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SESTON FLUXES AND SEDIMENTATION DYNAMICS IN SMALL ESTONIAN LAKES

Abstract

JAANUS TERASMAA

TLÜ KIRJASTUS

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Chair of Geoecology, Faculty of Mathematics and Natural Sciences, Tallinn University, Estonia

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Supervisor: Jaan-Mati Punning, DGeogr, Director and Head of the Environmental Research Department of the Institute of Ecology at Tallinn University, Professor and Head of the Chair of Geoecology of the Faculty of Mathematics and Natural Sciences at Tallinn University.

Opponent: John F. Boyle, PhD, Department of Geography, University of Liverpool.

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CONTENTS

LIST OF PUBLICATIONS

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I. Punning, J.-M., Terasmaa, J. & Tõugu, K. 1999. Changes in the human impact on Lake Ruusmäe in recent decades and their reflection in the sedimentary organic matter. *Proceedings of the Estonian Academy of Sciences. Biology. Ecology*, **48(2)**: 130–142.

II. Punning, J.-M., Koff, T., Alliksaar, T. & Terasmaa, J. 2002. Tracing the pathways of particles settling into a small lake. *Proceedings of the Estonian Academy of Sciences. Biology. Ecology*, **51(4)**: 227–241.

III. Punning, J.-.M., Terasmaa, J., Koff, T. & Alliksaar, T. 2003. Seasonal fluxes of particulate matter in a small closed lake in northern Estonia. *Water, Air and Soil Pollution*, **149**: 77–92.

IV. Punning, J.-M., Koff, T., Sakson, M. & Terasmaa, J. 2004. Human impact on the ecosystem of Lake Ruusmäe (southern Estonia) traced in the sediments. *Polish Journal of Ecology*, **25–3**: 285–299.

V. Punning, J.-M., Alliksaar, T., Terasmaa, J. & Jevrejeva, S. 2004. Recent patterns of sediment accumulation in a small closed eutrophic lake revealed by the sediment records. *Hydrobiologia*, **529(1)**: 71–81.

VI. Punning, J.-M., Terasmaa, J. & Kadastik, E. 2005. Grain size of the bottom sediments of Lake Juusa (southern Estonia) as the indicator of water level fluctuations. *Proceedings of the Estonian Academy of Sciences. Geology*, **54(1)**: 40–51.

VII. Terasmaa, J. 2005. Bottom topography and sediment lithology in two small lakes in Estonia. *Proceedings of the Estonian Academy of Sciences. Biology. Ecology*, (accepted).

VIII. Terasmaa, J. 2004. Factors affecting sediment accumulation and sedimentation analysis in two small lakes in Estonia. Kadastik, E. & Punning, J.-M. (eds.). *Geoecological Studies,* Institute of Ecology Publications, **8**: 36–60 (in Estonian).

Other publications in the relevant area:

IX. Terasmaa, J. 2001. Influence of morphometric characteristics on sediment accumulation in small Estonian lakes. Master's thesis, Tallinn Pedagogical University, 102 pp (in Estonian).

Author's contribution:

The author holds complete responsibility for papers **VII** and **VIII**. In the case of papers **V** and **VI** the author was responsible for analysing and discussing problems connected with the lithology of surface sediments, developing the general concept and visualisation. In papers **II** and **III** the author's contribution was the collection and processing of sediment trap data and finding and visualising regularities of seston fluxes. In the case of papers **I** and **IV** the author was mainly involved in the collection of historical data and analysis of problems connected with changes in land use.

ABBREVIATIONS

DM – dry matter
OM – organic matter
MM – mineral matter
SFAP – spherical fly-ash particles
DR – dynamic ratio
SI – slope inclination
D – water depth
DS – distance to shore
CP – composite parameter

PREFACE

The present study focuses on seston fluxes and sediment accumulation in small Estonian lakes. The study of these processes in small lakes is necessary because the research made in the world so far has been devoted mainly to large lakes, where the processes are to a great extent affected by wave action. As sediment reflect changes that have occurred in the lake and in its vicinity, they are a rewarding material for studying events that took place in the past. To correctly interpret palaeoinformation it is necessary to understand the spatio-temporal dynamics of the sedimentation process. It is this aspect of the process that the present study attempts to clarify.

