Abstract When dealing with lake restoration, we should bear in mind that inland water ecosystems are not static units but subject to continuous evolution. Palaeolimnological studies have helped us to understand the development of lakes and their catchments. In particular, the development of northern European lakes has been studied very thoroughly. It has been revealed that the initially high productivity of lakes (shown by sediment growth rate) was due to the leaching of nutrients from the nutrient-rich moraine after the last deglaciation. With time, however, lake productivity dropped as the supply of nutrients from the catchment area diminished. This reduction depended partly on the decreased leaching and partly on the development of terrestrial vegetation as it accumulated and recycled nutrients. In southern Sweden, the current sediment growth rate is about 0.2 mm per year in more-or-less-intact, shallow oligotrophic lakes, and about 0.5–1.0 mm per year in shallow eutrophic lakes. If a lake becomes polluted by the discharge of nutrient-rich sewage, the sediment growth rate can increase to about 10 mm per year. The ageing of lakes, and their potential terrestrialisation, depends on the balance between production and decomposition of organic matter. In northern latitudes, the break-down of organic matter in cold and oxygen-free sediment and peat is much slower than in warmer waters in the south where mineralisation processes take place at higher rates and over a longer period of the year. It is therefore much harder to prevent lakes in the north from being terrestrialised.

Keywords Lake evolution • Northern European lakes • Palaeolimnology • Sedimentation rates • Terrestrialisation

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2.1 Postglacial Evolution of Lakes and Wetlands

Inland water ecosystems are not static units but subject to continuous evolution. The speed of these changes is high in shallow, productive accumulation basins and extremely slow in deep, large, oligotrophic lakes. Palaeolimnological studies on ecological succession clearly demonstrate how important it is to take the time-factor into account when dealing with the restoration of systems that have been degraded and which then possess all the characteristics of rapidly ageing wetlands.

From the perspective of geological time, shallow lakes and inland wetlands are short-lived ecological units which become filled up with inorganic and organic material. During, and immediately after, the latest deglaciation of northern Europe, layers of minerogenic matter (i.e. mineral in origin) were deposited in depressions. Coarse particle fractions settled close to the shore beside the mouths of feeder streams, while clay and other fine particles settled further lakewards.

The landscape of northern Europe has been characterised by its original richness of lake and wetland basins produced by glacial action. By comparison, the region south of the glaciated area is poor in lakes. In northern Europe, former lake and wetland basins were cleaned of sediment and peat by glaciers; after deglaciation, starting from scratch, as it were, lakes developed in shallow moraine depressions with a minerogenic bottom. South of the glaciated area, tundra conditions had prevailed during the ice age; consequently, as a result of the frost erosion – cryoturbation – the topsoil layers resembled the moraine of the deglaciated region, as they were also largely unleached. Also, the processes in these soils, including the leaching of nutrients and the influence of the successively developing vegetation, corresponded to that found in the moraine-covered, formerly-glaciated part of Europe. The postglacial (Holocene) relations between catchment areas and lakes are therefore comparable in both regions. Because the developmental history of northern European lakes is so well known, the following description refers to these systems (cf. Digerfeldt 1972; Digerfeldt and Håkansson 1993). As to the origin of lake basins see, for example, Hutchinson (1957).

2.2 Development of Northern European Lakes

After deglaciation, the fresh moraine was generally rich in nutrients. These were subsequently leached and transported by water to the lakes, where they supported a high production of algae. In the sediment, the transition from minerogenic to successively more organogenic strata (i.e. organic in origin) reflects this course of events. In several lakes, the lowest and oldest organogenic sediment consists of algal gyttja deposited during a short period of high primary productivity in the lake but equally a low supply of organic matter from the surrounding areas. Even in regions which now have a typically oligotrophic character, the oldest layers can consist of algal gyttja and lake marl, sediment types in sharp contrast with the present-day leached and unproductive character of the lake surroundings.
After this initial phase of high productivity, lake productivity dropped as the supply of nutrients from the catchment area diminished. This reduction depended in part on the decreased leaching and partly on the development of terrestrial vegetation accumulating and cycling nutrients. However, during the Holocene of the last 10,000 years, changes in temperature, precipitation and vegetation cover have caused variations in the productivity of lakes. Along with the climatic changes, the water level of lakes has also changed, and this, in turn, meant either a lakeward expansion of the littoral macrophytic vegetation or its landward retreat and reduction (Digerfeldt 1972). At the same time, the sedimentation limit, i.e. the highest level up to which organic particles settle below the shoreline, has been dislocated downwards (due to erosion) during periods of low water and upwards (because of deposition) during high water periods.

