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A long-term record of human impacts on an urban ecosystem in the sediments of Töölönlahti Bay in Helsinki, Finland

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Summary

Ecological impacts of urbanization are receiving increasing scientific attention, yet few data sets permit long-term effects on terrestrial and aquatic ecosystems to be assessed. Töölönlahti Bay, in the centre of Helsinki, Finland, provided on opportunity to characterize recent human impacts especially by means of chemical and biostratigraphical analyses of a sediment core. Periods of coniferous forest, forest clearance, urbanization and the development of parks, can be distinguished in the pollen record of the core. Palynological diversity was highest before the forest clearance at the turn of the century. The character of the sediment and the water have changed substantially in response to rapid population growth, the construction of sewage systems and building within the catchment of the bay. This is reflected in marked increases in organic matter, phosphorus and heavy metal (Cd, Cu, Ni, Zn and Pb) concentrations between 1890 and 1960, accompanied by a rapid increase in diatom species indicative of eutrophication and a decline in diatom species diversity.

Since the cessation of waste-water disposal in the 1960s, concentrations of a number of pollutants have declined and water quality has gradually improved, but conditions are still affected by internal and atmospheric loadings. As a consequence of land uplift (2 mm per year) and the rapid sedimentation rate (6 mm per year), the volume of the bay is decreasing. Within 200 years, the shallow bay, which is skirted by extensive parks and famous cultural buildings such as the Finlandia and the Opera Houses, will fill with sediment unless it is dredged.

Keywords: urbanization, water pollution, geochemistry, vegetation history, diatoms, ecosystem disturbance, ecosystem recovery

Introduction

The bottom sediments of a water basin may serve as an archive of information on environmental changes (Haworth & Lund 1984). As lakes and rivers have only been monitored in Finland since the 1960s, many of the changes associated with the natural dynamics of these ecosystems and the longer-term effects of human activity are unknown. Indirect data obtained from geochemical and microfossil analyses of bottom sediments regarding earlier events, perhaps stretching back hundreds or even thousands of years, are therefore of particular significance (Håkanson & Jansson 1983; Elliot 1990; Smol 1992; Anderson 1993; Charlesworth & Foster 1993; Walker *et al.* 1994). One of the reasons why information on earlier events is of such importance is that it can be used to distinguish human interference from natural developmental processes.

The most pronounced and rapid environmental changes have taken place in urban areas, where the natural environment has been replaced by an environment of human creation. Earthworks, buildings, waste-water disposal, the construction of power stations and industrial activities, taking place in the catchments of urban lakes and rivers, may all contribute to enhanced sedimentation and reduced water quality (Foster *et al.* 1991; Charlesworth & Foster 1993). However, the construction of artificial channels and causeways, the filling in of water areas and, above all, dredging of rivers and lakes often make it difficult to find long, undisturbed sediment records from urban environments for palaeoenvironmental analyses. It is partly for this reason that comparatively little research has been carried out to date into long-term environmental change in urban areas, even though information on such changes would be of relevance to many people. The Greater Helsinki area, for instance, houses about one-fifth of the total population of Finland.

Our work is concerned with the history of Töölönlahti Bay and its surroundings, which we investigated using a number of methods. Töölönlahti is the only basin in the centre of Helsinki which has not yet been dredged or filled in. Our work has focused on the formation of the Bay as a result of shoreline displacement and reinforcement, urbanization of its catchment, and developmental processes operating in the basin itself, as reflected by the geochemical and microfossil stratigraphy of the sediments. Results regarding the diatom and pollen stratigraphy have been discussed in Korhola & Blom (1996) and Seppä (1997). This paper provides an overall account of the environmental history of Töölönlahti Bay and factors contributing to it. The bay and its surroundings can be regarded as the most important recreation area in the centre of Helsinki.

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Material and methods

Old maps and other historical sources were consulted to determine the settlement history of the area, land-use changes, water quality and sedimentation (Hornborg *et al.* 1950; Sundman 1980). Two parallel sediment cores were taken, down to a depth of 450 cm, from the deepest point of the bay, with a Russian peat sampler (Jowsey 1966), and a Limnos gravity corer was used to obtain samples from the sediment surface. The cores were cut into 1 cm slices down to a depth of 100 cm, and the slices and the rest of the core were packed in plastic sheeting and stored at 4°C (277K). The location of the sampling site is shown in Figure 1. Data on the stratigraphy of the bottom sediments below 450 cm are based on corings carried out by the Geotechnical Department (1989).

The organic content of the sediment was determined by loss on ignition (LOI) at 550°C (823K) for 2.5 h, and the upper part of the core was dated by the ^{137}Cs, ^{210}Pb and spheroidal carbonaceous particle (SCP) methods (Goldberg 1963; Oldfield 1987; Rose 1990). Concentrations of heavy metals, alkaline and alkaline earth metals were determined from wet digested samples (HNO_3 – $HClO_4$ – H_2SO_4) by atomic absorption (AA) spectrophotometry. Total phosphorus was determined spectrophotometrically using the ammonium-molybdate blue method (Enell & Larsson 1986) at intervals of 1 cm to a depth of 100 cm. Concentrations were normalized by dividing the values by the lithophilous aluminium concentration, which reflects changes in the rate of erosion (Finney & Huh 1989; Windom *et al*. 1989; Norton *et al*. 1992; Owens & Cornwell 1995). The geochemical data were processed by principal component analysis (PCA), performed using the STATGRAPHICS V 5.0 statistics programme (Statistical Graphics Corporation, USA).

Pollen and diatom analyses were carried out on sediment samples in order to examine changes in vegetational history and water quality. Pollen slides were prepared by the standard method (Fægri & Iversen 1989). Terrestrial plants were calculated as percentages of total terrestrial plants (ΣP), and aquatics as percentages of total terrestrial and aquatic plants (ΣP + ΣAqua). Pollen taxonomy followed that of Moore *et al.* (1991), and pollen were identified using Moore *et al*. (1991) and Reille (1993). Subsamples for pollen counting were taken at intervals of 2 cm, 4 cm, or 8 cm in the basal part, down to a depth of 130 cm, and a total of 500–1100 pollen grains and spores were counted in each sample. Trends in vegetation diversity were examined by rarefaction analysis (Simberloff 1979; Birks & Line 1992) using the computer programme RAREPOLL (Birks & Line 1992).

