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Meromixis as a part of lake evolution — observations and a revised classification of true meromictic lakes in Finland

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Based on Finnish lakes, meromixis is viewed from a paleolimnological perspective as a part of lake evolution. The study concludes that theoretical search of meromictic lakes is almost impossible, due to inconsistent and insufficient basic data and the complexity of meromixis as a phenomenon. An estimation of possible Finnish meromictic lakes turned out to be a few dozen. Meromictic lakes are more numerous than formerly expected, but still rare. Based on the present estimation, only one lake in 800 is truly meromictic. Their most probable geographical location, besides the coastal lakes, are the Salpausselkä end-moraine zone and the areas between the Salpausselkä zone, Ostrobothnia, the Kainuu Region, and the eastern border of Finland. Terminology concerning holomixis/meromixis is presently confusing and this study favors a strict use of the term meromictic and grouping complete and incomplete holomictic lakes as one group and true meromictic as another. The revised classification recognizes meromixis that has resulted from (1) flow/precipitation of saline water over freshwater or freshwater over saline water, (2) superficial diffuse nutrient load and/or turbidity currents from the catchment, (3) subsurface inflow of groundwater, (4) inadequate mixing due to the lake morphology and surrounding topography.

Introduction

Lakes can be classified as holomictic or meromictic. In holomictic lakes, the water body circulates at least once a year due to homothermal conditions, and mixing is complete or partial. The circulation homogenizes oxygen and nutrient concentrations throughout the water mass. In Finland, as well as elsewhere in the northern temperate zone, lakes usually circulate twice a year, and are therefore called dimictic.

Recent studies have revealed the frequency of meromictic periods in lake evolution (e.g. Salonen *et al*. 1984, Kjensmo 1988, Hickman and White 1989, Radle *et al*. 1989, Hickman *et al*. 1990, Simola 1990, Barland 1991, Mees *et al*. 1991, Rask *et al*. 1992, 1993, Kennedy 1994, Sack and Last 1994, Schenk *et al*. 1994, Lindholm 1995, Valero-Garcés and Kelts 1995, Hodgson *et al*. 1996, 1998, Tracey *et al*. 1996, Löffler 1997, Melack and Jellison 1998, Schmidt *et al*. 1998, Hodgson 1999, Hongve 1999, 2002, Hollibaugh *et al*. 2001, Jellison and Melack 2001, Lotter 2001, Ojala 2001).

In Finland, and in similar lake regions with a high rate of isostatic land uplift, lake evolution is fast. The first meromictic phase usually occurs at the birth of a lake, when a marine or brackish-water bay changes into an isolated freshwater basin (e.g. Lindholm 1975a). During maturation, lakes tend to become holomictic; most lakes at northern temperate latitudes are dimictic (e.g. Lewis 1983). Water circulation can later be altered due to varying environmental changes, the most important of which are human interference and climatic change. Anthropogenic influence has frequently transformed the circulation status of many lakes due to eutrophication and pollution (e.g. Kjensmo 1997), and engineered construction (e.g. Hodgson *et al.* 1996). Natural transitions between holomixis and meromixis have also occurred as a result of altered temperature and humidity (e.g. Löffler 1997).

The first list of known meromictic lakes of the world was compiled by Yoshimura (1937). The list comprised 44 lakes, mainly situated in Japan and Europe. In Scandinavia, studies on meromictic lakes were carried out extensively, especially in Norway (e.g. Strøm 1945, 1957, 1962, Holtan 1965, Kjensmo 1967, 1968, Hongve 1980). A list of meromictic lakes compiled by Walker and Likens (1975) comprised 121 meromictic lakes around the world. The number of lakes classified as meromictic continues to increase. In a survey in North America, Anderson *et al.* (1985) were able to identify about 100 lakes that are, or are likely to be, meromictic. In a small area in southeast Norway, nine meromictic lakes were observed (Bremmeng and Kloster 1976, Hongve 1980, 2002). In Finland, only a dozen meromictic lakes have been identified so far. However, in palaeolimnology the interest of meromixis has grown along with that of annually laminated sediments. Sediment records from meromictic lakes may consist of annually laminated or varved sediments that provide a variety of chronological and high-resolution data concerning the immediate surroundings of lakes and watersheds (e.g. Ojala 2001). To examine such sediments, meromictic lakes must first be identified, and their origin and history thoroughly investigated. The rarity of meromixis makes such studies potentially attractive. After all, meromictic lakes are almost as rare geological phenomenona as metorite craters!

The number of identified meromictic lakes in Finland is small, and therefore a theoretical estimation of the real number and occurrence was made in this study. The confusing terminology of meromixis was discussed and a strict use of the term meromictic was recommended. A classification for Finnish meromictic lakes was revised based on Hutchinson (1937) and Walker and Likens (1975).

Definitions of meromixis

Meromictic lakes are chemically stratified with an incomplete circulation. Findenegg (1935) first introduced the word meromictic as a divergence from holomictic. In a meromictic lake, the water mass is permanently stratified into two layers that do not interact with each other. Circulation is possible only within a restricted layer, which prevents overturn from top to bottom.

Overturns are possible because water density changes with temperature. In meromictic lakes, thermal convection aided by wind action is too weak to break the stratification. This may be because of reduced wind action due to sheltering topography, forests or lake morphology, or because of these effects being overcome by stronger stabilizing forces. A rise in density is a stabilizing force that can result from changes in water temperature or electrolyte concentration. In a meromictic lake, the mixing can occur only to a depth where the mixing forces are greater than the stabilizing forces. At this depth, a transition zone develops, which Hutchinson (1937) named a chemocline. The layer below the chemocline was defined as a monimolimnion by Findenegg (1935) and the layer above as a mixolimnion by Hutchinson (1937).