In any individual lake, the location of the actual sedimentation limit is lower along those shores exposed to winds than along more sheltered shores. As prevailing winds are westerly in large parts of Europe during the ice-free season, the littoral zone is washed clean of organic particles down to a greater depth along eastern, wind-exposed shores than along sheltered, western shores where particles settle in more shallow, calmer water.

### 2.2.1 Growth Rate of the Sediment

The rate at which sediment thickness increases is dependent on the productivity of the lake itself, on the supply of matter from the catchment area, and the efficiency of the mineralisation in the lake ecosystem. Intact lakes, within previously glaciated regions, had the highest productivity and sediment growth rate during the first phase of their evolution (cf. Digerfeldt 1972; Digerfeldt and Håkansson 1993). After that, these processes were reduced at the same time as the leaching and supply of nutrients from the surroundings decreased (Fig. 2.1). The thickness of sediment varies from lake to lake as well as within the individual lake depending on the topography of its minerogenic bottom. The deposition of organic matter ‘flattens’ the bottom such that the thickest sediment is found in the deepest depressions of the minerogenic bottom.

The normal, average thickness of organogenic sediment in, for example, a south Scandinavian lake with an age of 12,000–13,000 years is about 5 m. In this region, the current sediment growth rate is about 0.2 mm or less per year in a more-or-less intact, shallow oligotrophic lake, and about 0.5–1.0 mm per year in a shallow eutrophic lake. If a lake becomes polluted by the discharge of nutrient-rich sewage, the balance between production and mineralisation is disturbed. Organic matter accumulates and the sediment growth rate can increase to about 10 mm per year. Thereby, the speed of ageing of a shallow lake is multiplied – as a result of the addition of an internal nutrient supply from the sediment added to that of the increased external loading (i.e. from the catchment area).
**Fig. 2.1** Lake Trummen, Sweden. Upper Diagram: Rate of sediment deposition. (The indicated rates during the Preboreal (PB) and Early Boreal (BO 1) periods are mean values.) Lower diagram: Radiocarbon dating of the sediment (From Digerfeldt 1972)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Number of sediment sample</th>
<th>Depth (m)</th>
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<tbody>
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<td>Boreal period</td>
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<td>B.P.</td>
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**Key**
- Rec. poll. = recent pollution
- SA = Sub-Atlantic period
- SB = Sub-Boreal period
- AT = Atlantic period
- BO = Boreal period
- PB = Pre-Boreal Period
- B.P. = before present
2.2.2 Primary Productivity and Vegetation Succession in Lakes and Wetlands

In a naturally ageing lake, there is a successive decrease in the primary productivity based on plankton. However, a very dramatic change in the productivity takes place when the lake has become so shallow that it is possible for peat-forming macrophytes – such as the common reed (*Phragmites*), bulrush (*Schoenoplectus*) and cattail (*Typha*) – to colonise the organogenic bottom (Fig. 2.2). The plankton is then replaced by communities of microorganisms (periphyton) that develop in the water on the stems and leaves of emergent, floating-leaved and submerged macrophytes.

The most productive phase in the whole evolutionary history of a lake is the period when the shallow lake has just been transformed into a wetland overgrown by emergent vegetation. The reasons for this sudden increase in productivity are as follows:

- There has been a continuous supply of nutrients from the catchment area to the lake which has acted as a trap for these elements.
- There is never a shortage of water in a wetland.
- The perennial, highly-productive emergent macrophytes are well adapted to an efficient utilisation of the environmental conditions in all three media: sediment, water and air.

Macrophytes, rooted in the sediment, can thus make use of the accumulated, nutrient-rich resources which until now, i.e., during the previous stages of ecosystem development, have not been available for deeply-rooted plants. Wetlands overgrown by plants such as *Phragmites* and other perennial, emergent macrophytes constitute the most productive ecosystems of any at the same latitude.

In northern latitudes, the break-down of organic matter in cold and oxygen-free sediment and peat is much slower than in waters of warmer latitudes where mineralisation processes take place at higher rates and over a longer period of the year. This makes it especially troublesome to preserve northern, highly-productive wetlands characterised by high rates of accumulation of coarse detritus produced by the emergent macrophytes. The general ecological succession and terrestrialisation process includes various stages where *Typha*, *Schoenoplectus* and *Phragmites* are replaced by *Carex*, and the formation of peat above the sediment prepares for the invasion of *Salix* and *Betula*. A lowering of the water level in shallow lakes brings about a tremendous speeding up of the ageing process (Fig. 2.3).

2.2.3 Palaeolimnological Studies

The composition of a lake’s sediment directly reflects the organism communities which have inhabited a lake and its catchment area over the millenia. Provided the sediment growth rate is known, it is possible, by means of chemical analysis, to
1. Lake with deposition of organogenic sediment (gyttja) on the minerogenic bottom.