Diatom slides were prepared by H_2O_2 treatment with decanting. Core was sampled at intervals of 3 cm down to a depth of 70 cm, and approximately 400 frustules were counted for each sample and identified to species by reference to the standard literature, employing the nomenclature of Hartley (1986). The diatom stratigraphy was zoned using the

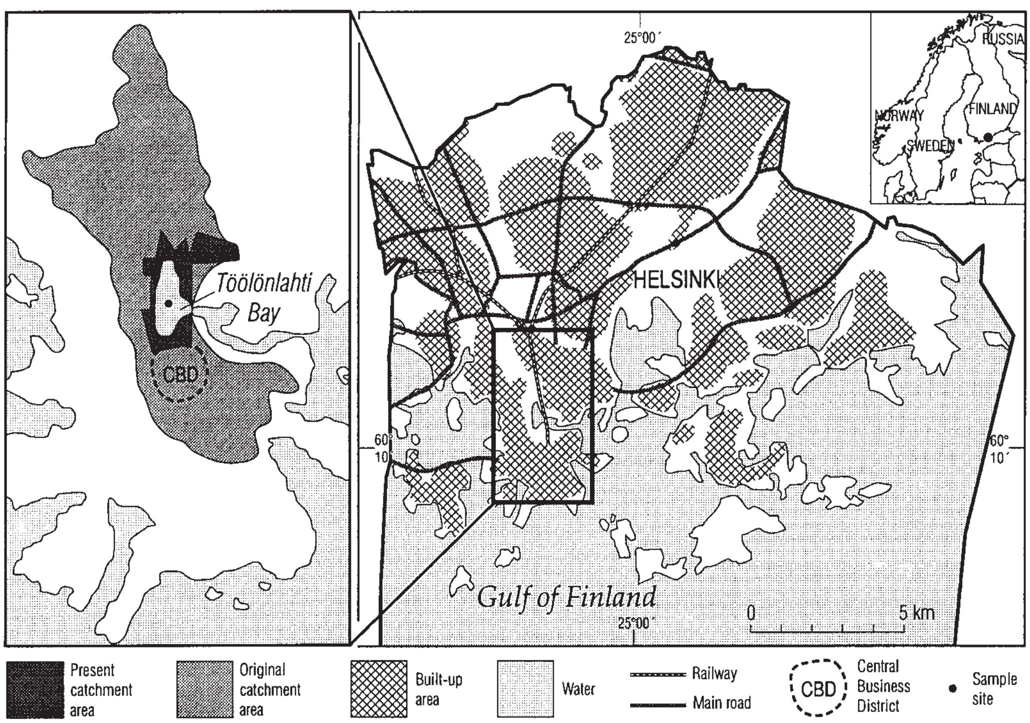

Figure 1 Location of Töölönlahti Bay and its catchments.

programme ZONE (Lotter & Juggins 1991) which segments the stratigraphic material on the basis of six alternative grouping techniques. Variations in the diatom flora were analysed by detrended correspondence analysis (DCA), using the programme CANOCO, Version 3.12 (ter Braak 1990).

The Töölönlahti area and its long-term history

The Töölönlahti Bay of today is a lagoonal inland bay, just over 2 m in depth, with an area of 20 ha. It is linked to the Baltic Sea by a bridged opening in the railway embankment, which borders the bay, and narrow channels that extend from this opening (Figs. 1 and 2). The original catchment area of approximately 5 km^2 has been reduced by the diversion of sewage water elsewhere, so that it now gathers runoff water only from an area of 0.4 km^2. The bay and its immediate surroundings have undergone major changes over the last two centuries, particularly with the spread of urban settlement to the Helsinki peninsula and the shores of the bay itself. By contrast, the process of land uplift has been going on for thousands of years, leading first to the formation of islands around the bay and finally to the creation of a peninsula extending out into the Baltic Sea.

Once the sound extending westwards from Töölönlahti had dried up around 1800 years ago, the only channels connecting the bay with the Baltic Sea were those leading to the east and south-east, the latter of which was closed some 500 years ago as a result of land uplift (Tikkanen *et al*. 1996). The current rate of land uplift is 2.1 mm per year (Kakkuri 1990). The area of Töölönlahti Bay was reduced artificially in the 19th century, by filling in the shallow south-eastern part, and the turnover of water in the bay was impaired substantially by the construction of a railway embankment across it in the early 1860s. Almost completely isolated from the sea, sedimentation could take place under less disturbed conditions.

Although there was some settlement in the catchment area of Töölönlahti Bay by the 16th century at the latest, the number of inhabitants living close to it remained small for a long time. Helsinki still had only 3000 inhabitants at the beginning of the 19th century, and settlement was concentrated at the southern end of the bay (Sundman 1980). However, large areas of fields and meadows had been cleared on the low-lying land around its shore by the beginning of the 18th century, and these were expanded further in the course of the 18th and 19th centuries. No extensive building or rapid increase in population took place in the surroundings of the bay until the late 19th and early 20th century, and the northern part of the catchment was developed only in the decades following the Second World War (Figs. 3 and 4). Nowadays the centre of Helsinki, which borders the bay, has some 180 000 inhabitants out of the city's total of 530 000.

Figure 2 A view from northwest over Töölönlahti Bay. The dark opening in the embankment on the opposite side of the bay marks the connection with the Gulf of Finland. Photograph: M. Tikkanen.

The growing population and urbanization led to increased amounts of waste water being conducted into the bay, initially via open ditches. Impacts of the effluents were compounded by waste disposal from a sugar refinery that moved to a site on the shore of the bay in 1823. The first enclosed sewage pipe leading into the bay was completed in 1878, and the water had become substantially polluted by the beginning of the present century (Enkvist 1974). Two waste-water purification plants located close to the bay discharged waste water into it, but a gradual reduction in loading was observed when the effluents were diverted elsewhere and the sugar refinery