The division between holomictic and meromictic was initially based on whether complete mixing had occurred in a lake at least once a year (Findenegg 1935). Despite the fact that complete mixing never occurs in a meromictic lake *sensu stricto*, the term meromictic later included lakes with irregular mixings and stratification periods. Other terms in use are e.g. semi-meromictic, temporary meromictic, periodic meromictic and spring meromictic; all found in Finnish lakes. Walker and Likens (1975) also used the term meromictic *sensu lato* and included lakes showing permanent stratification most years (> 50%). For distinction, Miracle *et al.* (1993) used the term extreme meromixis for meromictic lakes, where the chemocline is sharp. It is important to clarify definitions concerning meromictic lakes (e.g. Tyler and Vyverman 1995), although there are opinions claiming that distinctions between holomictic lakes with irregular mixing and meromictic lakes are impractical (Hongve 2002). Another view considers holomictic lakes with complete or irregular mixing as one group and meromictic as another. If a separation between different kinds of holomictic lakes is needed, H. Simola (pers. comm.) has proposed the term "incomplete holomixis" for lakes with irregular circulation resulting in fluctuating conditions. This would restrict the term meromixis for meromictic lakes *sensu stricto* and eliminate confusion. Nevertheless, here I use the term meromictic in the strict sense of the word.

Classifications of meromixis

Findenegg (1937) classified meromictic lakes as having either static or dynamic origin. In the static type, the water layers primarily differ in densities due to the geological environment. In the dynamic type, the layers are primarily homogeneous, but the external mixing agents cannot overcome the internal resisting forces. Yoshimura (1937) divided meromictic lakes into three categories: biochemical stratification, non-biochemical stratification and combined stratification of biochemical and non-biochemical origin. The biochemical stratification is of the same type that Findenegg called dynamic. Through biochemical reactions, the primarily homogeneous water mass becomes heterogeneous and separated into two layers which the mixing agents cannot homogenize. The non-biochemical stratification is approximately equivalent to Findenegg's static category.

The most commonly used classification of meromixis was introduced by Hutchinson (1937): (1) Ectogenic meromictic lakes, where the meromictic condition is initiated by some external superficial event (e.g. saline water intrusion), which, acting for a limited time, leaves the lake in a chemically stratified condition. Unless the event reoccurs, the lake changes into holomictic after some period of time; (2) Crenogenic meromictic lakes, where submerged mineralized springs bring a continuous supply of denser water into the lower stratum of the lake; (3) Biogenic meromictic lakes, where the electrolyte concentration in the lower strata increases due to decomposition of organic material at the bottom of the lake.

Walker and Likens (1975) introduced a twofold classification by expanding the original Hutchison's (1937) division. They recognized a meromixis originating primarily from factors external to the lake basin (ectogenic meromixis) and another meromixis where internal factors were most important (endogenic meromixis) (Fig. 1.).

The comparison between classifications of Hutchinson (1937) and Walker and Likens (1975) is presented in Fig. 1 to clarify the confusions and difficulties in the classifying of meromixis. The greatest difficulty concerns biogenic meromixis *sensu* Hutchinson (1937), or types I, II and IV meromixis *sensu* Walker and Likens (1975). It is a question of stability. If a meromixis state that has started from an ectogenic (type I) event remains stable, it is considered biogenic (type IV), not ectogenic (type I). Similarly, if a meromixis state that has started from a type II event remains stable, it is considered biogenic (type IV), not type II. Only if the holomictic state returns after the event passes, was the meromixis considered as ectogenic (types I and II). The classifications do not pay enough attention to the primary initiating cause itself. Biogenic meromixis is not an independent category but a secondary cause: irrespective of the process by which a meromixis has developed, the development leads to permanent stratification which eventually results in anaerobia. In anaerobic conditions, electrolyte concentration increases due to decomposition of organic material, and this is the definition of biogenic meromixis. It is often expressed in the literature that (the primary) factors which have lead to biogenic (type IV) meromixis are difficult to define. It seems that the biogenic (type IV) is a left-over category for lake cases where the primary cause is difficult to comprehend. Therefore, the modified classification based on Hutchinson (1937) and Walker and Likens (1975) categorize meromictic lakes by only the original primary factor that initiated the meromictic processes (Table 1). The classification includes four principle groups that can be further divided into subgroups.

