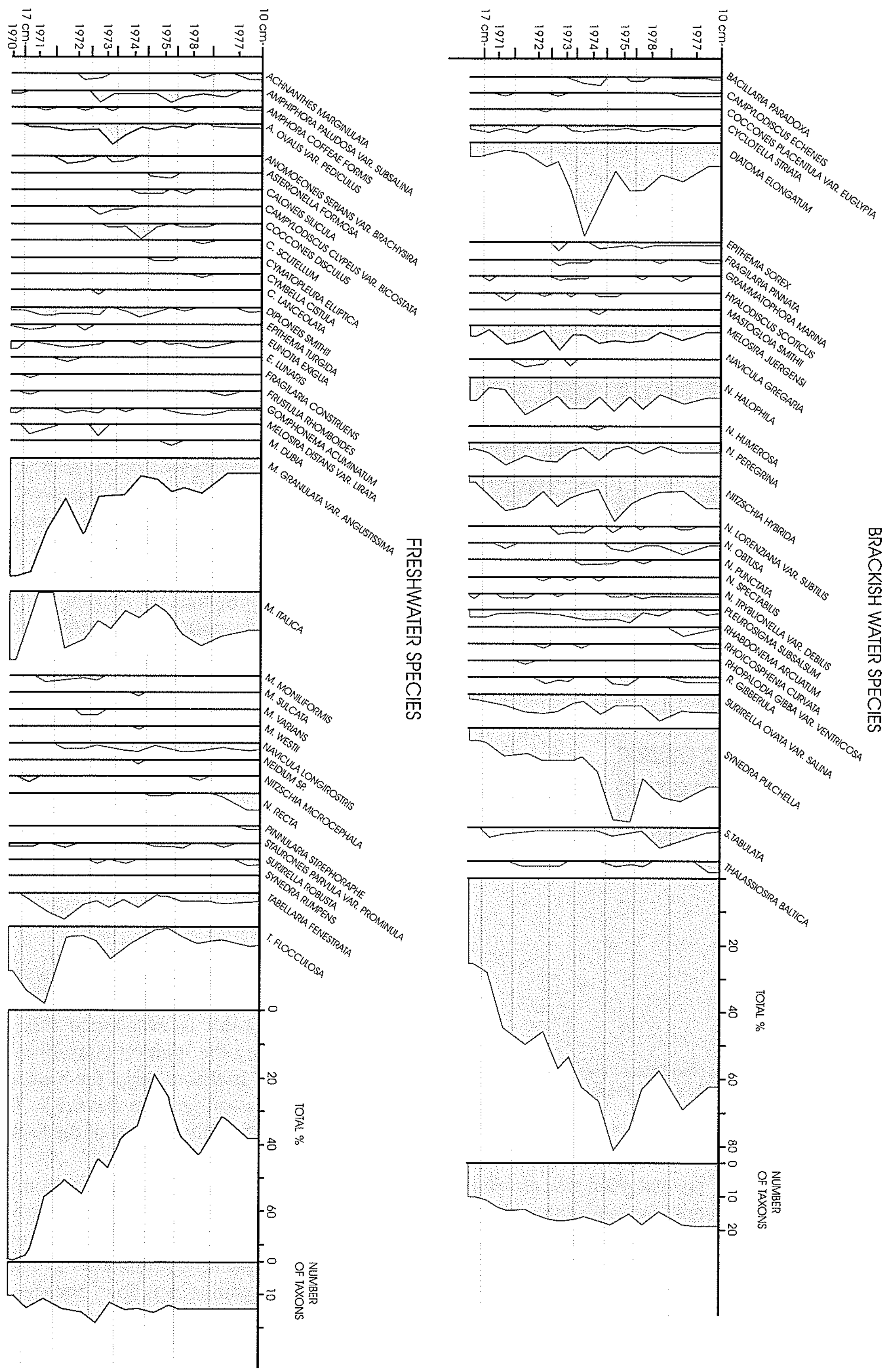


Fig. 50. Diatom stratigraphy in the sediment of Nabbviken Bay (Site 22).

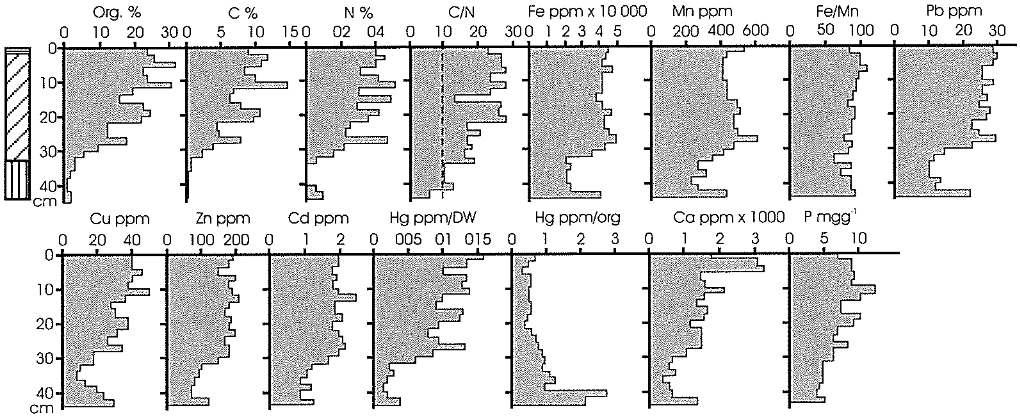


Fig. 51. Vertical variation of the content of organic matter and different elements in the sediment of Fransesgrundet (Site 21). In Figs. 51-56 the vertical bar shows the quality of the sediment as follows: Vertical lines: clay, diagonal lines: dark reduced gyttja, horizontal lines: light brown oxidized gyttja.