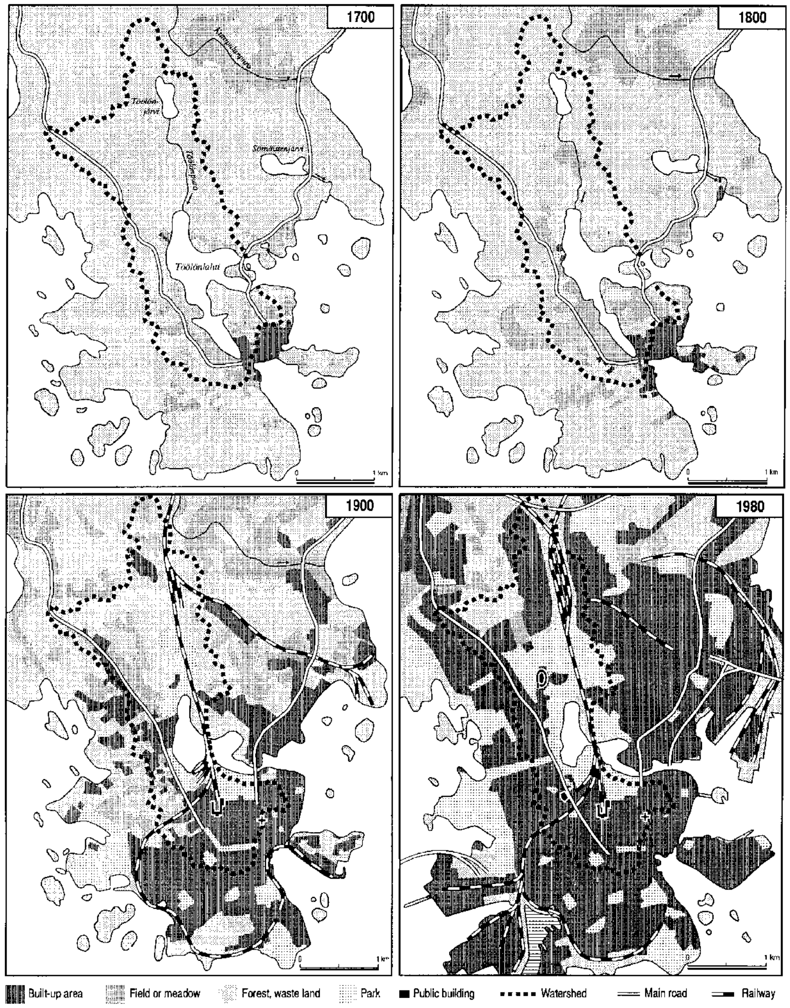

Figure 3 Changes in land use in the vicinity of Töölönlahti since 1700.

was closed in 1965. Today, waste water enters the bay only through occasional overflows or by seeping through leaks in the sewerage system. Although its quality has improved slightly in recent times, the water is still nutrient-rich on account of internal loading, sewage and urban runoff and the long replacement times of water in the basin.

Results and discussion

Stratigraphy

The Töölönlahti basin is located at an intersection of bedrock fractures, which has led to pronounced erosion of the bedrock as it fragmented as a result of tectonic movements. Drillings indicate that there is an extensive area over which solid bedrock is reached at a depth of only *c*. 30 m (Geotechnical Department 1989). The bedrock is overlain by several metres of till and sand, the thickest sand beds being located on the western edge of the basin where there is a small esker buried beneath clay layers. Most of the subaquatic sediment consists of clay and clay-gyttja, which reaches a thickness of over 20 m in the central and southern parts of the bay (Fig. 5*a*).

The 450 cm sediment layer examined in the laboratory was composed of clay-gyttja with a consistent LOI of 8–11% continuing from the bottom up to a depth of 60 cm, above which the LOI begins to rise towards the surface layers, varying in the range 12.5–20.1% at depths of 56–23 cm (Fig. 5 *c* and *e*). The rapid urbanization in the catchment at the time represented by these deposits is reflected in the presence of light-coloured mineral-rich streaks and temporary drops in LOI values, which stabilize at around 13-14% in the uppermost 23 cm of sediment.

The basic colour of the upper sediment layer, which is 95 cm deep, is dark grey, becoming slightly lighter at the very surface. Black clay-gyttja is encountered at depths of 95–200 cm, having been laid down under anoxic conditions on the bottom of the shallow bay. Black sulphide clay-gyttja streaks occur to varying extents down to 350 cm, after which the sediment assumes a lighter colour, changing to a homogenous light grey clay-gyttja from 390 cm downwards (Fig. 5*b*).

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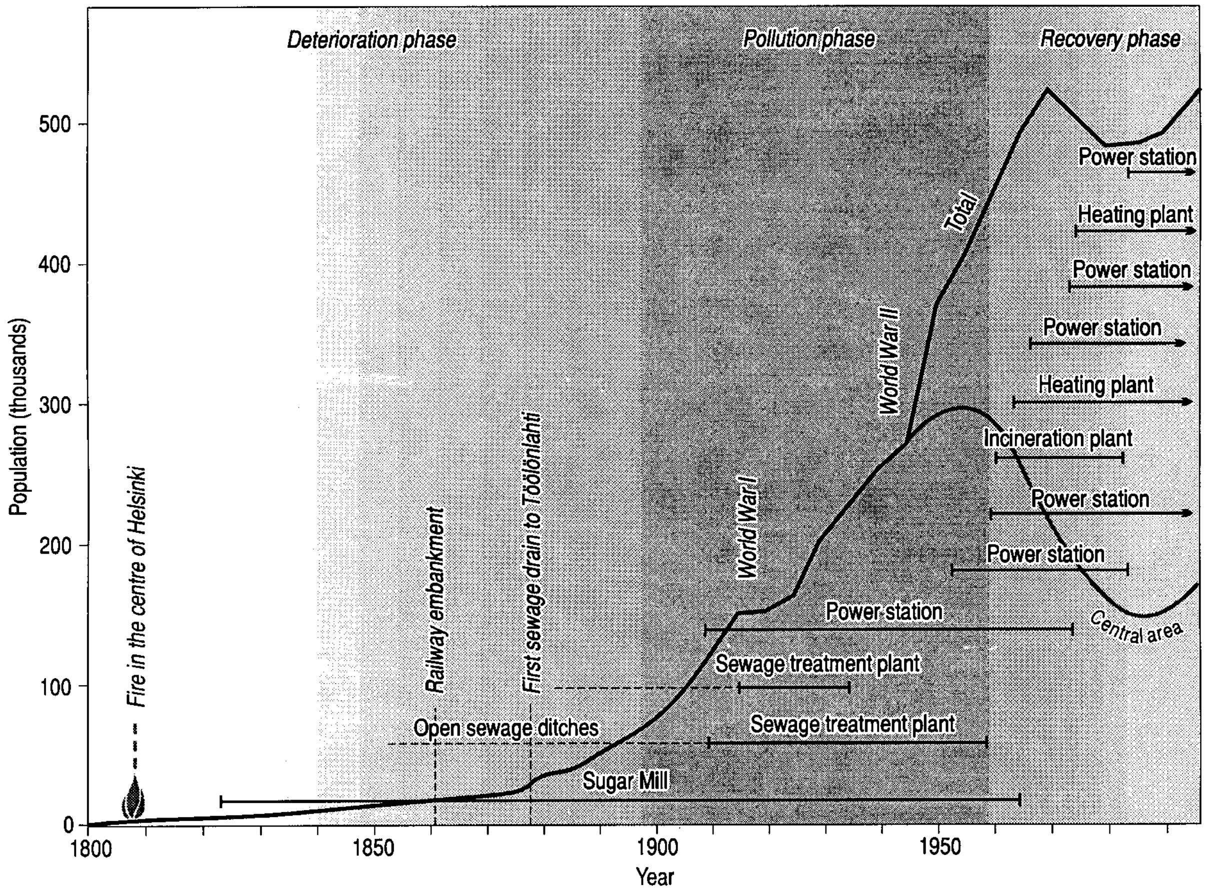