During a number of years the author has studied seston fluxes and sediment accumulation in several small lakes of Estonia. Analysis of findings and generalisations for four of these lakes are presented in the present dissertation. As the lakes chosen for study are similar with respect to part of the parameters and quite different with respect to others, the direction and thoroughness of study differ.

Lake Jussi Pikkjärv was selected as the main object for the study of seston fluxes (**II, III**) because of its location in a region with rather limited human activity as well as variable bottom topography, which offered wide opportunities to expose sediment traps at different depths and in areas with different bottom configuration. A shorter experiment with sediment traps was conducted on Lake Viitna Linajärv, where a balance of seston fluxes was compiled in parallel with investigation of already deposited material, to elucidate causes and effects of different processes within a lake accompanying changes in meteorological conditions.

The spatial development of the lithological composition of sediment over the whole lake bottom was studied in two lakes – in Lake Viitna Linajärv and in Lake Väike Juusa (**VII**, **VIII**). The results obtained created a good base for finding the principal regularities and factors as well as for building a model for determining areas with different sedimentation regimes within a lake.

In applying the results obtained in the interpretation of palaeorecords, it is important to calibrate the results and study cause–result relationships. The best way to do this is to make use of historical information and to compare the affecting factors and changes in the sediment layers formed during the time concerned. As the time factor does not yet play an important role in the case of sediment surface layers (compaction of sediment has not yet taken place), it is important to elucidate for the investigation of deeper layers whether and how information is preserved in sediment. The respective studies were conducted in sediments of Lake Ruusmäe, in whose drainage basin and in the lake itself the anthropogenic changes during the last decades are well documented (**I, IV**). In addition the effect of water-level change on the formation of sediment was studied in Lake Viitna Linajärv, to clarify its reflection in changes in the lithological composition of sediment (**V**).

During the last stage of studies the knowledge obtained from the investigation of surface sediments and seston fluxes of Lake Väike Juusa were applied to study older sediments (**VI**). For this purpose the regularities found in the grain-size composition of sediments were used for the zonation of long cores and for delimiting periods with different sedimentation conditions.

The present dissertation consists of two parts – the first part is a brief survey of the main results of investigation and the second consists of published papers.

1. INTRODUCTION

Lake sediment can be regarded as a mirror that provides long-term records of past changes in climate–catchment processes as well as changes in biological communities in lakes. In order to improve understanding and interpretation of information hidden in sediments there is need for better knowledge about spatio-temporal dynamics of sediment processes. Every particle that has reached into the lake and accumulated into the sediment can be regarded as carrier of information about its origin and pathways. However, this information is available only since certain level of generalisation.

As to its origin, the material deposited in lakes is either autochthonous (formed *in situ*) or allochthonous (transported into the lake from outside) (Håkanson & Jansson, 1983). The spatial distribution of sediments in a lake represents a complex interaction between sources in the catchment, the characteristics of the sediment that reach the lake, the limnological processes occurring in the lake, and the morphology of the lake basin (Gilbert, 2003). The interpretation of all sedimentological data requires knowledge of principal regularities of sediment accumulation: how the sediment is formed in the lake, which factors have influenced the sedimentation process, the composition of the deposited material and its origin. Sedimentation in lakes is controlled by different forms of energy input, in small closed lakes these are mainly heat transfer and gravitational energy, which causes slumping and sliding on steep underwater slopes (Dearing, 1997). The amount of MM and grain-size composition of sediment are the indicators of processes in the lake basin (Boyle, 2001) and changes in water-level, which enable reconstruction of the hydrological balance of the lake. Grain-size distribution can be used as an environmental indicator in sedimentary investigations (Sun *et al.*, 2002). The bulk of the (organic) material in the sediment has formed in the lake itself, mainly in the trophogenic water layer in the course of plant life; however, also the vegetation outside the lake is of rather great importance. The OM can have a significant role in the ecology of a lake. Studies show that mobilisation of this material in the ice-free period happens very often; especially nutrients influence the productivity of micro- and macro-vegetation in lake (Wetzel, 1983; Huttula, 1994). Ecologically, sedimentation of organic particles transfers energy from the trophogenic to the tropholytic layer, thus forming an important pathway in the metabolism of the lake ecosystem (Simola, 1981).