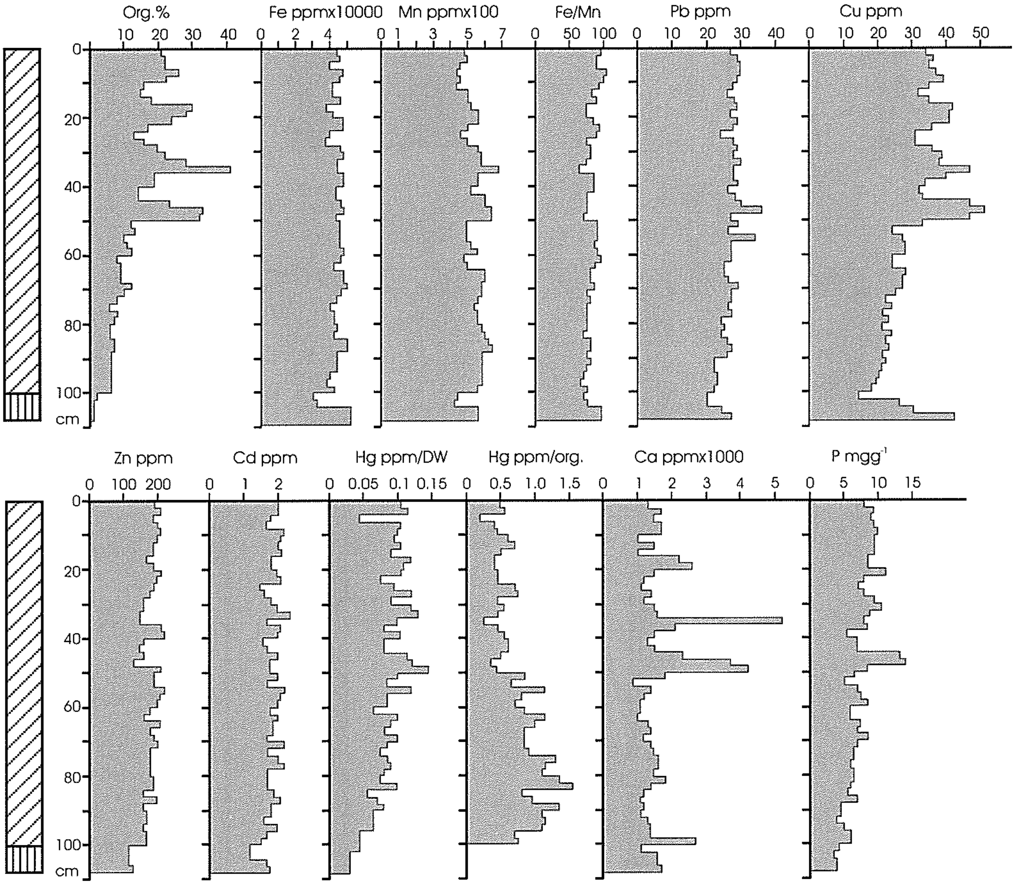


Fig. 52. Vertical variation of the content of organic matter and different elements in the sediment of Fransesgrundet (Site 23).

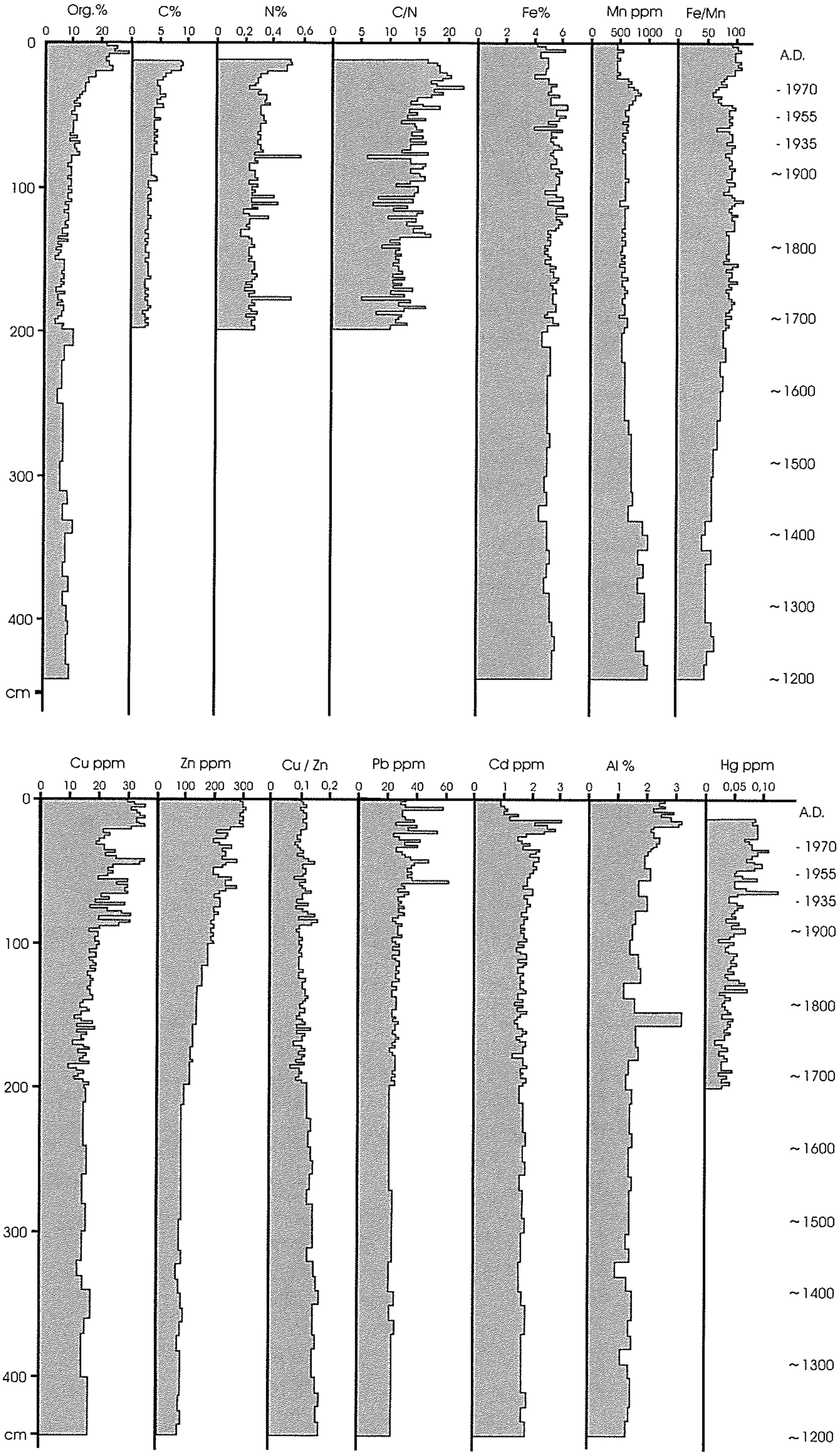


Fig. 53. Vertical variation of the content of organic matter and different elements in the sediment of Nabbviken (Site 22). The whole studied column consists of dark reduced gyttja.

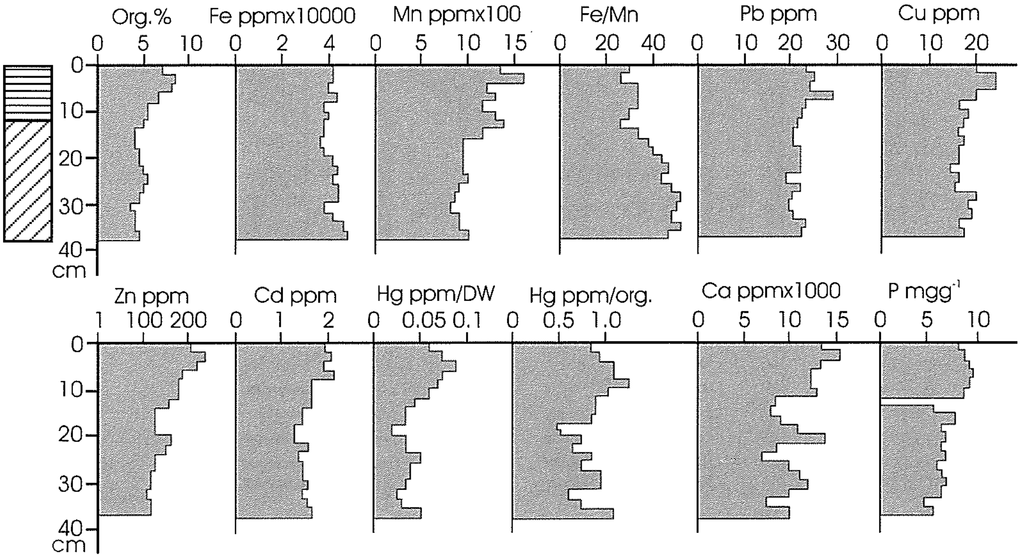


Fig. 54. Vertical variation of the content of organic matter and different elements in the sediment of Storskatan (Site 30).