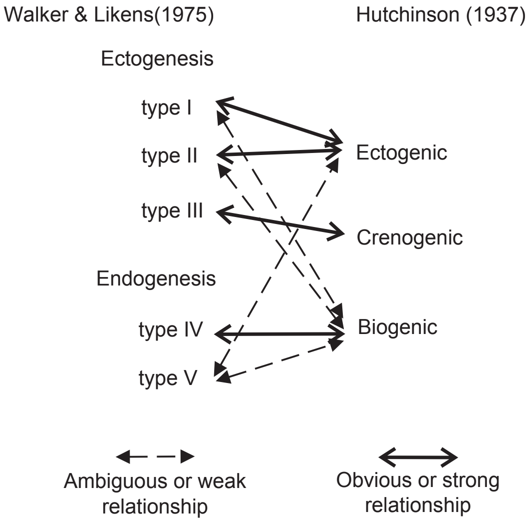

Fig. 1. Comparison between classifications of Walker and Likens (1975) and Hutchinson (1937). The solid lines indicate the obvious relationship between the original classification (Hutchinson 1937) and its expansion (Walker and Likens 1975). The dashed lines indicate the ambiguous relationships that exist. Walker and Likens (1975) include five categories (I–V). Ectogenesis is divided into three types, I, II and III. Type I resembles Hutchison's ectogenic meromixis and it is subdivided into type Ia, which refers to coastal situations where marine or brackish water contact freshwater, and type Ib, which refers to inland situations. Type Ib correlates with Hutchinson's biogenic type, because a part of the lakes in the biogenic group initiates from ectogenic inflow (Hutchinson 1957: p. 482). Type II develops due to surface inflow of turbidity currents, a definition that also places it into Hutchinson's category of biogenic lakes, because a part of the lakes in the biogenic group initiates from turbidity currents (Hutchinson 1957: p. 489). Type III resembles Hutchinson's crenogenic meromixis. Endogenesis is divided into two types, IV and V. Type IV resembles Hutchison's biogenic meromixis in the sense of accumulation of salts liberated from the sediments. Type V develops due to deep water accumulation of salt precipitated by freezing out from a surface ice layer. When categories are combined, the relationships lead to confusion, because biogenic meromixis and type IV meromixis are not independent categories but secondary causes in meromixis development.

Meromictic lakes in Finland

Lakes in Group 1: salinity gradient

The lakes in this group comprise coastal basins, lagoons and lakes along the coasts of the Gulf of Bothnia and the Åland Islands (Fig. 2). They were formed as a result of land uplift, when brackish or marine bays were completely or partly isolated and became independent basins. Brackish or salt water has either been captured in the new basin, or the basin is still in contact with the sea, receiving occasional brackish water pulses. Denser brackish water forms the monimolimnion, which is overlaid by a mixolimnion of freshwater from watershed and precipitation. Basins which have permanently lost their connection to the sea tend to become holomictic over time. Limnic evolution is relatively fast in coastal lakes, which results in rapid changes in circulation status and, ultimately in holomictic conditions. Bagge and Tulkki (1967), Bonsdorff and Storberg (1990), Eriksson and Lindholm (1985), Helminen (1978), Karlsson *et al.* (1981), Lindholm (1975a, 1975b, 1975c, 1975d, 1975e, 1976, 1978a, 1978b, 1979, 1982a, 1982b, 1995), Lindholm and Eriksson (1990), Räsänen (1983), Sundblom (1964), Sundblom and Moliis (1962), Wikgren (1965), Wikgren *et al.* (1961). Table 2 shows morphometrical and hydrological properties and a summary of the meromixis history of the lakes studied by the above-mentioned authors.

In addition to these Group 1 lakes, many deep coastal lakes, basins and bays, such as Inre Verviken, Kaldersfjärden, Holmsjön (e.g. Lindholm 1975a, 1975c, 1982a, 1995, 1996, Lindholm *et al.* 1985), Bolstaholmssundet and Borgsjön (Lindholm 1991; T. Lindholm pers. comm.) on the Åland Islands, Kärinsviken and Gyltöträsk (Bagge and Tulkki 1967) on Nauvo and Korppoo, SW archipelago, and Gennarbyviken in the Tenhola area (Räsänen and Tolonen 1983; K. Tolonen pers. comm.), show fluctuating circulation tendencies.

Lakes in Group 2: oxygen defiance by load

This forms the largest group of meromictic lakes in Finland (Fig. 2). The group is also heterogeneous, but common classifying factors are superficial runoff that is a mix of diffuse nutrient load and turbidity currents from dry land (mainly of anthropogenic origin) and/or from bogs (mainly of natural origin). Other common factors for all these lakes, which can be classified as biogenic lakes *sensu* Hutchinson (1937), are related to their morphology, i.e. small area and great depth, locations sheltered by topography and/or vegetation, continental climate (Hutchinson 1957), increased water colour, and shallow thermoclines (Hongve 2002). Many lakes in this group are either groundwater or seepage lakes. Morphometrical and chemical properties of these lakes are outlined in Table 3.

Humic forest lakes

The formation of humic forest lakes is closely linked to a cooling and moistening climate during the Sub-Boreal and especially the Sub-Atlantic periods (Donner 1995 and references therein) when catchments were characterized by paludification, coniferous forest domination and maturing of podsol soils. In Finland, the lake type has been extensively investigated in the Lammi area (e.g. Arvola 1983, 1986, Salonen *et al*. 1983, 1984, 1992a, 1992b, Jones and Arvola 1984, Rask and Arvola 1985, Rask *et al*. 1985, 1986, 1992, 1993, Arvola *et al*. 1986, 1987, 1990a, 1990b, 1992, Salonen and Arvola 1988, Smolander and Arvola 1988, Arvola and Kankaala 1989, Kuuppo-Leinikki and Salonen 1992, Salonen and Lehtovaara 1992). The lakes are typically small (< 0.3 km^2), relatively deep, dark-coloured, humic and acidic, and surrounded by bogs and sheltering coniferous forests. Sheltering forests combined with a small area/depth ratio and quick thermal stratification due to improved solar energy adsorption by humic water (Jones and Arvola 1984) reduce the mixing potential of the lakes. However, inflow-

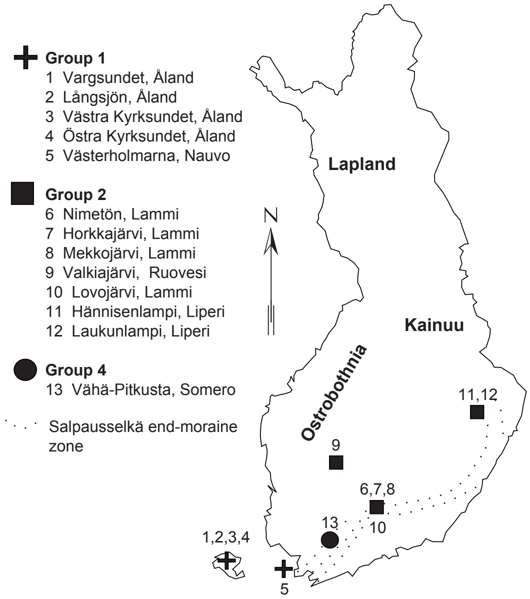

Fig. 2. Locations of identified Finnish meromictic lakes.