Figure 4 Events occurring in the vicinity of Töölönlahti from 1800 onwards and trends in the population of Helsinki. Lower curve (post 1940) denotes situation in city centre; upper curve in whole city. The intensity of the shading represents the supposed severity of pollution.

Chronology and sedimentation rate

Radioactive ^{137}Cs nuclides are found in the surface sediment from a depth of 30 cm upwards (Fig. 5 *d*), the activity peak encountered at 25–26 cm being attributable to the atmospheric nuclear tests of the 1960s, which caused substantial fallout, especially in 1962–1964 (Rowan *et al*. 1993; Walling & He 1993). The peak observed at 8–9 cm is most probably connected with the Chernobyl nuclear accident in 1986.

The analyses of SCP are well in line with the ^{137}Cs dating results. Small quantities of these products from the combustion of fossil fuels begin to occur in the sediment from 54 cm upwards and their abundance rises significantly from 37 cm upwards, with a very rapid increase to many times the previous values in the interval 27–24 cm (Fig. 5 *f*). This sudden rise reflects the rapid expansion in the use of fossil fuels which took place in Finland at the beginning of the 1960s (Tolonen *et al.* 1990). In the Töölönlahti area large power stations were constructed in Helsinki at this time (Fig. 4). The decline of the SCP levels in the near-surface sediments, despite a continued increase in fuel consumption, can be attributed to improved filtering techniques employed in the power stations and the introduction of a district heating system.

The dates obtained are again supported by changes in the loss-on-ignition curve, which probably reflect the major fluctuations that have taken place in the water quality in the bay and in the land use of its catchment. As will be suggested later in this paper, the dates are also supported by the increase in the amount of pollen produced by park vegetation, e.g. *Aesculus hippocastanum* and *Salix*, at approximately 30 cm depth in the pollen stratigraphy.

The ^{210}Pb and radiocarbon dates proved problematic, however, in that the activity profile obtained from the former was highly irregular, with high values even at a depth of 140 cm, apparently due to the rapid sedimentation and vertical migration of the nuclide. The radiocarbon dates recorded for depths of 150 cm, 250 cm and 350 cm in the stratigraphy were in the range 1950–1650 ± 100 years before present, with the youngest at 350 cm. This may be explained by contamination of the upper samples with older sediments washed off the slopes in the course of land uplift and field clearance.

While the average accumulation rate for the 25 m of sediment laid down during the 12 000 years since the Ice Age is 0.2 cm a year, the dates for the surface samples suggest that some 55 cm of sediment has accumulated in the 20th century, giving an average sedimentation rate of some 0.6 cm per year.

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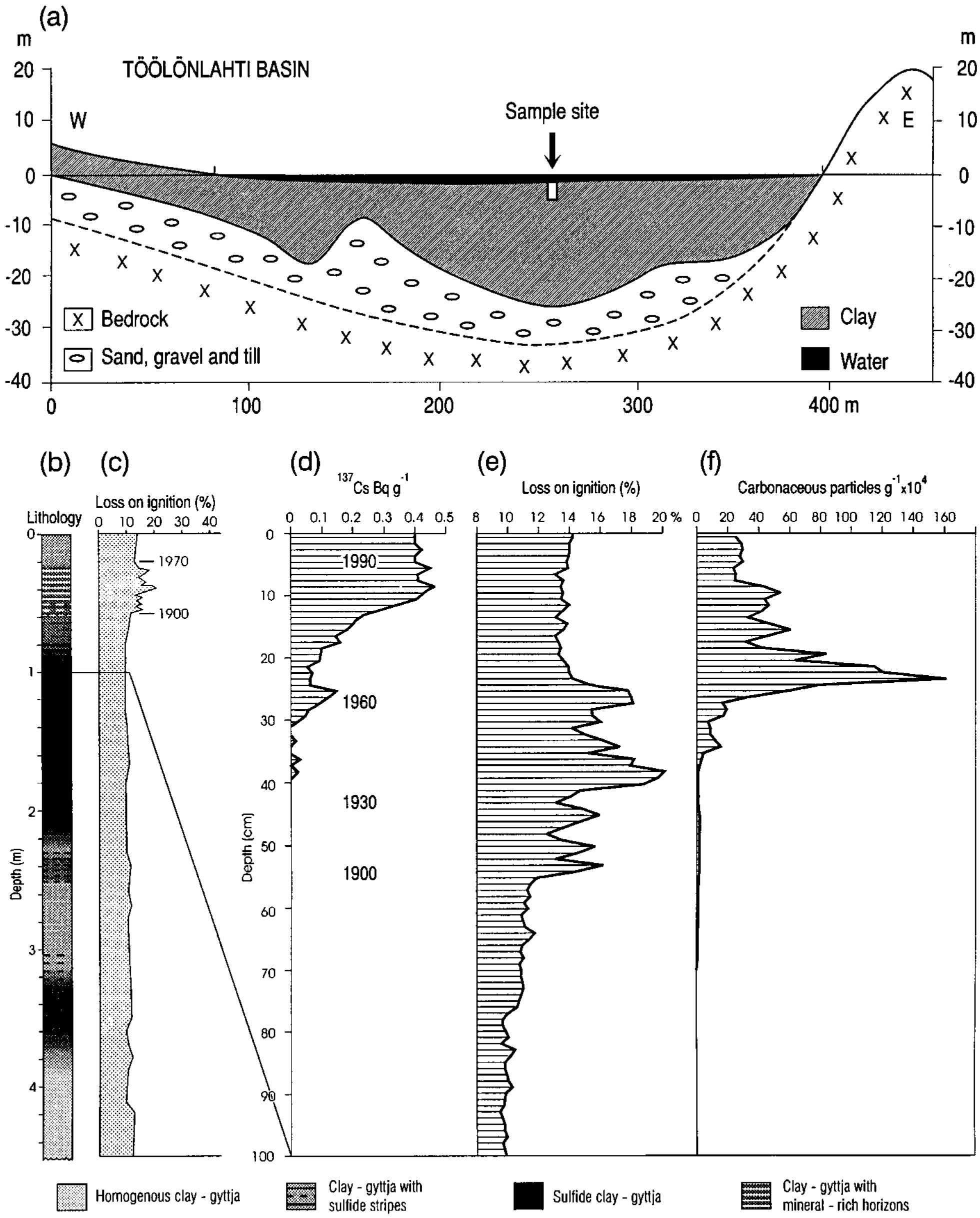