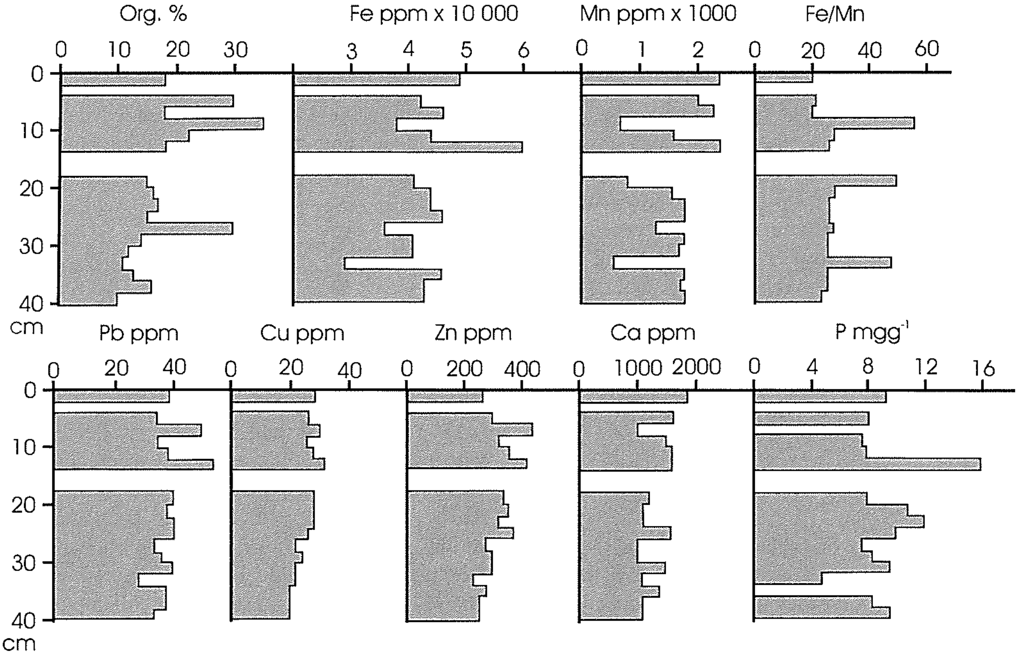


Fig. 55. Vertical variation of the content of organic matter and different elements in the sediment of Prästholmen (Site 48).

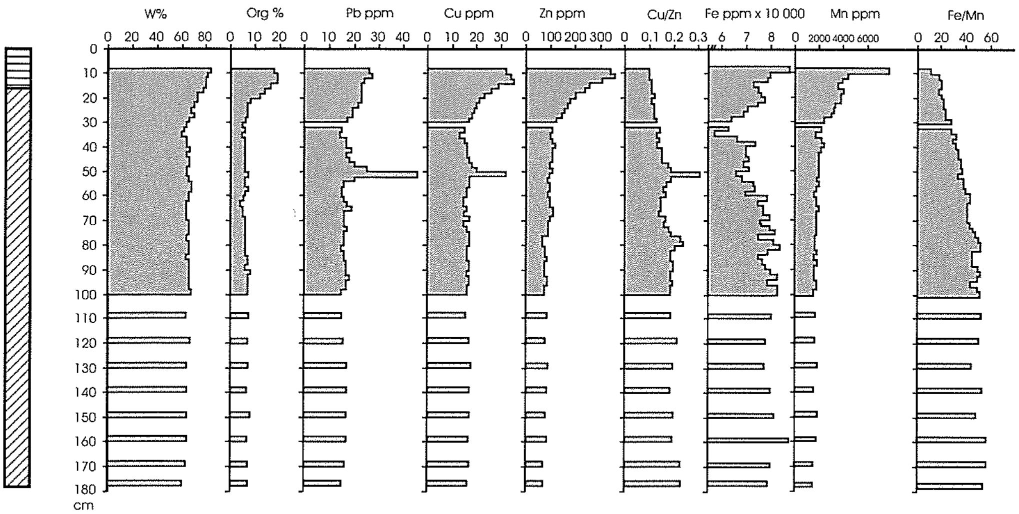


Fig. 56. Vertical variation of the content of organic matter and different elements in the sediment of Getlaxfjärden (Site 38).

Part of the difference is explained by decaying of organic matter after deposition. The differences between surface and deeper parts are relatively large. On the other hand, at least in Nabbviken (site 22, Fig. 26) decaying probably is not active due to anoxic conditions. Thus, organic content in the sediment has increased during the latest decades, especially in the 1970s (Fig. 53). Obviously, the main reason for this is the increased leaching of organic matter from drained mires and peat mining areas. Also eutrophication due to municipal waste waters and losses of fertilizers from arable fields can partly explain the increase in organic content. Eutrophication due to atmospheric deposition of nitrogen also adds to the organic content of the sediments.

4.7.2 Carbon

The relationship of organic matter and organic carbon in the sediment is usually linear. The ratio is typically in the order of 2 : 1 (Håkanson and Jansson 1983, 76). Dean and Gorham (1976, 280) have given a ratio 2.13 : 1. In this material the ratio of organic matter and total carbon was 2.32 : 1 ($r = 0.93^{***}$). Because of the rarity of inorganic carbon in the Kyrönjoki drainage basin all the carbon in the sediment can be estimated to be of organic origin.

The variation of carbon content accurately follows the variation of organic content (Figs. 51 and 53). The reason is the rarity of carbonates in the bedrock and soil of the drainage basin of the river Kyrönjoki (Laitakari 1942, 56-57). In the estuary of the river the fresh water is acid (Meriläinen 1985), which prevents the accumulation of carbonates in the sediment (Simola 1983b, 52).

4.7.3 Nitrogen

Most of the nitrogen in the sediment has an organic origin (Simola 1983b, 52). There was a considerable correlation between organic matter and nitrogen content in the sediment in this material ($r = 0.52^{***}$) (Figs. 51 and 53), but the correlation was much weaker than between organic and carbon content. This is partly explained by the abundance of denitrified allochthonous sediment. Part of the difference is explained by the analysis method. The deviation between parallel sample analyses was much greater than in the carbon analyses.

4.7.4 C/N ratio

The C/N ratio of the organic matter of the sediment gives an indication of the origin of the sediment. The longer the organic matter has decayed and denitrified the higher the ratio is. In other words, in autochthonous sediment which mostly consists of planktonic organisms, the ratio is lower than 10. In mostly allochthonous sediment the ratio can be much higher because the greatest proportion of the sediment originates from the drainage basin and consists of older organic matter redeposited in the delta (Hansen 1961, 288). In the sample series analysed in this study (Figs. 51 and 53) C/N ratio was mostly higher than 10. Thus, the sediment is mostly allochthonous from the 1930s on. However, during a few periods up to the 1920s, autochthonous sedimentation was dominant. On the basis of this, the production of biomass in the delta seems to be great during periods of big nutrient transport by the river (see also Meriläinen 1986). In the tape peel preparates of the annually laminated sediment of Nabbviken abundant accumulation of organic particulate matter can be clearly seen. For example, in the spring layers one can see a lot of *Sphagnum* leaves.