The origin of settling particles and their time- and space-dependent variations in a waterbody determine the flux of matter to the sediment. Therefore studying fluxes and composition of trapped particles in a lake is of great importance for estimating internal pollution fluxes as well as for interpreting information stored in sediments (Boers & Uunk, 1991; Weyhenmeyer

& Bloesch, 2001). Most particles suspended in water (seston) have a density greater than that of water and are therefore sedimenting or sinking in relation to the surrounding medium; for this reason particles of seston possess a wide range of sinking rates (Simola, 1981). In limnological studies the measurement of sedimentation fluxes of seston is important for the determining water quality and studying biogeochemical cycles (Tartari & Biasci, 1997). Seston concentration in a lake has great importance for the light climate and subsequently for the growth of phytoplankton (Markensten & Pierson, 2003). The release of nutrients from the sediment affects the production of autochthonous particles and the trophic state of lakes (Søndergaard *et al.*, 1992; Martinova, 1993). In many cases, the intensity of resuspension and focusing of sediments directly control the reliability of palaeolimnological reconstructions. The application of sediment traps enables to estimate the flux of matter in the water column (Bloesch & Uehlinger, 1986) or sediment accumulation in the bottom of the lake to be measured (Weyhenmeyer *et al.*, 1995**;** Heiskanen, 1998) and helps to determine the importance of sediment resuspension in lakes with different morphometry (Evans & Håkanson, 1992; Stheinman & Parparov, 1997; Mieszczankin & Noryskiewicz, 2000). The rates of sedimentation of particles can be thought as the sum of new particles production and resuspension of old, sedimented particles from the lake bottom (Evans & Håkanson, 1992).

Resuspended sediment affects near-bottom seston composition and is also important due to its impact on internal phosphorous loading (Gons *et al.*, 1986; Carmichael & Valiela, 2005). Istvanovics *et al.* (1992) showed that resuspension plays a leading role in the cycling of nutrients in lakes and, therefore, determines the resistance, resilience and capability of lakes for recovery. Trap data and different model calculations (Bloesch & Uehlinger, 1986**;** Weyhenmeyer *et al.,* 1996) have also been applied to quantify particle fluxes and resuspension in lakes with different morphometric parameters and trophic state. In these cases, the studies were concerned mainly with the fluxes of total DM and its organic fraction in traps exposed in different sites and depths. Davis (1968) studied sedimentation rates of pollen in lakes and concluded that pollen influx in lakes rather varies with factors not associated with the surrounding vegetation. These include sedimentary processes within the lake, and differences between the lakes due to lake size and morphometry.

Sediments that accumulate in lake basins consist of numerous source materials. The composition of sediment is influenced to a great extent by the geomorphology of the lake basin (Wetzel, 1983; Gilbert, 2003). On the basis of sediment composition and bottom morphometry of the lake, areas with different sedimentation regimes can be distinguished (Håkanson, 1977; Håkanson & Jansson, 1983; Blais & Klaff, 1995; Dearing, 1997; Håkanson *et al.*, 2000). The main areas are erosion, transportation and accumulation areas. Erosion areas are most frequently in shallow waters and/or on deep slopes (SI > 14%) and are characterised by coarse or consolidate deposit. The sediments within the areas of transportation are generally very variable – from sand to loose mud, slopes are gentler than in erosion areas (SI = 5-14%). The depositions within the accumulation areas are comparatively loose and mainly fine-grained, with a high water and organic content (SI < 5%). An approach that distinguishes the area of accumulation and treats the area of transportation and accumulation as one is also used; the slope inclination is regarded as the best parameter for distinguishing the areas (Rowan *et al.*, 1992; Blais & Klaff, 1995; Terasmaa, 2001).

The amount of matter accumulated yearly depends on water depth – the deeper an area is located, the greater the amount of matter deposited and the smaller the particles reaching it (fractionation of sediment is taking place) (Hilton *et al.*, 1986; Rowan *et al.*, 1992; Imboden & Wüest, 1995; Chang *et al.*, 2001; Gilbert, 2003). The mean size of mineral deposits decreases with increasing distance from the shore at which the sediment can be supposed to originate, so the mean size and sorting of the sediments at a point in an extensive deposit measure the local sorting of the deposit (Allen, 1970). Gravitational movement of sediment is expressed as focusing, i.e. movement of sediment from shallower areas towards deeper ones, caused by water currents, especially during overturn (Likens & Davis, 1975; Davis & Ford, 1982). The intensity of sediment focusing may change over time (Davis & Ford, 1982). Focusing is more intensive in lake depressions with steeper slopes but it also occurs in lakes with gently sloping bottoms (Blais & Klaff, 1995). Sediment focusing brings about uneven accumulation of sediment within the lake, providing a good basis for distinguishing areas with different sedimentation regimes (Lehman, 1975; Richard *et al.*, 2001; Yang *et al.*, 2002).