Figure 5 (*a*) Cross-section of the Töölönlahti basin from west to east, (*b*) sediment lithology, (*c–f*) loss on ignition and dating.

Geochemistry

The geochemical changes observable in the near-surface sediments evidently reflect the effects of urbanization under the sedimentological conditions prevailing in the bay. A major rise in concentrations of cadmium, copper, zinc, phosphorus, nickel and lead (Fig. 6 *a–f*), can be traced to around the turn of the century, when the bay is known to have already been polluted by waste water. The same point is also reflected in the diagram for the principal components analysis (PCA), in that the second principal component divides the samples into two horizons at a depth of approximately 58 cm (Fig. 7), the depth at which phosphorus, for example, reaches its peak level. The highest concentrations of Cd, Cu, Zn, P, Ni and Pb are recorded in the depth range 60–25 cm, i.e. they can be dated to 1890–1965. This is particularly evident in the case of the heavy metals capable of giving rise to organometallic compounds, which constitute a group of their own in the PCA-plot and are closely intercorrelated (Fig. 7).

Although the sedimentation of mineral material as a consequence of erosion has declined in the last century, it has been largely replaced by material accumulating as a result of waste-water loading and air pollution. The diversion of purified waste water away from the bay and the closure of the sugar refinery in 1965 are reflected in lower LOI values. The solid matter transported into the bay in the waste water contained large quantities of Cd, Zn, Cu, Pb, and P, which would appear from the PCA results (Fig. 7) to correlate positively with the LOI (Hart 1982; Salomons *et al.* 1987; Finney &

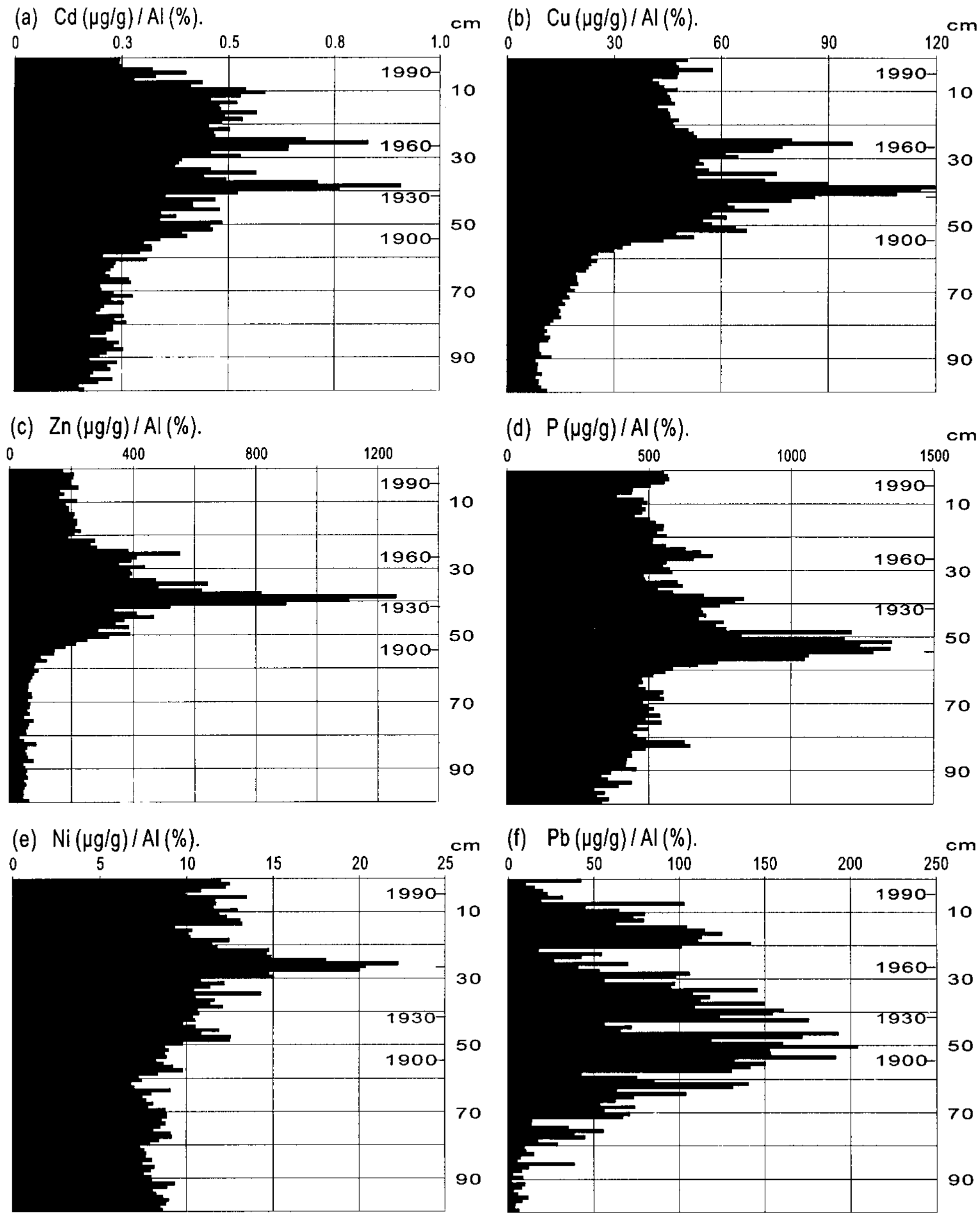

Figure 6 Normalized concentrations of (*a*) cadmium, (*b*) copper, (*c*) zinc, (*d*) phosphorus, (*e*) nickel and (*f*) lead (dry weight), analysed at centimetre intervals.