Table 1. Revised classification of meromictic lakes based on Hutchinson (1937) and Walker and Likens (1975) for Finnish meromictic lakes.

Group	Meromixis
1 salinity gradient	Results from inflow or precipitation of saline water (or solid salts) over freshwater or freshwater over saline water (ectogenic and biogenic *sensu* Hutchinson (1937), since a part of biogenic meromixis initiates from ectogenic inflow). This group can be subdivided into (a) coastland, (b) inland and (c) cryogenic [*sensu* Goldman *et al*. (1972)] situations.
2 oxygen defiance by load	Results from superficial diffuse nutrient load and/or from turbidity currents from the catchment, which (a) stabilize the hypolimnion and (b) consume the hypolimnetic oxygen (triptogenic *sensu* Frey (1955) and biogenic *sensu* Hutchinson (1937), since a part of biogenic meromixis initiates from a sudden inflow of turbidity currents). This group can be subdivided into (a) anthropogenic and (b) natural situations.
3 dense groundwater	Results from subsurface inflow of groundwater (crenogenic *sensu* Hutchinson (1937).
4 morphogenesis	Results from inadequate mixing due to morphology (morphogenic *sensu* Northcote and Halsey (1969)) leading to anoxic bottom and to accumulation of electrolytes liberated from the sediments (biogenic *sensu* Hutchinson (1937)).

ing waters highly concentrated in inorganic and organic humic substances increase the stabilizing forces. In these lakes, the anoxic volume is great and the chemocline is situated at shallow depths. In summary, increased water colour, shallow thermocline and small surface area predict the development of meromixis, especially in these types of lakes (Hongve 2002). Meromictic phenomena in humic forest lakes are a common feature rather than an exception. Most lakes have incomplete spring circulation. So far, three meromictic lakes have been reported. This is, however, misleading. According to Salonen *et al*. (1984), these types of humic forest lakes with irregular mixing patterns are abundant in Boreal areas. A summary of the meromixis history of these lakes is given in Table 3.

Valkiajärvi

Valkiajärvi is a small (0.078 km^2), relatively deep lake surrounded by sheltering hills with a pine- and spruce-dominated forest rising 40–50 m above the lake surface. There are *Sphagnum* bogs in the northwestern and southeastern parts of the lake, from where three man-made ditches allow inflow of inorganic and humic waters. The lake has no other influents and only a small effluent. The monimolimnion is anoxic due to the humic load from the bog waters.

Meromixis in Valkiajärvi was first identified by Kaila (1964) and studied in detail by Meriläinen (1967, 1969, 1970, 1971a, 1971b). Valkiajärvi is the best-known and most thoroughly studied meromictic lake in Finland (Koivisto and Saarn-

Table 2. Morphometrical and chemical epilimnic properties of Vargsundet, Långsjön, Västra Kyrksundet and Östra Kyrksundet, according to Lindholm (1975a, 1975c, 1982a), Karlsson *et al.* in Räsänen (1983) and Lindholm and Eriksson (1990), and some morphometrical and hydrological values for Västerholmarna according to Bagge and Tulkki (1967). A short summary of the meromixis history of each lake is also presented.

	Vargsundet	Långsjön	Västra Kyrksundet	Östra Kyrksundet	Västerholmarna
Location	Åland Islands	Åland Islands	Åland Islands	Åland Islands	Nauvo
Length (km)	5.0	4.5	2.5	4.0	–
Breadth (m)	300	400	300	500	–
Area (ha)	110	143	60	200	–
Maximum depth (m)	35	18	18	22	8.0
Catchment (km^2)	24	16.3	40	39	–
Depth of halocline (m)	8–18	5–10	4–9	12–15	–
Volume (m^3)	–	9000×10^3	–	–	–
pH	7.2–9.3	7.5–9.0	7.5–9.1	8.0–9.5	–
Salinity (‰)	1.3–3.0	0.6	0.3–3.3	0.3–0.6	6.7
Alkalinity (mevk)	1.5–1.6	1.6–1.7	0.7–1.2	0.8–1.0	–
COD (mg l^{-1})	35–50	28–53	25–40	28–35	–
PO_4-P (mg l^{-1})	–	< 0.1	< 0.1	–	–
NH_4-N (mg l^{-1})	–	0.1–0.5	0.3–0.5	–	–
Colour (mg Pt l^{-1})	–	< 55	0–20	–	–
Secchi (m)	–	1–2	1–4.5	–	3–5
Conductivity (mS m^{-1})	–	–	–	–	4.96
Meromixis history	Meromictic during isolation process. Holomictic after isolation. Meromictic after sea reconnection 1930s. (Räsänen 1983).	Meromictic after sea connection improvement 1935. Holomictic after dam isolation 1972. (Wikgren 1965, Räsänen 1983, Lindholm 1975a).	Meromictic after sea connection improvement 1932. Holomictic after aeration and dam isolation 1979. (Sundblom 1964. Wikgren 1965, Lindholm 1975a; 1982b, Bonsdorff and Storberg 1990).	Meromictic after reconnection to V. Kyrksundet 1932. Slow process to holomixis after sea connection improvement of V. Kyrksundet. (Lindholm 1975a).	Meromictic after isolation. (Bagge and Tulkki 1967).

isto 1978, Alapieti and Saarnisto 1981, Saarnisto 1985, Eloranta 1987, Simola 1990, Ojala and Saarnisto 1999, Ojala 2001). Meriläinen (1969) called the lake "iron-meromictic" since he interpreted iron as the main factor counteracting the mixing in the lake. It has been found that the meromictic stability is a result of gases, e.g. carbon dioxide, methane, hydrogen sulphide, forming from decaying organic material (e.g. Kjensmo1968, Hongve 1980, 2002). These dissolved gases cause accumulation of metals, e.g. iron and manganese, which in turn increase the density and therefore the stability. Other factors favouring meromixis are the small area/depth ratio, sheltering topography and continental climate.