Sedimentation is also affected by the vegetation in the lake – in addition to producing OM plants act as a barrier holding sediments on slopes and modifiers of near-bed water flow (Hannon & Gaillard, 1997; Rooney, 2003). Besides plants inhibit the movement of water, and thus resuspension (Madsen *et al.*, 2001). On the other hand, however, submersed aquatic vegetation itself is sensitive to underwater light conditions, physical bed-sediment characteristics, and nutrient availability in water column and sediment (Best *et al.*, 2001). An area that is classified as an area of erosion on the basis of other parameters may actually be an area of accumulation as an intensive accumulation of sediment occurs there due to the vegetation.

The above-mentioned principles are mainly valid for relatively small lakes where the role of internal waves is small. In shallow lakes with large areas wind affects sedimentation more than in small and deep lakes that have steeper slopes. In large lakes, where wind-induced waves are acting strongly, a critical depth of resedimentation can be calculated. It is defined as the depth above which the critical shear stress for erosion is exceeded (Huttula, 1994). In small lakes the wind and wave influence is not so important. To describe such difference, a dynamic ratio DR (DR = $S^{1/2} \bullet D_{\text{average}}^{-1}$, where S is the lake area (km^2) and D_{averge} its average depth (m)) has been developed (Håkanson & Jansson, 1983). It is regarded as a good diagnostic parameter for describing areas with different sedimentation regimes. The higher the DR value, the greater the importance of taking into account the influence of the wind and waves on sedimentation. When DR is very small (<0.05), the slope inclinations are of great importance and the accumulation area in the lake is smaller. It has been proved that there exists a relationship between the value of DR and the focusing of the sediment (Håkanson & Jansson, 1983; Weyhenmeyer *et al.*, 1995; Lindström *et al.*, 1999). Studies in small Estonian lakes (Punning *et al.*, 2003) show that in lakes of small DR the flux of resuspension of deposited particles is relatively small. The role of resuspension is greater below the thermocline and is mainly determined by the near-bottom transport fluxes (focusing), which are stronger in areas with steeper slopes.

The state and evolution of the ecosystem are affected by various biotic and abiotic factors, natural and man-induced processes of variable level and duration. The problem of human influence is particularly difficult to solve due to the multitude of variables that determine the changes in the biogeochemical cycling in lakes, as well as in the chemical and biological composition of the sediments. As the total impact of different processes on ecosystem will have complex consequences, the study of the acting mechanism and relations between the impact on the ecosystem and its results is extremely complicated. The information (biological, geochemical, lithological) stored in sediments allows us to follow the changes in the processes affecting the sediment deposition over certain periods (Chambers, 1993; Charles & Smol, 1994; Smol *et al.*, 1997).

Another important aspect is lake-level fluctuations, which has a major impact on rates of net sedimentation in lakes (Verschuren, 1999, 2001), the reconstruction of past lake-level changes can best be achieved by the examination of several types of complementary litho- and biostratigraphical evidence (Hannon & Gaillard, 1997). Sedimentary signals for lake-level changes in small lakes are usually found in marginal sediments that are sensitive to fluctuating lake levels in various ways, e.g. water depth may control the distribution of sediments and macrophytic vegetation; good indicator for determining lake-level changes is grain-size distribution (Digerfeldt, 1986; Dearing, 1997). Fluctuations of lake water-level alter the lake morphometry and transform the characteristics of sediment zones of the lake bed, thereby directly influencing sedimentation and resuspension, and also properties of sediments, for example their MM content and grain-size distribution, and will lead to an increase in the rates of MM delivery (Shteinman & Parparov, 1997). Grain-size distribution in small Estonian lakes is not studied very widely (Vaasma, 2004), for large lakes a comprehensive lithological approach was developed by Raukas (1999).