Huh 1989; Windom *et al*. 1989). However, concentrations well in excess of those observed a century ago were recorded for copper, zinc, lead, and particularly vanadium, in the surface sediment, evidently on account of deposition from the air.

Snow is dumped in the sound connecting the bay with the Baltic Sea during the winter, and as the area where this takes place is dredged in the summer, substances derived from the sediments released from the snow may be transported and deposited in the bay. Similarly, periods of anoxia that affect the bay will have caused a shift in redox potential towards reducing conditions, which will presumably have increased the solubility of redox-dependent compounds in existing sediments. Thus, the sediment may have become a source of internal loading, hindering the improvement in water quality despite the reduction in extended nutrient loads.

The effect of waste-water loading on the geochemistry of the surface sediments of the bay was so overwhelming in the past that it is difficult to estimate the degree to which the element concentrations could have been affected by atmospheric loading (Dorten *et al*. 1991; Schmidt & Reimers 1991; Paalman *et al*. 1994). High concentrations of lead, which are encountered at depths of 20–16 cm in the sediment, reflect traffic emissions in the 1970s (Owens & Cornwell 1995; Smith & Flegal 1995). The higher lead concentrations observed at greater depths must have been caused by the extensive waste-water loading dated to the early part of the century.

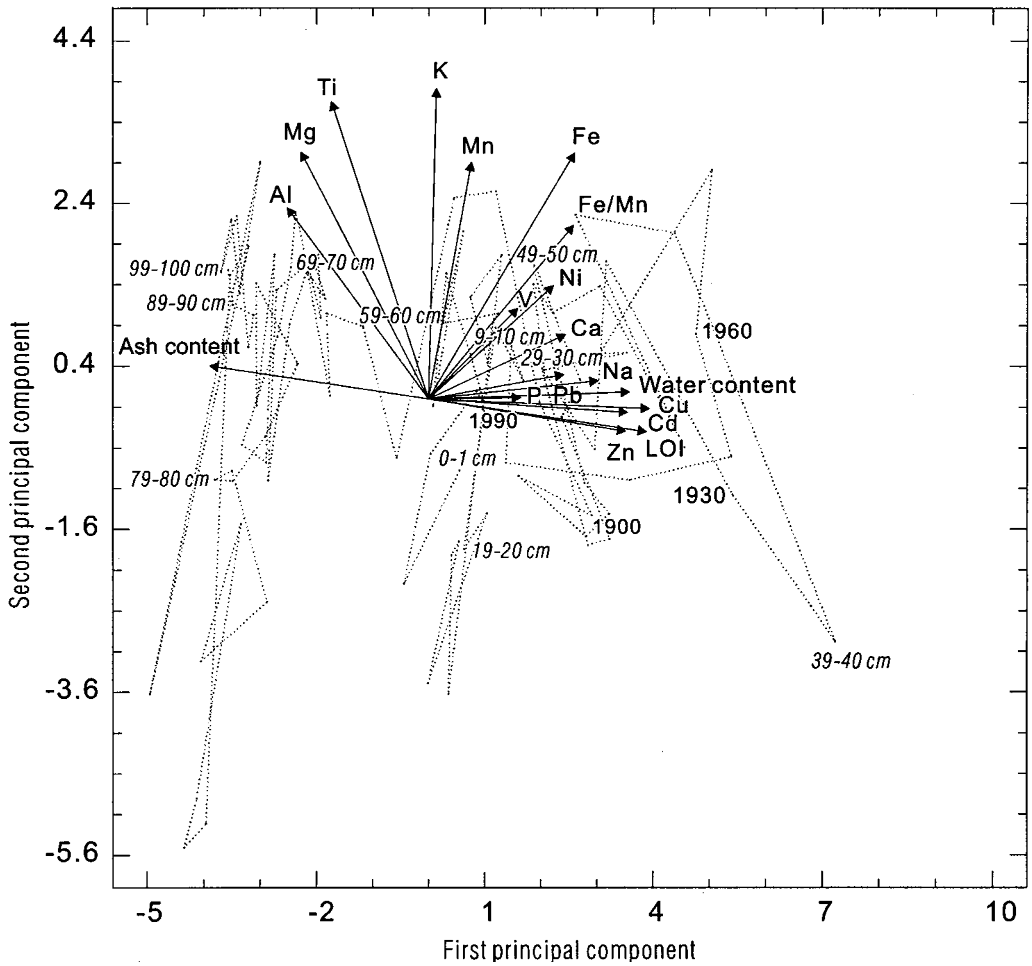

Figure 7 Diagram representing the results of principal component analysis (PCA) of the total material.

Vegetation history

Four pollen assemblage zones (PAZ) can be distinguished in the upper part of the Töölönlahti sediment (Fig. 8). The oldest, Töölö I, accounts for the time up to the late 18th century, prior to the rapid expansion of the city. During this time, pine and spruce were the dominant tree species on the Helsinki peninsula. Few indicators of human activity are present, and those that are encountered, notably spores of *Pteridium aquilinum*, and pollen grains of Cerealia, *Rumex*, Chenopodiaceae and *Artemisia*, point to small-scale grazing and grain cultivation around a centre located to the south of the bay. The Töölö II PAZ covers the period from the end of the 18th century to the beginning of the 20th century and is characterized by a decline in coniferous pollen, suggesting increased deforestation as the city expanded. This feature is accompanied by a rise in the proportions of anthropogenic indicators (*sensu* Behre 1981), with Ranunculaceae, Chenopodiaceae, *Rumex*, Apiaceae, Lactuceae, *Polygonum aviculare* type and *Artemisia*, for example, reflecting the spread of grazing, open fields, waste land and roadside habitats in Helsinki (Behre 1988; Gaillard & Berglund 1988; Peglar 1993).