4.7.5 Phosphorus

In water courses phosphorus is normally the factor most clearly controlling biological production. During recent decades the transport of phosphorus into the water courses has increased especially due to waste waters and agriculture (e.g. Håkanson and Jansson 1983, 108-109, Rekolainen 1993). Phosphorus, and also nitrogen losses from agricultural land are higher than industrial and municipal loads together (Rekolainen *et al.* 1992). In Finland also forestry drainage of mires and fertilising of forests have been noticed to increase the phosphorus load at least locally (Kauppi 1979, 42, Simola 1983b, 53).

Phosphorus is mainly deposited as inorganic complexes with iron and aluminium hydroxides. The role of depositing phosphorus is dualistic: phosphorus stimulates biological processes in the sediment, but it can dissolve back into the water and cause eutrophication (Håkanson and Jansson 1983, 108). In reduced sediment phosphorus is mainly diluted in the interstitial water. Therefore, phosphorus is mobile in the sediment, and its enrichment can occur in the water-sediment interface as iron hydroxide complex (Mortimer 1941, 326, Callender 1982, 433, Simola 1983b, 53).

In the water of the river Kyrönjoki there is very high phosphorus content and a maximum concentration of 490 $\mu g l^{-1}$ has been measured. However, the contents have decreased since 1979, when a sewage purification plant was established in Seinäjoki (Storberg 1983, 13-14). In the 1980s the mean P content of the water was in the order of 100 $\mu g l^{-1}$ (Meriläinen 1985). In eutrophic lakes the P content of the water is typically about 80 $\mu g l^{-1}$ (Heinonen 1983, 165). The phosphorus load of the river Kyrönjoki is very high, more than five times higher per surface area than from natural forest and mire catchments. The river Kyrönjoki causes 6.3% of the phosphorus load in the Gulf of Bothnia from the Finnish side (Pitkänen 1994).

In the sediment samples studied, the phosphorus content was mostly very high. It varied between 2 and 20 $mg g^{-1}$ of dry matter (Figs. 51, 52, 54 and 55). The phosphorus content was typically somewhat higher in the sediment surface than in the deeper layers. It is partly due to the increase in the phosphorus load of the river during earlier decades, but the main reason is the movement of phosphorus to the surface with interstitial water. The decrease in phosphorus load after 1979 cannot be shown in the analyses due to the mobility of phosphorus (see Callender 1982, 433).

The phosphorus content in the sediments of the delta of the river Kyrönjoki at its highest are about three times higher than highest values given in the literature (e.g. Premazzi and Ravera 1976, 123, Cato 1977, 138-156, Håkanson and Jansson 1983, 111, Simola 1983b, 51). Only Keulder (1982, 351) in South Africa has measured equally high values.

4.7.6 Aluminium

Aluminium is mainly leached from the soil to watercourses in acidic conditions. A decrease in pH from 5.2 to 4.2 has caused a 4-fold leaching of aluminium (Nelson and Campbell 1991). The pH of water flowing from Litorina clay areas beside the river Kyrönjoki has been reported to be as low as 3.0 (Storberg 1983).

The aluminium content in the sediment column of Nabbviken Bay (site 22, Fig. 26) has been fairly stable at a level of 1.5% from the 1200s up to the end of 1700s (Fig. 53). The present aluminium content is at a level of 2.5%. Already at the depth of 160 cm in the sediment, which has been estimated to represent the end of 1700s, there is a sudden peak in the aluminium content. It corresponds very well to the large-scale cultivation of sulphide-bearing Litorina clay soils along the river in Ilmajoki, which was started in 1783. Later there are less abrupt peaks in aluminium content approximately in the years 1830, 1935 and 1950, which correspond to major dredging in the river channel in the lower reaches of the river Kyrönjoki. The peak in the early 1970s corresponds to the worst acidification problems of the river water (Storberg 1983).

4.7.7 Calcium

The calcium content of the sediment varies greatly vertically. However, there is no trend in the changes in the content, but it is similar in postglacial clays and recent sediments (Figs. 51-55, cf. Tolonen 1983, 80).

4.7.8 Iron

The iron content has not clearly increased over the background values (20 000 - 60 000 ppm) measured from the deepest sediment layers, and no enrichment of iron in the sediment surface can be detected (Figs. 51-56). The stratigraphy of the sediment in Getlaxfjärden (site 38, Fig. 26) differs from the others in this respect. In the uppermost layer iron content is higher than at depths of 30-60 cm, evidently due to the change in conditions of sedimentation, caused by the damming of Getlax in 1957 (Fig. 56). However, the iron content at the surface is not higher than in the layers deeper than 60 cm.

4.7.9 Manganese

The manganese content of the analysed sediment sample series has mostly been relatively stable (500 - 2000 ppm in different cores), and enrichment in the surface could not be observed unless in Getlax fjärden (Figs. 51-56). For example, in the sediment at site 21 (Fig. 26) there was a thin (a few mm) oxidized layer at the surface, but while analysing 2 cm slices an obviously higher Mn content in the surface was not detected (Fig. 51). Instead, at site 38 in Getlaxfjärden (Fig. 56) the manganese content is clearly higher in the upmost 30 cm than in the deeper layers, which is obviously caused by the change in sedimentological conditions. After the damming of Getlax in 1957 fresh water from the river has no longer flown to Getlaxfjärden, and there has been brackish water in the bay ever since then. On the basis of the result the sediment can be roughly dated: a clear change in Mn content (and Fe/Mn ratio) has occurred in the deposits after the damming. Thereafter, during 27 years in Getlaxfjärden about 30 cm of sediment has been deposited. The mean accumulation rate has been about 1 cm/year, which is very close to the sedimentation rate in Nabbviken (site 22, Fig. 26). In general, the manganese content is higher in the outer parts of the delta than in the areas dominated by fresh water from the river (Figs. 51-56).

4.7.10 Fe/Mn ratio

The behaviour of iron and manganese in watercourses is relatively similar. Their oxidized ions (Fe^{3+}, $Mn^{3+,\ 4+}$) tend to be deposited as hydroxides, while the reduced ions (Fe^{2+}, Mn^{2+}) are easily soluble. Oxidizing conditions prevail in the sediment in oxic and neutral or basic circumstances, reducing conditions in anoxic and/or acidic circumstances (e.g. Brümmer 1974). In the oxidizing-reducing gradient, Mn is reduced more easily than Fe. Therefore the Fe/Mn ratio in the sediment can be used as an indicator of earlier hypolimnetic conditions in the gradient (Brümmer 1974, Simola 1983b, 53).

On the basis of the Fe/Mn ratio, the sedimentary conditions in the Nabbviken (site 22) and Fransesgrundet (sites 21, 23, Fig. 26) depressions have been constantly reducing (Figs. 51-53). Fe/Mn ratios are very high (70-110) due to low Mn concentrations. In Storskatan (Site 30, Fig. 54) there is a 20 cm thick oxidized layer, where the ratio is relatively low (25-35). Deeper sediments have deposited in reducing conditions(Fe/Mn ratio 40-50). In the sediment column of Prästholmen (site 48, Fig. 55) The Fe/Mn ratio is mostly low (20-25), and oxidizing conditions have prevailed. In the profile there are three layers with a high ratio (50-60). They are possibly caused by flood periods, during which the acid river water has prevailed in the site for a long period. In the sediment of Prästholmen the bioturbation is visibly strong, and therefore the formation of clearly distinguishable layers is surprising (see Håkanson and Jansson 1983, 225). In Getlaxfjärden (site 38, Fig. 56) the Fe/Mn ratio is relatively low(15-30) in a surface layer of 30 cm, indicating oxidizing conditions. Deeper the ratio is high (45-60) indicating reducing conditions.