Lakes are dynamic response systems that integrate environmental and climatic response into a continuous, high-resolution archive of local and regional change (Schnurrenberger, 2003). The best way to obtain long-term data on the development of a lake ecosystem is the palaeoecological approach. An important task of palaeoecology is to understand the main outlines in the history of a lake ecosystem and on this base to generate ideas for lake restoration (Battarbee, 1999). The potential of a lake to accumulate high-quality records is primarily determined by it topography: undisturbed sediment accumulation requires great water depths or a suitable DR (Håkanson & Jansson, 1983; Verschuren, 1999). Because spatio-temporal regularities of horizontal and vertical matter fluxes determine the sedimentation regimes and redistribution of settling matter within the lake basin, understanding of the accumulation mechanism has high importance in the palaeolimnological studies (Bloesch, 1995).

2. OBJECTIVES

The main aim of the investigations was to model seston fluxes and sediment accumulation in small Estonian lakes located in different landscapes and different land-use conditions, with different bottom topography and trophic state. The objectives of the study were:

- to work out an comprehensive methodology to identify the main pattern in the distribution of particles with different characteristics inside the lake and their pathways to the sediments;
- to study recent sediment deposition in relation to basin morphometry parameters (water depth, distance to shore, underwater slopes) and work out a composite parameter to describe the patterns of sediment composition and its temporal dynamics over the whole lake basin;
- to relate the catchment disturbances and land-use changes in the surroundings to the changes of different palaeoindicators in the lake sediments;
- to apply the spatio-temporal regularities of the lacustrine sedimentation process in palaeolimnological study.

3. STUDY AREAS

The studied lakes are located in different landscapes with different land-use patterns and have different bottom topography (Fig. 1, Table 1). Selection criteria for studied lakes was their size (less than 10 ha), closeness and all lakes being in the same development line – Lake Jussi Pikkjärv (hereafter Lake Jussi) is meso-eutrophic, Lake Väike Juusa (hereafter Lake Juusa) and Lake Viitna Linajärv (hereafter Lake Linajärv) are eutrophic and Lake Ruusmäe (hereafter Lake Ruusmäe) is hypertrophic.