The beginning of the Töölö III PAZ, datable to the beginning of the 20th century, is indicated in the sediment by a marked fall in the proportion of *Pinus* and the almost complete disappearance of the *Picea* (Fig. 8). This may reflect the decline in coniferous forests as a consequence of urban development. Particularly rapid urbanization took place in the early 20th century in the working-class residential areas east of the bay. Extensive felling carried out during the First World War will undoubtedly have accelerated the decline of the coniferous forests. On the other hand, planned, well-managed parks began to play a more important role in the urban vegetation from the turn of the century onwards, when new parks were established in the areas south of the bay in particular (Häyrynen 1994). The pollen data suggest that the oldest of these parks contained mainly deciduous trees, such as *Betula* and *Alnus*, that are native to Finland. The major rise observed in Gramineae in the Töölö III zone suggests local expansion of grasses close to the sampling site, probably as a result of the filling in of the shores of the bay and the creation of open areas in connection with urban development. The construction of the railway and the Helsinki marshalling yard in the late 19th century was a major factor increasing the numbers of ruderal plants, as suggested by the occurrence of the *Rumex* peak (4%) in this zone.

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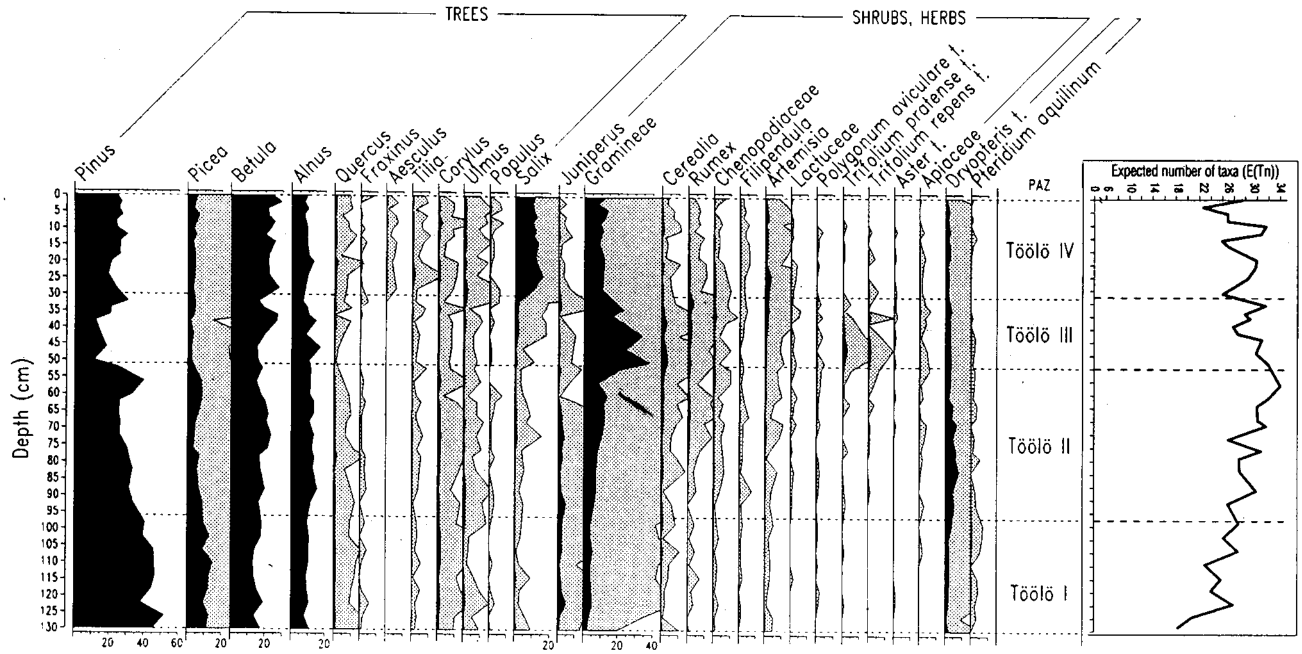

Figure 8 Pollen diagram for Töölönlahti, showing only the most common taxa. The black silhouette shows the percentages of each pollen taxa; the stippled sihouette indicates 10 × exaggeration for the less frequent taxa. Palynological richness, $E(T_{640})$, is shown on the right.

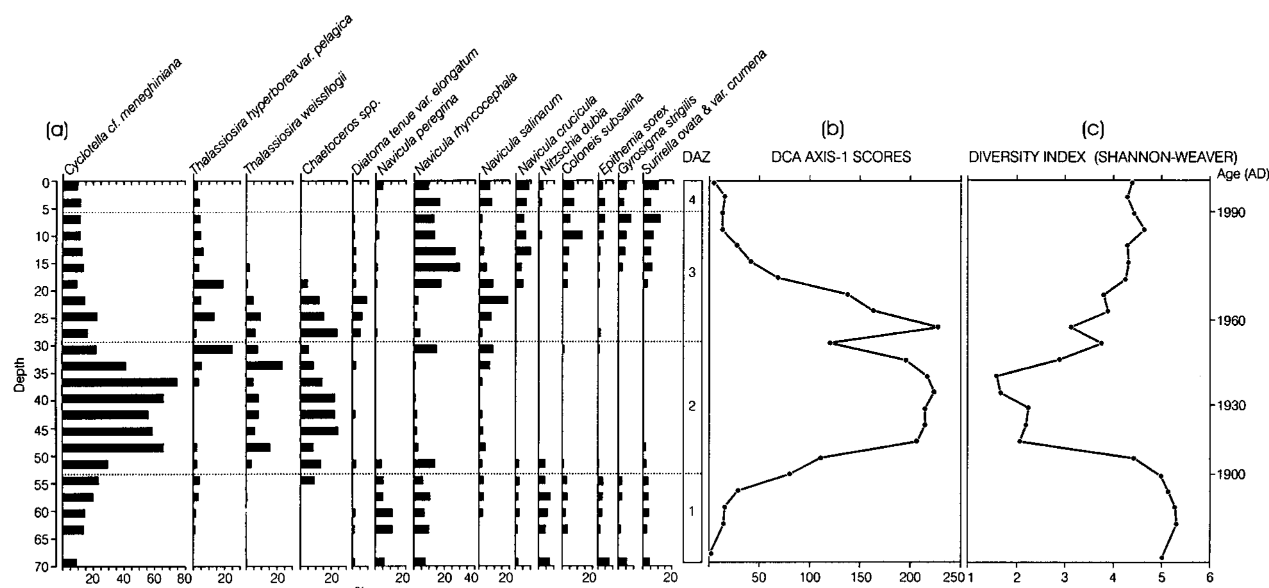

Figure 9 (*a*) Diatom stratigraphy of Töölönlahti, (*b*) sample scores on the first axis in DCA and (*c*) diversity of the diatom flora in terms of the Shannon-Weaver index. The vertical axis denotes depths of the samples in centimetres and the horizontal axis the main taxa (>5% at least one level) as percentages of all diatoms counted.