Unfortunately, no data on the age of the meromixis is available. Through its history as an isolated lake, Valkiajärvi has formed laminates annually, i.e. varves (Alapieti and Saarnisto 1981). This can be interpreted as a sign of lifetime meromixis even if varve formation is not restricted to meromictic lakes. On the contrary, varves occur frequently also in holomictic lakes (Ojala and Saarnisto 1999).

Human impacted kettlehole lakes

The lakes in this group are scattered around Finland, but have all been negatively affected

Table 3. Morphometrical values and average chemical water properties of Nimetön, Horkkajärvi and Mekkojärvi, according to Arvola (1983), Arvola *et al.* (1990b) and Münster *et al.* (1992), and the morphometry and selected water properties of epilimnion in Valkiajärvi according to Meriläinen (1969) and Eloranta (1987). A short summary of the meromixis history of each lake, excluding Valkiajärvi, is also presented.

	Nimetön	Horkkajärvi	Mekkojärvi	Valkiajärvi
Location	61°13´N, 25°10´E	61°13´N, 25°10´E	61°13´N, 25°10´E	61°54´N, 23°53´E
Surface altitude (m a.s.l.)	–	–	–	110
Length (km)	–	–	–	575
Breadth (m)	–	–	–	220
Area (ha)	0.4	1.1	0.35	7.8
Maximum depth (m)	11	13	3.5	25
Mean depth (m)	8	7	2.2	8.4
Catchment (ha)	34	70	–	–
Depth of chemocline (m)	–	–	0.5–0.9	17
Volume (m^3)	33.6×10^3	78.6×10^3	–	662×10^3
Volume of monimolimnion (m^3)	–	–	–	43×10^3
Volume of mixolimnion (m^3)	–	–	–	619×10^3
pH	5.69	5.49	5.50	6.40
Alkalinity (mmol l^{-1})	0.07	0.04	0.11	0.02
Conductivity (mS m^{-1})	4.4	4.3	4.8	0.0245
Colour (mg Pt l^{-1})	231	248	372	25
P_{tot} (µg $l^{-1)}$	36	18	33	5
N_{tot} (µg l^{-1})	836	798	815	330
Ca (mg l^{-1})	3.58	3.36	5.31	0.1
Mg (mg l^{-1})	0.88	0.79	0.98	–
Al (mg l^{-1})	0.22	0.24	0.23	–
Fe (mg l^{-1})	0.35	0.48	0.55	0.053
Na (mg l^{-1})	2.01	1.91	2.14	1.6
K (mg l^{-1})	1.12	0.89	0.94	0.4
Meromixis history	Meromictic until loss of sheltering position by clear-cut 1981–1982. Afterwards incomplete holomixis. (Salonen *et al.* 1984, Similä 1988).	Meromictic	Incomplete holomictic or meromictic. (Kankaala 1988, Arvola and Kankaala 1989, Salonen and Lehtovaara 1992).	In text.

because of their location in areas of prehistoric or historic settlement. The change from holomixis to meromixis in these lakes was associated with the initiation of agriculture, and the transition occurred through eutrophication of anthropogenic origin. The lakes have been influenced in their catchment areas by forest clearance, slash-and-burn cultivation, modern cultivation and grazing, and, most importantly, retting and soaking of hemp and flax in their actual waters (Tolonen *et al*. 1976, Tolonen 1978). The deep, small basins of these lakes are situated in kettleholes, and have sheltering surroundings. Such physical factors combined with the increased input of minerogenic electrolytes and organic load in the existing continental climate have led to meromixis. Typical features of these lakes are high alkalinity and pH values, and increased concentrations of basic elements, heavy metals and nutrients. By increased environmental awareness, anthropogenic influence can be minimized, leading to environmental changes and evolutionary return to the holomictic period. Table 4 shows morphometrical and chemical properties of the lakes.

Lovojärvi

Lovojärvi was studied by Kukkonen and Tynni (1972), Ilmavirta *et al*. (1974), Hirviluoto (1975), Huttunen and Tolonen (1975), Keskitalo (1976, 1977), Saarnisto *et al*. (1977), Simola (1977, 1979, 1981, 1983, 1984), Huttunen (1980), Simola and Tolonen (1981), Jaakkola *et al*. (1983) and Simola *et al*. (1990). The lake basin forms an elongated narrow kettlehole in an esker, and it is small and rather shallow except for the main basin, which is relatively deep. The glaciofluvial esker rises about 50 m above lake level, giving shelter to the lake. In the catchment area there is sorted sand and gravel, along with bogs and cultivated fields. The lake has four inlets, one of which is predominant, and an outlet. The ditches pass through bogs and cultivated areas, their water carrying a load of humic substances and electrolytes. After its isolation, the lake was clear and oligotrophic, but, due to the bogs, the trophic status was raised and the water became more humic and darker-coloured (Kukkonen and Tynni 1972). However, the true eutrophication

Table 4. Morphometrical and chemical epilimnic properties of Lovojärvi (according to Ilmavirta *et al.* 1974, Huttunen and Tolonen 1975, Keskitalo 1977, Simola 1979), Hännisenlampi (according to Vuorinen 1978) and Laukunlampi (according to Jaakkola *et al.*1983, and Simola *et al.* 1984).