4.7.11 Heavy metals

The concentrations of the heavy metals: lead, copper, zinc, cadmium and mercury have clearly increased in the environment as a consequence of human activities (e.g. Håkanson and Jansson 1983, 113, Moore and Ramamoorthy 1984). The concentrations of different elements have increased in the following order when compared with the pre-industrial background values of lake sediments in South Finland: Pb>Cd>Ca>Ti>Zn>Hg>Fe>Mn=Al>Cu>Ni (Tolonen 1983, 80). Therefore, heavy metal concentrations are in general higher in the sediment surface than in the deeper layers.

It is evident that some metals, e.g. Cu, Zn and Cd are released to water from sediment in reducing conditions. This decreases the content of the metals in the sediment, when the water is acid or anoxic. Then the metals can be bound to biotic processes, as well as from sediments through benthos (de Groot 1976, 106). Especially Hg bound to humic substances easily gets into nutrition chains, where it is enriched.

The enrichment of heavy metals in the surface sediment does not necessarily give quite exact information about the deposition of heavy metals at different times. According to Förstner (1976, 96) the diffusion of metals from deeper layers to the surface in one case caused an increase in the metal contents, varying between 2% (Zn) and 22% (Ni).

4.7.12 Lead

The lead content of the sediment dry weight varied between 7.8 and 73 ppm. The background content of postglacial clay with certainly no human impact ranged from 7.8 to 27 ppm. Usually, the background content was below 20 ppm. In deltaic sediments the lead content varied between 15 and 73 ppm (Figs. 51-56). In the bottom sediments of the Baltic Sea the background content was in the same order or a little higher than in the delta of the river Kyrönjoki (Niemistö and Voipio 1981, 90), but in the west coast of Sweden it was considerably lower (Cato 1977, 138-156). In Wisconsin lakes the background content was approximately the same as in the study area, but clearly higher in Lake Michigan (Förstner 1976, 98). In the studied delta, in the surface layers of the sediment lead content in general is slightly higher than the background content, typically approximately 30 ppm which is due to the use of leaded petrol in cars(Figs. 51-56). Along most of the river course roads follow the river on both sides. In addition, there are layers with much higher content of lead, from 40 to 60 ppm. On the basis of datings, in Nabbviken (site 22, Fig. 53) and Getlaxfjärden (site 38, Fig. 56) this layer corresponds approximately to the year 1942. An army ammunition dump exploded 20.10.1941 in Ilmajoki about 1 km from the river, and obviously large amounts of metals, especially lead and copper were spread in the surroundings. The deposition of lead and copper probably could be used as a trace surface along the lower course of the river and in the delta. In water courses polluted by the mining of lead, the lead content in the sediment has increased up to 100 times higher than background values (Skei *et al.* 1972, Maxfield *et al.* 1974, Moore and Ramamoorthy 1984, 109).

4.7.13 Copper

The measured copper content of dry weight varied between 4 and 64 ppm. The background content ranged from 4 to 40 ppm, being mainly below 15 ppm. In deltaic sediments the copper content varied between 10 and 64 ppm (Figs. 51-56). The background content was clearly lower than in the Baltic Sea (Niemistö and Voipio 1981, 90), and in the lakes of North America (Förstner 1976, 98), but a little higher than in the western coast of Sweden (Cato 1977, 138-156).

The copper content of the sediment in general increases towards the surface. In the sediments of the delta of the river Kyrönjoki it is in most cases about 4 times higher than the background content (Figs. 51-56). In Nabbviken (site 22, Fig. 53) the copper content has varied irregularly since the year 1900, probably due to local small-scale handicrafts and a boat harbour in the bay. In the sediment of Getlaxfjärden (site 38, Fig. 56) there is a peak in copper content coincident with that of lead, evidently also due to the explosion of the ammunition dump in Ilmajoki in 1941. The generally increased copper content from the 1950s is evidently due to the large-scale use of wood preservatives containing arsenic and copper in Kestopuu Ltd. in Ilmajoki nearby the river Kyrönjoki beside the tributary Nahkaluoma. In the 1990s after the bankruptcy of the company it was observed that the soil was very badly polluted in the factory area. In watercourses polluted by industry the copper content can increase up to 12 times higher than the background, but often it is only 3-4 times higher (Förstner 1976, 98). Häkkilä (1980, 24) has observed contents of up to 280 ppm in the sediments off the town Pori on the west coast of Finland, obviously caused by the metal industry in the nearby towns of Pori and Harjavalta. Near copper mines and smelters the copper content in sediment can be as high as 12 000 ppm (Skei *et al.* 1972, Boyden *et al.* 1979).

4.7.14 Zinc

In the sediment samples analysed from the delta of the river Kyrönjoki the zinc content ranged from 44 to 450 ppm. The background content of the old sediment at the bottom of the cores ranged from 44 to 128 ppm while in recent sediments the content varied between 82 and 450 ppm (Figs. 51-56). The results were in the same order of magnitude as those of Tolonen and Meriläinen (1983, 315) from southern Finland. Koivo and Oravainen (1982, 159) and Kansanen and Jaakkola (1985, 34) have measured much higher contents, up to 13 000 - 17 000 ppm in the sediments of Lake Vanajavesi, polluted by industry. Nearby metal mines and smelters the content can increase up to 200 000 ppm (Skei *et al.* 1972). The zinc content in North American lake sediments, even in polluted areas, excluding Lake Michigan, is lower than in the estuary of the river Kyrönjoki (Förstner 1976, 98). In the sediments of the Gulf of Bothnia and the Baltic Sea the zinc content is in the same order as in this study (Hallberg 1979, 267, Niemistö and Voipio 1981, 90). In the surface sediment zinc content is usually 2-4 times higher than the background values. In the long cores (Figs. 53 and 56) there is a clear increase in zinc content towards the surface. In the Kyrönjoki river system, the main source of zinc is probably increased soil erosion due to agriculture and forestry activities. Possibly also the small-scale metal industry in Kurikka has caused some of the recent increase in zinc content. In the sediment of Getlaxfjärden (site 38, Fig. 56) zinc content has increased recently obviously due to a change in the sedimentary conditions from reducing to oxidizing since the damming of Getlax in 1957.

4.7.15 Cu/Zn ratio

According to Hallberg (1974) the ratio of copper and zinc content is a good palaeoredox indicator in brackish water just like the Fe/Mn ratio. Vuorinen (1978, 449) has come to the same conclusion when studying lake sediments. On the basis of Cu/Zn ratio there seems to be a change in redox conditions in the sediments of Getlaxfjärden (site 38, Fig. 26) approximately at a depth of 30 cm just like that for the Fe/Mn ratio (Fig. 56). However, the change is not very drastic, because in addition to zinc content also copper content has increased. The Fe/Mn ratio seems to be a more sensitive indicator of the changes and gives more clear results.