The youngest PAZ, Töölö IV, extends from the early 1950s to the present day and is dominated by the pollen of park species. A major rise in *Salix* values is recorded in particular, reflecting the planting of white willows, *Salix alba*, in the parks around the bay. *Aesculus* appears in Figure 8 at the same time as the rise in *Salix*: *Aesculus* is a popular park and garden tree in Helsinki. A number of ruderal taxa are found to decline in this zone, however, pointing to a decrease in the incidence of open, untended habitats during the second half of the century.

Increasing attention is being paid nowadays to the natural environment in urban areas, and in particular to the vegetation, with the preservation of biological diversity occupying a key position in the management and protection of such environments (Sukopp & Sukopp 1987; Gilbert 1989; Sukopp & Hejný 1990). Vegetation diversity is usually mark-

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edly higher in towns than in natural areas (Rebele 1994). The present pollen data can be used to examine long-term trends in this diversity, the most convenient method available for this being rarefaction analysis (Birks & Line 1992). The results indicate a relatively low diversity in the early parts of the pollen diagram but an increase with the growth of human activity. The highest diversity was achieved during the period covered by the Töölö II zone. The maximum values were recorded at the turn of the century, when settlement was spreading most rapidly in the areas close to the Bay (Figs. 4 and 8) but some of the original coniferous forests remained, and Helsinki possessed a variety of plant habitats. Moderate disturbance of vegetation may reduce competition between plant species and increase diversity (Peet *et al*. 1983). The peak in diversity recorded for the beginning of the century may well reflect both high within-habitat diversity and high landscape diversity, i.e. high alpha and gamma diversity (Whittaker 1965). Diversity declined after the end of the Töölö II zone on account of the more uniform habitats and increased management of green areas. This decline concerned not only the forests but also ruderal habitats, which often have a high alpha diversity. Most of the ground in Helsinki has been paved, and all forms of agriculture have now vanished. The vegetation of the area may be said to have become impoverished, as has happened, or is in the process of happening, in most other large cities (Rebele 1994).

Diatom analysis and water quality

The major changes which have taken place in the condition and water quality of the bay are also evident from the diatom stratigraphy in the sediment cores (Fig. 9*a*). Multivariate analysis (detrended correspondence analysis, DCA) indicates that the greatest change in the diatom assemblages occurred at a depth of approximately 60 cm, corresponding to the end of the last century (Fig. 9*b*). It is at this point that the previously dominant littoral forms, characteristic of shallow brackish water bays in the Baltic, were almost completely replaced by planktonic species, most notably *Cyclotella* cf. *meneghiniana*, which accounts for as much as 70% of total diatoms at its maximum. *Thalassiosira weissflogii* and *Chaetoceros* flagellates (Fig. 9*a*), which together with *C*. cf. *meneghiniana* are known to favour eutrophic environments (Krammer & Lange-Bertalot 1986–1991; Wendker 1990; Snoeijs 1993; Witkowski 1994), also increased. The increase in planktonic diatoms is associated with a reduction in diatom diversity values (Shannon-Weaver diversity index; Fig. 9 *c*), indicating, most obviously, system stress under the heavy perturbation. Diversity values begin to rise again from 30 cm upwards to the sediment surface, accompanied by a gradual decline in the proportion of planktonic species, which are once more replaced by littoral communities typical of shallow brackish waters.

The changes observed in the diatom communities, as represented in the sediment, may be linked with fluctuations in eutrophication and salinity in the water of the bay. Four diatom assemblage zones (DAZ) can be distinguished on the basis of cluster analyses and DCA (Fig. 9). In the first zone (DAZ 1), which continued up to the end of the 19th century, the bay was already nutrient rich, but its salinity was slightly higher than at present because of the broader channels connecting it with the Baltic. The bay became more eutrophic from the end of the 19th century until the 1960s (DAZ 2), and widespread algal blooms occurred (Enkvist 1974).

The gradual re-emergence of mesotrophic periphytic diatoms indicate that by the next zone (DAZ 3) the state of the bay had improved, since sewage was diverted from the bay in the 1960s. It is evident, however, that it was occasionally subjected to waste-water loading in the form of overflows from the sewerage system, at least until the 1980s. Although the state of the bay still cannot be regarded as good, it has undergone a slow recovery to the situation that prevailed prior to human interference. This is demonstrated by the fourth diatom zone (DAZ 4), in which the composition of the diatom flora and the proportions of the taxa are almost identical to those recorded for the lower part of the profile.

Conclusions

Töölönlahti Bay, which is located in a deeply-eroded bedrock fracture, is mostly filled with clay and clay-gyttja deposits and incorporates a local depression in which anoxic sedimentation conditions prevailed for a long period even before the appearance of human influence. The transport of material from the slopes during the formation of the bay and the effects of sea currents caused sufficient mixing of the sediments at that time. It was only the construction of the railway embankment in the 1860s that caused conditions to favour undisturbed sedimentation. This is reflected in the sediment stratigraphy, which records the environmental changes and problems connected with urbanization.

Three main phases connected with the process of urbanization in Helsinki can be distinguished in the recent history of Töölönlahti Bay, each covering approximately half a century (Fig. 4). In the first stage, the state of the bay deteriorated at an accelerating pace from the mid-19th century until the end of the century, on account of population growth and waste water loading. During the second stage, the bay was badly polluted with waste water. The third stage, which is still continuing, is marked by a gradual improvement in the state of the bay, resulting from reduced external nutrient loads, but recovery is being hampered by internal loading, animal faeces, long water-retention time and atmospheric deposition of pollutants.

A major problem for the future of the bay is the high sedimentation rate. This will, in time, reduce the volume of water contained in it and its surface area, and finally lead to its disappearance. Provided that the relation between sea level and land uplift is not altered markedly by the greenhouse effect, the bay will revert to a marshland and then become dry land within the next 200 years, unless preventive measures are taken. In fact, the only form of intervention that can save the bay and preserve it for a long time to come is dredging, to remove precisely those sediments that were studied here.

The present results agree with historical documents, and in this sense reinforce the claims that extensive information can accumulate in bottom sediments even in severely-disturbed urban environments, and that this information can be used to obtain reliable assessments of the long-term effects of urbanization on the vegetation and water bodies of urban areas. Such information is important for planning the management and restoration of urban ecosystems.

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