	Lovojärvi	Hännisenlampi	Laukunlampi
Location	61°05´N, 25°02´E	62°05´N, 30°12´E	62°40´N, 29°10´E
Surface altitude (m a.s.l.)	108.2	–	84
Length (km)	600	–	–
Breadth (m)	130	–	–
Area (ha)	4.8–5.4	1.5	8.8
Maximum depth (m)	17.5	16	27
Mean depth (m)	7.7	5.2	6.3
Catchment (ha)	570	3.5	ca. 20
Depth of chemocline (m)	ca. 12–13	ca. 10–11	15–18
Volume (m^3)	369×10^3	78.3×10^3	558×10^3
Volume of monimolimnion (m^3)	–	4.7×10^3	–
Volume of mixolimnion (m^3)	–	73.6×10^3	–
pH	7.4–10.1	7.4–7.9	7.1–7.6
Alkalinity (mmol l^{-1})	–	–	0.5–0.6
Conductivity (mS m^{-1})	0.077–0.103	0.068	9–11
Colour (mg Pt l^{-1})	60–80	–	5
Secchi (m)	0.9	1.5–2.5	4–7
P_{tot} (µg l^{-1})	40–90	–	8–14
N_{tot} (µg l^{-1})	500–790	–	200–270
Ca (mg l^{-1})	4.0–8.6	–	–
Mg (mg l^{-1})	1.75–3.4	–	–
Na (mg l^{-1})	4.2–4.65	–	–
K (mg l^{-1})	0.9–3.3	–	–

did not begin until the anthropogenic influence commenced. The meromixis started after 400 BC according to Huttunen and Tolonen (1975), or around 700 AD according to Kukkonen and Tynni (1972). Kukkonen and Tynni (1972) suggested that Lovojärvi has re-entered its holomictic status due to shallowing, but Ilmavirta *et al.* (1974) considered the lake still meromictic. Huttunen and Tolonen (1975) stated that Lovojärvi is in a transition from meromictic to holomictic, supported by Keskitalo (1976, 1977), Saarnisto *et al.* (1977), Huttunen (1980) and to some extent by Simola (1977, 1979) and Simola *et al.* (1990). However, H. Simola (pers. comm.) and L. Arvola (pers. comm.) believe that Lovojärvi is still meromictic.

Hännisenlampi

Hännisenlampi was studied by Vuorinen (1977, 1978), Pirttiala (1980) and Huttunen and Meriläinen (1986). The lake basin is a small, round-shaped kettlehole with relatively great depth. It is located in an esker, which forms a sheltered location for the lake. Hännisenlampi is a groundwater lake without inlets or outlets, so the retention time is long. The history of Hännisenlampi resembles that of Lovojärvi. There was a Neolithic settlement nearby and the start of rye and hemp cultivation is dated back to the 15th century. Eventually, the slash-and-burn cultivation and hemp soaking led to meromixis in 1504 AD (Vuorinen 1978). Artificial lowering of an adjacent lake resulted in a water level drop in Hännisenlampi as well, which increased electrolyte inflow and strengthened the meromixis (Huttunen and Meriläinen 1986). Vuorinen (1978) considers Hännisenlampi to be meromictic or in transition to holomictic, and Huttunen and Meriläinen (1986) state that the circulation is still insufficient to oxygenate the sediment.

Laukunlampi

Laukunlampi was studied by e.g. Huttunen and Meriläinen (1978), Appleby *et al.* (1979), Hartikainen (1979), Battarbee *et al.* (1980), Tolonen (1980), Battarbee (1981), Jaakkola *et al.* (1983), Rummery (1983), Simola *et al.* (1984), Tolonen *et al.* (1992) and Pitkänen (2000). Laukunlampi occupies a small, round-shaped kettlehole with steep slopes and relatively great depth. The esker surrounding the lake rises about 30 m above the water surface, giving shelter from winds. Water exchange takes place through groundwater, and therefore the retention time is long. The catchment area includes a coniferous forest and cultivated fields. Similar to Hännisenlampi, it suffered from the early anthropogenic influence of slash-and-burn cultivation and retting of flax, which led to the initiation of meromixis (Battarbee 1981, Simola *et al.* 1984). The density gradient has increased over time; the water level has dropped due to engineered water level lowering in adjacent lakes. The exposure of former water-saturated sand deposits resulted in intensified erosion and increased electrolyte inflow, as in Hännisenlampi (Hartikainen 1979).

In addition to these Group 2 lakes, the following lakes are presumed to belong to Group 2: Polvijärvi, Kalliojärvi and Suuri-Rostuvi in the Juuka area (Liehu *et al.* 1986, Rönkkö and Simola 1986; H. Simola pers. comm.), Laikkalammi in the Jokioinen area (Salonen *et al.* 2001) and Törönlampi in the Parikkala area (K. Tolonen pers. comm.).