4.7.16 Cadmium

The cadmium content of the studied samples varied from 1.0 to 3.6 ppm. The background content ranged from 1.0 to 1.5 ppm, and in delta sediments the content varied between 1.2 and 3.6 ppm (Figs. 51-54). When compared with the background content the values have increased about 2.5 times higher in the surface sediments. Cadmium content seems to increase in the 1950s when phosphate fertilizers which contain cadmium were taken into agricultural use (Hartikainen 1979, Hutton *et al.* 1987). From 1983 the Cd content of the sediment in Nabbviken (site 22, Fig. 26) has returned back to background level in line with the change in the quality of phosphate fertilizers.

The background content was somewhat higher than those in Baltic Sea sediments (Niemistö and Voipio 1981, 90) and the sediments of large Swedish lakes (Håkanson 1981, 140), but in surface sediments the content was of the same order (see also Olausson *et al.* 1977). In North American lakes background contents of 2.5 ppm have been measured, and in polluted sediments 4-5 ppm

(Förstner 1976, 98). In the sediments of the river Rhine the Cd content was as high as 9 ppm (Förstner 1982, 279). In water courses heavily polluted by industries using cadmium the content can be as high as 50 000 ppm (Moore and Ramamoorthy 1984, 40).

4.7.17 Mercury

The mercury content in the sediment in the delta of the river Kyrönjoki varied from 0.00 (below the limit of analysis accuracy) to 0.18 ppm of dry weight (Figs. 51-54). The background content ranged from 0.00 to 0.04 ppm. The mercury content of organic matter varied between 0.2 and 1.5 ppm (Figs. 51, 52 and 54). Published values of mercury content in sediments are generally higher than in this study (Table 6).

Compared with background content the mercury content in the surface sediment has increased by about 5 times (Figs. 51-54). The change is in the same order as in the sediments of North American lakes (Förstner 1976, 98), but in water courses polluted by industry much higher increases have been observed (Table 6).

The annual deposition of mercury in the sediment of Nabbviken (site 22, Fig. 26) ranges from 0.8 to 1.8 mg m^{-2} a^{-1} (Fig. 57). The deposition is slightly higher than in Lake Polvijärvi in eastern Finland and in Lake Pääjärvi in southern Finland (Simola and Lodenius 1982, 302-303), but clearly lower than in Lake Ekoln in the delta of the river Fyris, middle Sweden (Axelsson and Håkanson 1975, 37). In 1980 the mercury deposition in Nabbviken was about 2 times higher than at the beginning of the 1960s (Fig. 57). The main sources of mercury have been leaching from drained mires and reservoirs (Verta 1990), fuel burning (Moore and Ramamoorthy 1984, 128-129) and mercury-containing pesticides of cereal seeds (Moore and Ramamoorthy 1984, 127-128).

4.8 EDS-analyses of elements in the tape peel preparates of sediment

While analysing some elements in the tape peel preparates of the varved sediment of Nabbviken (site 22, Fig. 26) using an energy dispersive micro analyzer in a scanning electron microscope (Smart and Tovey 1982), it was observed that there was some relationship between elements, which gives some indication about the seasonality of the sedimentation of them (Figs. 58 and 59, Table 7). The maxima of aluminium and silicon content are distributed similarly, and coincide with the minimum of sulphur content. In the middle of Fig. 59 there is the boundary of winter and spring layers for 1965, above which there is the maximum deposition of sulphur and minimum deposition of aluminium and silicon. The analysis is at its best semiquantitative. The unevenness of the tape peel surface and variation in thickness of the sample may cause errors as well as the large

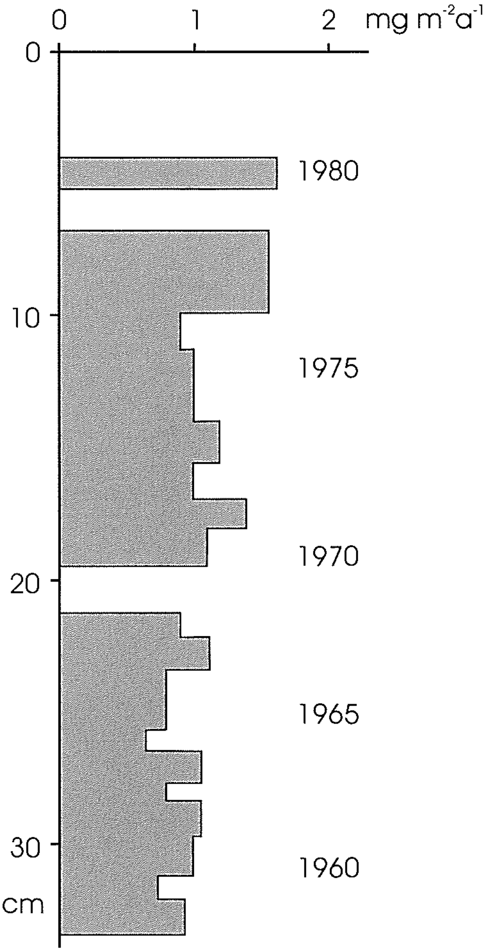


Fig. 57. Vertical distribution of mercury deposition in Nabbviken (Site 22) in 1958-1980.

Table 6. Mercury content in the bottom sediments of some water courses.

Water course	Hg ppm of dry weight background	 maximum	Source
Delta of the river Kyrönjoki	0.04	0.18	This study
Lake Ekoln	..	0.9	Axelsson and Håkanson 1973, 19
Lake Björken	..	1.1	Axelsson and Håkanson 1972, 39
Lake Vättern	..	0.03	Axelsson and Håkanson 1972, 39
Lake Michigan	0.04	0.2	Förstner 1976, 98
Wisconsin Lakes	0.24	1.12	Förstner 1976, 98
Lake Washington	0.1	1.0	Förstner 1976, 98
Lake Erie	0.04	0.48	Förstner 1976, 98
Välen	0.01	10.4	Cato 1977, 132
Baltic Sea	0.02	0.35	Niemistö and Voipio 1981, 90
Lake Polvijärvi	0.25	0.55	Simola and Lodenius 1982, 301
Lake Iso-Kontunen	0.14	0.2	Sandman and Simola 1983, 68
Lake Sysmäjärvi	0.08	0.8	Ahtiainen *et al.* 1983, 306
Bothnian Bay Oulu	0.1	171	Alhonen *et al.* 1973, 7-10
Bothnian Sea Pori	0.05	3.7	Alhonen *et al.* 1973, 12
Lake Tammijärvi	0.05	3.0	Alhonen *et al.* 1973, 18
Minamata Bay	..	630	Matida and Kumada 1969