2. The lake filled up with gyttja overgrown by peat-forming emergent macrophytes.

3. The macrophyte peat covered by sphagnum peat. During a period with dry climate the bog is colonised by *Pinus*.

4. The former lake completely transformed to a raised bog with fast-growing *Sphagnum* during a wet climate period. The bog surrounded by a fen (lagg), i.e. the zone influenced by water from the mineral soil. The raised bog totally dependent on precipitation and airborn matter (ombrogenous bog).

**Key**

A = moraine, B = sand-silt, C = silt-clay, D = gyttja, E = peat of emergent macrophytes, F = Sphagnum peat.

**Fig. 2.2** The transformation of a lake from an open water ecosystem to a raised bog.
estimate the supply and calculate the deposition of different elements during the various phases of development. By means of such palaeolimnological investigations, using a long series of analytical methods, the developmental history of both the lake and its catchment area can be reconstructed. The presence of frustules of diatoms, cysts and other remnants of algae, remains of insects and cladocerans, seeds and other diaspores, roots, etc., allows an ecological interpretation to be made of the conditions prevailing when various layers of sediment and peat were deposited. Pollen analysis, dating of sediments by determination of the content of radio-isotopes of carbon ($^{14}$C), caesium ($^{137}$Cs) and lead ($^{210}$Pb), and palaeomagnetic investigations, are used to determine the age of sediment layers. When the age is known, the sediment growth rate and the accumulation of different elements per unit of time can be determined (cf. Digerfeldt 1972). This means that both natural and man-induced leaching and transport processes from the catchment area to the lake can be revealed by studying the sediment’s ‘archives’ (Fig. 2.4).

Palaeolimnological investigations are often an essential pre-requisite for the design of restoration plans because the aim is usually to try to re-create ecosystem qualities which have been lost. Past and present relationships between the catchment area and the lake have to be elucidated and used as guidelines in
restoration planning. With a collapsed ecosystem as the patient, and with a holistic approach in space and time as a necessity, the pre-project investigations need to be organised as team-work in order to gain an understanding of the system as a whole.

Fig. 2.4 Lake Trummen, Sweden. The transport of phosphorus (indicated by arrows) from the catchment area for deposition in the sediment during four periods. The figures within the lake denote: lake depth, rate of deposition, and the annual deposition of phosphorus (compiled on the basis of data from Digerfeldt (1972), from Björk et al. 1972)
2.2.4 Important Physical Processes

The influence of man on lakes and wetlands often eliminates important natural agents such as ice movements and seasonal water level fluctuations. The temperature changes that took place during the various Holocene climate periods have involved variations in the development of lake ice cover. A general feature is that ice can have an influence on shorelines both when it covers the whole lake and when the ice breaks up. In cold winter periods, especially at night when the ice cools down and contracts, tension cracks appear in the ice cover. When cracking, a sound like thunder is heard – the ‘bellowing’ of Scandinavian lakes. The cracks are immediately filled with water which then freezes. In warmer periods, as on sunny days, the volume and area of the ice cover increases and a very strong pressure is exerted against the shorelines, which are subject to ice-pressing. With the changes in winter temperatures, this process is repeated continually and means a successive increase in ice pressure over the winter. The erosive zone of the shore (Fig. 2.5) which is influenced by the ice, can be cleaned of vegetation, bottom material (including big boulders) can be forced landwards, and building constructions demolished. In regions covered by coarse moraine deposits, barricades of boulders along the shores have been built up by ice-pressing (Fig. 2.6). These barricades were probably mainly formed in the early sub-Atlantic period (about 2,000 years before present), when the ice-pressing is considered to have been stronger than at present.

In a very large number of Scandinavian lakes, water levels nowadays reach far below the barricades, indicating that the lakes have been lowered. However, in intact lakes, the water level is still found at the base of the barricade (Fig. 2.3).

Fig. 2.5 Schematic distribution of vegetation in different littoral zones in a Lobelia lake (Lake Fiolen, Sweden). The upper portion of the minerogenic zone is under the erosive influence of ice movements. The minerogenic zone is lakewards followed by the organogenic bottom (From Thunmark 1931)
Besides ice-pressing, another type of ice movement can occur, which is also important in the physical sculpting of the shore. This is ice-pushing, brought about by ice-floes in connection with the break-up of the ice. When a sudden break-up of the ice is caused by strong winds, the ice-floes are pushed against the shore and piled up along the wind-exposed side of the lake. In this way, the shore is also cleaned of vegetation and trees are de-barked on the lakeward side.

Whenever possible, in the restoration and management of lakes and wetlands, the conditions for the formation of qualitatively good ice in order to make use of ice movements, as well as of water level fluctuations, should be re-created. The utilisation of ice movements is a cheap way to protect lakes from the overgrowth and heavy detritus production of macrophytes, and to preserve open shores suitable for wading birds, etc.
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