Lake in Group 4: Vähä-Pitkusta

Vähä-Pitkusta is the smaller of the Pitkusta twin lakes, which are separated by a narrow esker. Vähä-Pitkusta is small, very deep (35 m), has steep shores, and its basin is a round-shaped kettlehole. Glaciofluvial eskers with a thick coniferous forest rise 30 m above the lake, giving shelter from the winds. Vähä-Pitkusta is a groundwater lake without inlets or natural outlets. The retention time is long. The water table slopes to the north, feeding Vähä-Pitkusta through its southern shores, but the outflow has decelerated due to the low permeability of the northern shores of Vähä-Pitkusta. The monimolimnion of Vähä-Pitkusta is poor in electrolytes and the difference between the monimolimnion and the mixolimnion is marginal (Table 4). The whole Holocene in the area (about 11 500 years) is represented in the lake sediment layer (about 160 cm) of Vähä-Pitkusta, indicating a steady sedimentation rate of about 0.14 mm yr^{-1}. Signs of anthropogenic activity are sparse in the sediment, but a very slight increase in the trophic level due to climatic change is seen for the last 1500 years (A. Hakala *et al*. unpubl. data). The long history of Vähä-Pitkusta has been influenced by oxygen rich groundwater inflow through the whole basin, maintaining circulation also in the bottom area. Gradual sedimentation which has blocked groundwater flow and diminished circulation in the bottom area, the slight increase in lake water density and the cold climate could all have attributed to the ending of overturns. As the bottom turned anaerobic, the organic sediment started to decay, producing dissolving gases and electrolytes. This occurred about 600 years ago (Alhonen *et al*. 2000; A. Hakala *et al*. unpubl. data). The main governing factor initiating and stabilizing the meromixis is the weakness of wind-induced mixing due to the morphology rather than to the strength of the chemical stratification. In this type of lake, increase in conductivity from surface to bottom is very slight and the absolute values often low. Suujärvi in Tammela is probably of the same type of meromixis (A.E. Ojala and L. Korkalainen unpubl. data). Table 5 shows morphological and chemical properties of Vähä-Pitkusta.

Table 5. Morphometrical values for Vähä-Pitkusta and chemical water properties at 1 and 33 m, according to the water quality database of the Finnish Environmental Institute and to A. Hakala *et al.* (unpubl. data).

	Vähä-Pitkusta	1 m	33 m
Location	60°29´18´´N, 23°39´15´´E		
Surface altitude (m a.s.l.)	93.3		
Length (km)	ca. 500		
Breadth (m)	ca. 300		
Area (ha)	ca. 11		
Maximum depth (m)	35		
Mean depth (m)	ca. 12		
Depth of chemocline (m)	17–25		
Volume (m^3)	1300×10^3		
pH		6.5	6.2
Alkalinity (mmol l^{-1})		0.13	0.33
Conductivity (mS m^{-1})		3.7	4.7
Colour (mg Pt l^{-1})		5	30
P_{tot} (µg l^{-1})		13	280
N_{tot} (µg l^{-1})		340	1200
Ca (mg l^{-1})		3.6	5.0
Mg (mg l^{-1})		1.35	1.4
Na (mg l^{-1})		1.35	1.2
K (mg l^{-1})		1.0	1.3
Mn (mg l^{-1})		0.1	0.75
Fe (mg l^{-1})		0.02	0.85
Cl (mg l^{-1})		2.2	2.0

Discussion

This study demonstrates that changing circulation patterns as a part of lake evolution are common in the northern temperate zone. Changes in evolution are of natural or anthropogenic origin; natural as shaped physically and climatologically by the Ice Age, and anthropogenic as shaped by man. However, true meromictic lakes seem to be rare in Finland.

Lakes with irregular circulation are much more numerous than the true meromictic ones, which form a small, more homogenous group. The terms partial meromictic, semi-meromictic, temporary meromictic and periodic meromictic in fact characterize lakes in the large, heterogenous group with irregular circulation. The term spring meromictic is especially confusing, since recent studies have shown that lake-mixing conditions are greatly dependent on autumnal circulation, whereas incomplete vernal circulation is common and of minor importance (e.g. Hongve 2002). The term meromixis should be used as unambiguously as possible, as most lakes are holomictic.

Classifications by e.g. Hutchinson (1937) and Walker and Likens (1975) form the basis of grouping meromictic lakes and are widely used. However, as discussed earlier, they are ambiguous and it is difficult to apply them as such to Finnish meromictic lakes. The classification of Finnish lakes has been revised (Table 1), based on the original primary factors causing the meromictic processes. This enables us to estimate occurrence, frequency and distribution of yet unidentified meromictic lakes in Finland.

Thirteen Finnish meromictic lakes are included in this study, eight lakes belonging to Group 1 and five lakes to Group 2. There is only one lake in Group 4 and none in Group 3.

Lindholm (1975, 1991, 1995) has identified seven Group 1 lakes on the Åland Islands and has estimated that the number of this lake type is twice this amount. It must be remembered that distribution is only possible along the coastline. Similar lakes with similar occurrence are well known along Norwegian coasts (e.g. Strøm 1957, 1962, Holtan 1965, Barland 1991). Finnish Group 1 lakes are rather shallow and contain brackish water, but Norwegian lakes are formed in deep fjords and developed due to inflow of real marine water, which makes them much more stable. In order to find possible cases in lake Groups 2 and 4 (traditionally biogenic), a search in the lake databases (lake register and water quality register) of the Finnish Environment Institute (SYKE) was made. The hypothesis required deep and small basins, features that are commonly linked to biogenic meromixis *sensu* Hutchinson (1937). The following preconditions were set: surface area < 0.3 km^2 (e.g. Hongve 2002) and relative depth $> 8\%$ (e.g. Salonen *et al.* 1984). Relative depth (z_r) is given by Eq. 1:

$$z_r(\%) = \frac{50 z_m \sqrt{\pi}}{\sqrt{A}} \quad (1)$$

where z_m is the maximum depth and A the area of the lake. The lake register database does not include lakes smaller than one hectare, so the majority of possible cases were already absent at this point. The number of lakes of size 0.01–0.3 km^2 is 48 823 in the database, but there is the maximum depth available only in 6964 cases. Of the 7000 lakes, 115 qualified in having a relative depth greater than eight percent, and 24 exceeded a relative depth of ten percent. To be able to study the 115 lakes, chemical water quality data were needed, but data were available for only 69. The majority of these lakes had been only analysed once, mainly in the 1970s or the 1980s. Only three lakes had been followed historically.