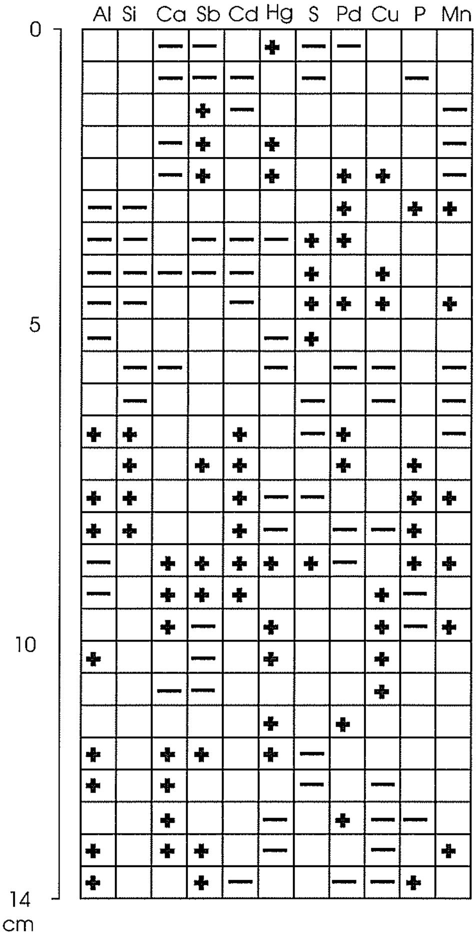
analysed area. The small content of some elements (e.g. Cd and Hg) makes it unreliable for calculating correlations due to the small number of observations. In four other analysed parts of the peel preparate the results were more unclear. The method has been applied to sediment with thin varves (Alapieti and Saarnisto 1981), and if the technique is developed, it would perhaps give better results also in sediments with thick laminae.

4.9 Trace layers

In addition to the easily distinguishable peak contents of lead and copper, attempts were made to uncover widely distributed trace layers which could be used to analyse the sedimentation rates in different parts of the delta. DCA ordination of the content of organic matter and different elements in the long cores separated different cores in different groups, and no trace layers were detected. Differences between cores from different sites were greater than differences within the cores.

Table 7. Statistically significant correlation coefficients between the stripe point sums of the analysed elements in Fig. 58.

	Al	Si	Hg	Cd	S	Pb	Cu	P	Ca	Sb
Si	0.53**									
Hg	-	-								
Cd	-	-	-							
S	-0.70***	-0.62***	-	-						
Pb	-	-	-	-	-					
Cu	-0.42*	-	-	-	-	-				
P	-	-	-	-	-	-	-			
Ca	-	-	-	-	-	-	-0.42*	-		
Sb	0.40*	-	-	-	-	-	-0.44*	-	0.48*	
Mn	-	-	-	-	-	-	-	-	-	-



Al	Si	Ca	Sb	Cd	Hg	S	Pd	Cu	P	Mn
		—	—		+	—	—			
		—	—	—		—			—	
			+	—						—
		—	+		+					—
		—	+		+		+	+		—
—	—						+		+	+
—	—		—	—	—	+	+			
—	—	—	—	—		+		+		
—	—			—		+	+	+		+
—					—	+				
	—	—			—		—	—		—
	—					—		—		—
+	+			+		—	+			—
	+		+	+			+		+	
+	+			+	—	—			+	+
+	+			+	—		—	—	+	
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—		+	+	+				+	—	
		+	—		+			+	—	+
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+		+				—		—		
		+			—		+	—	—	
+		+	+		—			—		+
+			+	—			—	—	+	

Fig. 58. Layer analysis of the point distribution of different elements in EDS pictures of the sediment of Nabbviken (Site 22). The analysis has been conducted using a systematic floating strip sampling in the direction of the visible layers. The width of strips was 1 cm and interval of the middle of the strips 0.5 cm. In each strip the number of impulses for each studied element was counted. Statistically (t-test) very significantly (***) larger values than mean have been marked with + and smaller values with - .

The elements formed groups according to their ordination: zinc, copper, lead and iron seemed to have similar sedimentation patterns, as did calcium and phosphorus with each other. There was also a similar tendency in the sedimentation of manganese and cadmium. Mercury differs clearly from all the other elements (see Hallberg 1991), and none of the elements seemed to be strongly bound to organic matter (Fig. 60).

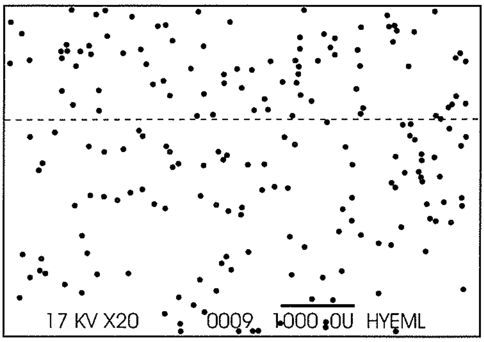

Fig. 59. Distribution of impulses for sulphur in an EDS picture of the sediment of Nabbviken (Site 22) in the winter and spring layers of the year 1965. The dashed line shows the boundary between the layers. The size of the area in picture is 4 x 6 mm.

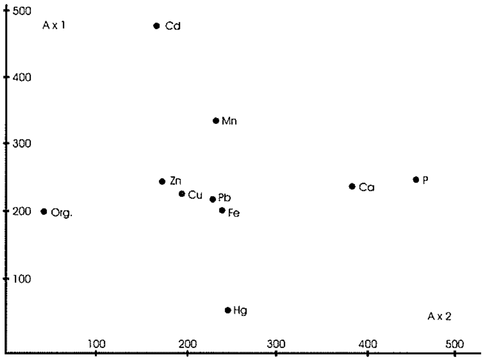

Fig. 60. DCA ordination of element content in the long cores (Figs. 49-54) from the delta of the river Kyrönjoki.

5 Discussion

5.1 Spatial differences in sedimentation

With increasing salinity (Calles 1983, Sundborg 1986), decreasing acidity and decreasing current the suspended solids are flocculated and deposited (Kranck 1984, Eisma 1986, Lick *et al.* 1992, Edelvang and Austen 1997). Therefore most of the suspended solids are deposited in the delta, and only a small proportion is transported further to the sea. In the outer parts of the delta resuspension of the sediment, caused by waves, gradually moves sediments further to the sea (Brydsten

1992). In the fine-grained sediment deposited in the outer part of the delta the content of organic matter and heavy metals is higher than in the more coarse sediment deposited in the inner part of the delta (e.g. Keulder 1982, 350).

Spatial differences in the surface sediments in the delta of the river Kyrönjoki are mainly dependent on five factors: 1) discharges of the river, 2) topography of the delta area, 3) differences in the salinity of the water, 4) differences in the acidity of the water and 5) land uplift. The salinity of the water in the different parts of the delta depends on the discharge of the river. During flood periods fresh water from the river stretches up to 30 km outwards from Pudimo fjärd to the sea. During mean discharge fresh water mixes with brackish water between Nabben and Storskatan, while during low discharge brackish water pushes up to Vassor Bay (Meriläinen 1985). The acidity of the river water is mainly caused by human factors, especially cultivation of the sulphide-bearing Litorina clay plains along the lower stretches of the river (Alasaarela 1982, Storberg 1983). When fresh water from the river Kyrönjoki is mixed with brackish water in the delta, salinity of the surface water increases outwards from the river up to 4 per mille in the outmost parts of the delta (Hudd *et al.* 1984, 4-5, Meriläinen 1985).

The river water is very acid due to the sulphide-bearing clays along the river. Many constituents excluding mercury compounds are dissolved in the acid water. When the river water is mixed with brackish water in the outer part of the delta, its pH rises, and some of the dissolved compounds are precipitated and deposited.