The search for meromictic lakes based on available databases is insufficient. If a speculative estimation based on the available data is made, it should start with lakes that exceed a relative depth of ten percent, since this starting point increases the theoretical probability of meromixis in each lake case. In the lake register database, 24 lakes reached ten percent. Water quality data were available for a half (12), and a third (4) of these showed intriguing meromictic signs. The other lakes could be meromictic, but no conclusions can be drawn based on the database. In the lake register database, 0.36% of lakes that have an area of 0.01–0.3 km^2 exceed a relative depth of ten percent. This yields about 180 lakes. Since a third of these, estimated using the available data, are possibly meromictic, we arrive at 60 lake cases. This number seems reasonable, and it suggests that there could be a few dozen meromictic lakes in Finland. Many such lakes are probably found among the small, humic forest lakes. Lakes greatly resembling Finnish lakes of Groups 2 and 4 have been studied in Norway for a long time, and they are rather numerous in the Cambro-Silurian part of the Oslo area (e.g. Strøm 1945, Kjensmo 1967, 1968, 1988, Hongve 1980, 1999, 2002). These lakes have similar features to those in Finland, which suggests that about the same magnitude of lake count should be also found in Finland.

Lakes that possess a smaller relative depth are typically influenced by anthropogenic activities. Their shallowness is compensated by more stable stratifications. Such lakes are obviously located in the vicinity of settlements and are therefore more likely to be found in southern Finland. The more natural origin of Groups 2 and 4 lakes require either rich inflow or sheltered morphology. The required morphology is attained in a glaciofluvial environment, in terrain of varying height and steep relief and in areas of light wind. These features are characteristic of southern, central, eastern and northern Finland, excluding central Lapland (Alalammi 1986, 1990). The acidic and moist southern Boreal forest zone supplying electrolytes covers southern, central and eastern Finland (Alalammi 1988). The same area also presents the highest surface coverage of lakes and lake percentage (Karlsson 1986). Western Finland and the whole of Ostrobothnia are conspicuously poor in meromictic lakes. The flat, windy (Alalammi 1987) and submesic coast area does not therefore fulfil the requirements for producing such lakes. The most likely regions containing most meromictic lakes is the Salpausselkä end-moraine zone and the area confined to the Salpausselkä zone, Ostrobothnia, the Kainuu Region and the eastern border of Finland (Fig. 2).

It has been found that meromictic lakes are an ideal environment for the formation and preservation of annually laminated sediments. Varves require an environment that lacks post-depositional disturbances of the sediment surface, such as bioturbation, water turbulence and gas bubbling (Renberg 1982, Saarnisto 1986). The anoxic monimolimnion can maintain only bacterial life, and therefore bioturbation is negligible. Water turbulence is also minimal because the lakes are stratified and overturn cannot reach the bottom. Therefore, meromixis and varves are often found in the same lakes. Studies on annually laminated or varved lake sediments are frequent in Finland (Ojala *et al*. 2000, Ojala 2001 and references therein). The amount of data on varved lakes is much greater than on meromictic lakes, although fortunately many inland meromictic lakes have been identified as a by-product of varve studies. However, because all meromictic lakes are not varved and *vice versa*, varved lake studies alone are inadequate for obtaining data on meromixis.

Many reports of irregular circulation tendencies and possible meromixis are provided vaguely or without confirmation. Valid meromictic status of a lake requires more than occasional water analyses. Water analyses should be regular and cover a period of several years. Fortunately, paleolimnological studies can provide a simpler and faster method. A paleoredox reconstruction with chemo- and biostratigraphy of a full-length sediment column gives data on the entire life span of a lake. While a sediment study alone is insufficient, if it is complemented by water analysis the whole history and temporal circulation status of a lake can be revealed (e.g. Tracey *et al*. 1996).

Conclusions

1. Only true meromictic lakes should be called meromictic; holomictic lakes with irregular circulation tendencies should be given some other term, for example incomplete holomictic.
2. This study led to a revised classification for meromictic lakes, based on the original primary factors that have initiated the meromictic processes, and it includes four principal groups (Table 1): (1) meromixis that results from inflow/precipitation of saline water over freshwater or freshwater over saline water, (2) meromixis that results from superficial diffuse nutrient load and/or turbidity currents from the catchment, (3) meromixis that results from subsurface inflow of groundwater, (4) meromixis that results from inadequate mixing due to the morphology.
3. Identified Finnish meromictic lakes are mainly from Group 1 and 2: five coastal lakes from Group 1 and seven inland lakes from Group 2. Three lakes from Group 2 are mainly of anthropogenic origin and four of natural evolutionary origin. At present, only one lake represents Group 4 and none Group 3.
4. The theoretical search on hitherto unknown meromictic lakes in Finland produced an estimation of a few dozen lake cases. The probability of finding them is not high, since, based on this estimation, only one lake in 800 is meromictic. Their probable occurrence, excluding the coastal lake cases, lies in the Salpausselkä end-moraine zone and in areas between the Salpausselkä zone, Ostrobothnia, the Kainuu Region and the eastern border of Finland (Fig. 2).
5. The importance of meromixis is due to its characteristic ecosystem and sedimentation structure, which as a depositional archive is valuable for research.
6. Meromictic lakes are very sensitive to environmental changes and require protection.

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