Due to acidity and high content of decaying organic matter the sedimentary conditions are strongly reducing in the inner part of the delta. The oxygen content in the river water is continuously high (Meriläinen 1984b). Thus, a lack of oxygen is not the reason for reducing conditions excluding the deep of Nabbviken where there is a more or less constantly anoxic saline hypolimnion. Benthos is very scarce in the inner part of the delta (Meriläinen 1984a), and bioturbation of sediment is not significant. Changes in discharge cause continuous deposition and resuspension of particulate matter. In the outer part mainly dominated by brackish water (Meriläinen 1985), the pH is clearly higher. Sedimentary conditions are mainly oxidizing. There is a rich benthos (Meriläinen 1984a), and bioturbation of the sediment is strong. Therefore, in most parts of the delta it is difficult to determine sedimentation rates accurately.

5.2 Sedimentation rates

Sedimentation rates in the delta of the river Kyrönjoki have clearly decreased from the rates in the 1950s, especially from 1970. Also the variation between years has decreased. Instead, the accumulation of organic matter has been relatively stable over the whole observation period 1931-1983, for which accumulation rates have been calculated. In this study it was not possible to determine pre-human sedimentation rates. Thus, only changes caused by different human activities have been studied.

The decrease of about 50% in bulk sedimentation rates is mainly due to the construction of the reservoirs in Pitkämö in 1971, Kalajärvi in 1974 and Kyrkösjärvi in 1981 (Mansikkaniemi 1982, Sundborg 1992). It corresponds well to observations of suspended load in northern Swedish regulated rivers (Nilsson 1976, Brydsten *et al.* 1990, 174, cf. Brandt 1990). In tropical Central America up to 80% trap efficiency for a reservoir has been detected (Sundborg 1992). A great deal of the sediment leached from the upper courses of the tributaries of the river is now accumulated in reservoirs. Especially coarse suspended solids are deposited in reservoirs. Fine-grained organic matter with a low density is driven through the relatively small reservoirs and mainly deposited in the delta as earlier, before the regulation of the river (see also Brydsten *et al.* 1990, 175). In the delta, the organic suspended solids are deposited as flocs with the increasing salinity, pH and biological activity (e.g. Calles 1983). According to Eisma (1986) and Lick *et al.* (1992) the formation of flocs is very complicated and cannot be explained only by the variation in salinity. Eisma (1986) points out that there are also biological factors that keep particles together. He considers the glueing effect of mucopolysaccharides produced by bacteria as the most important factor in aggregation.

In strongly humic water originating from mires Ca^{2+} has been found to be a very effective cation to coagulate dissolved Fe, Al and humic compounds (Eckert and Sholkowitz 1976). According to Sholkowitz (1976) inorganic trace elements behave similarly to organic matter in fresh water by complexation, chelation and adsorption. They are deposited together in aggregates formed in the mixing of fresh water and sea water. Therefore the mixing of humic water with brackish water in the delta causes the deposition of dissolved organic compounds, and probably explains why the estimated sedimentation rates in this study are higher than the measured discharges of suspended solids (Meriläinen 1986) and also explains the high content of trace metals in the outer part of the delta.

From the 1960s forestry drainage of mires, and from the 1980s maintaining of ditches , in addition to peat mining from the 1970s, have increased the leaching of suspended organic matter, replacing the amount deposited in the reservoirs (see Kenttämies 1981, Seuna 1982, Sallantaus 1984, 1988). Most of the increase in inorganic suspended solids is obviously deposited in the reservoirs.

The high sediment accumulation rates in the 1950s are evidently due to large land reclamation works in agricultural areas, mainly along the river. Also clearing of the river channel and simultaneous flood periods have probably caused erosion in the river banks and increased the accumulation of inorganic material in the delta. In the 1970s, however, a connection between works in the river channel and sedimentation rates in the delta could not be observed. A probable reason for this is improved methods in the clearing: avoiding excavation below the water level and right before spring flood periods.

The delta of the river Kyrönjoki moves gradually towards the sea due to land uplift and sediment accumulation. The influence of both factors is of the same order of magnitude and causes a two centimetre shallowing of the water in the estuary annually. For example, the maintaining of a boat harbour in Nabbviken Bay will demand dredging of the threshold of the Bay. The actual river channel will erode during flood periods and becomes deeper than at present.

5.3 Sediment stratigraphy

The concentrations of organic matter, lead, copper, zinc, cadmium and mercury are considerably higher in the surface sediment than in deeper layers. This is the case especially in sites where disturbance due to current or waves is of minor importance (sites 22, 30, 38, Figs. 53, 54 and 56). Instead, in disturbed sediments such a succession does not exist (sites 21, 23, 48, Figs. 51, 52 and 55). The increased content is mainly due to increased intensity of agriculture and forestry, especially forestry drainage of mires, and atmospheric deposition. The increase in cadmium content is mainly due to the usage of phosphate fertilizers (Hartikainen 1979, 330, Hutton *et al.* 1987, 40). The general increase in lead content is probably due to atmospheric fallout (Davis *et al.* 1984), at least partly caused by the use of lead-containing fuel in cars using the roads beside the river. Lead deposition does not seem to be bound to organic matter (Tables 4 and 5). Thus leaching from peat, forest soils of arable fields is not probable.

The intensive agricultural use of sulphide-bearing Litorina clay plains along the river seems to increase the leaching of most of the analysed heavy metals and added to their accumulation in the delta sediments (Alasaarela 1982, 12). Disposal of sewage or waste waters from industry cannot in general be separated from other sources of heavy metals or nutrients. Only the increase of copper content in the surface sediment is probably due to the usage of wood preservatives in Kestopuu Ltd. in Ilmajoki. For example the decrease in phosphorus content in the river water by 25% due to the establishment of sewage refinery in Seinäjoki in 1979 (Storberg 1983, 14) cannot be seen in the sediment stratigraphy because of the mobility of phosphorus in the sediment towards the surface (Callender 1982, 433).

The leaching of mercury from soil and its deposition in the delta is increased by human activities, especially the ditching of mires and construction of reservoirs (Verta 1990). Also atmospheric deposition has increased mercury content in sediments (Moore & Ramamoorthy 1984).

6 Conclusions

Due to land uplift and accumulation of sediment, the delta of the river Kyrönjoki is continuously moving towards the sea. The total influence of approximately 2 cm in a year will theoretically result in the filling of the Vassorfjärden Bay by the year 2030. Due to the dense vegetation in the Bay the development will probably be even faster. Also in Söderfjärden and Österfjärd the wide bays will disappear, and within 50 years also Nabbviken will be separated from the delta as a glo lake. The actual narrow river channel which now extends to Mälsor will stretch to Fransesgrundet approximately in 2030.

In the delta, the inner part of the delta will move towards the sea so that reducing conditions in the bottom will be prevailing in Pudimo fjärd and Peuskofjärden within a few decades. The oxidized sediments will be covered by reduced layers, which probably will decrease the bottom fauna (Meriläinen 1989).

There will not be major changes in the sediment quality from those of the early 1980s. Maintaining the ditches in drained mires causes continuous leaching of suspended solids and humic substances in the river system as well as the continuing peat mining during the first decades of the next millennium. Because most of the water construction works in the Kyrönjoki drainage basin have already been done, the transport of inorganic matter from the river channel will gradually decrease. Leaching of phosphorus from agricultural areas will not decrease drastically, and eutrophic conditions will prevail in the delta (see Ekholm 1998).

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