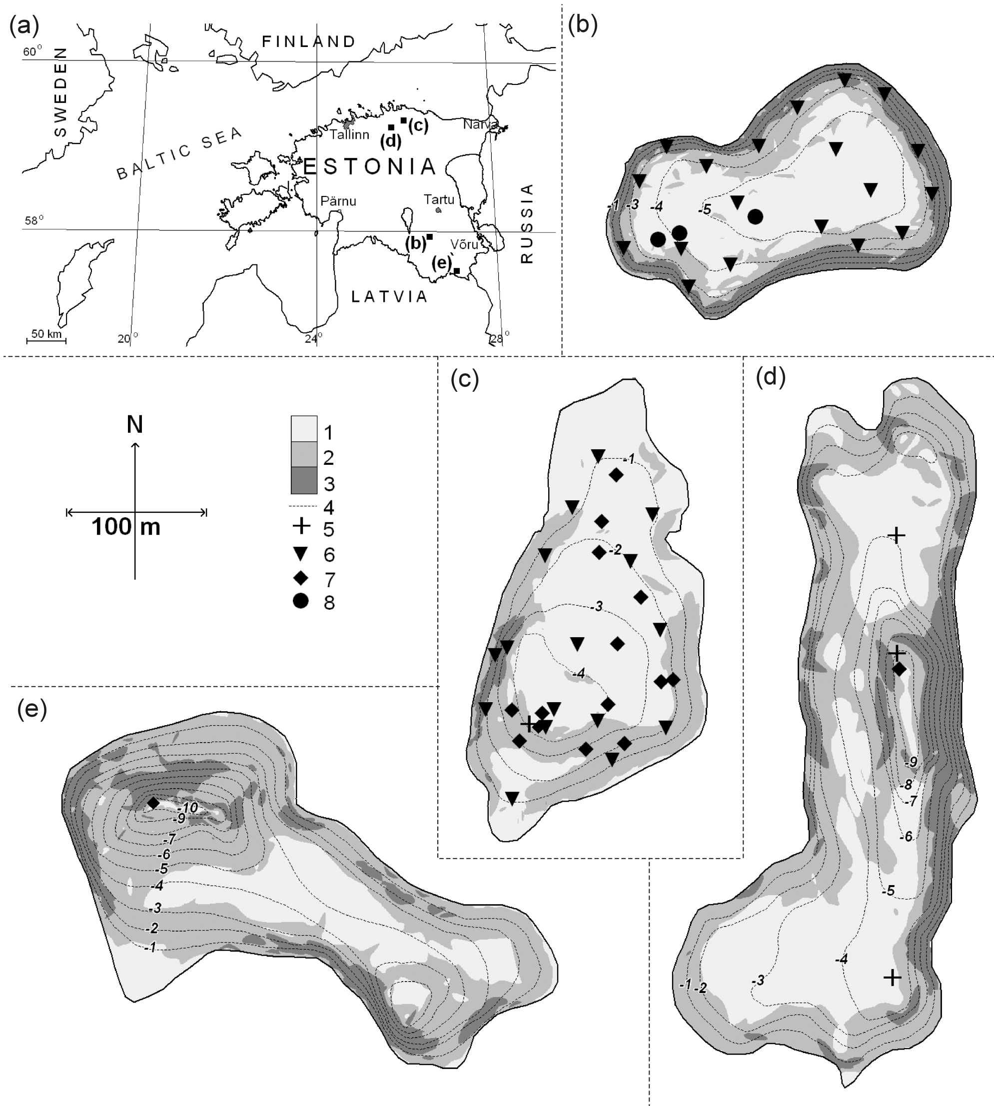

Figure 1. Location of the studied lakes (a), their bathymetry, slope inclination and location of sampling sites: Lake Juusa (b), Lake Linajärv (c), Lake Jussi (d), Lake Ruusmäe (e). 1 – SI < 5%; 2 – SI = 5 –14%; 3 – SI > 14%; 4 – bathymetric line; 5 – sediment traps; 6 – surface sediment samples; 7 – short cores; 8 – long cores (see Tables 1, 2).

Table 1. Characteristics of the studied lakes

Characteristic	Lake Juusa	Lake Linajärv	Lake Jussi	Lake Ruusmäe
Volume (V), m^3	111 000	69 000	215 000	160 000
Area (S), ha	3.0	3.8	6.4	4.7
Maximum depth (D_{max}), m	6	5	10	11
Average depth ($D_{average}$), m	3.9	1.8	3.4	3.4
Maximum length (L), m	250	350	520	390
Maximum width (W), m	160	170	200	230
Perimeter (P), m	710	870	1350	1040
Average slope inclination, ($SI_{average}$), %	8.7	4.5	8.2	9.1
Dynamic ratio (DR)	0.04	0.11	0.08	0.06
Shape factor (V_d^{-1})	0.49	0.91	0.99	1.07
Catchment area, ha	55	34	24	22

3.1. LAKE JUUSA

Lake Juusa (58°03´ N, 26°30´ E) is situated in the hilly part of the Otepää Heights in southern Estonia in the territory of the Otepää Landscape Reserve (Fig. 1). The climate in the area is continental, mean annual precipitation is a little over Estonian average, and the snow cover lasts somewhat longer. The lake is situated in semi-open cultural landscape. The northeastern and eastern shores are the steepest. The surrounding terrace is ca 2 m higher than the present water-level. The catchment lies at 122 to 180 m a.s.l., close to the lake the relative heights are within 20 m. The hillocks that border the lake are formed of glaciofluvial deposits and till and have steep slopes; there is a paludified area in the lake's western side. In the catchment *Eutric Histosols* and *Podzols* predominate. The forests are birch-dominated, but alder and willow are widespread close to the lake.

Lake Juusa is an E–W oriented small lake, the deepest area in the lake (6 m) is in it eastern part (Fig. 1b, Table 1). The lake is characterised by a concave hypsographic curve (approximately 70% of the total water mass in the lake is in the epilimnetic zone) and very small dynamic ratio (DR = 0.04) (Fig. 2a). The lake bottom has a relatively regular shape; the near-shore zone deepens abruptly. The deep area is large and gently sloping. The slope inclinations are greatest (up to 20%) at depths from 0 to 3 m. The inclination of the deeper slope decreases rapidly and is on average only 2% at depths of 5–6 m.

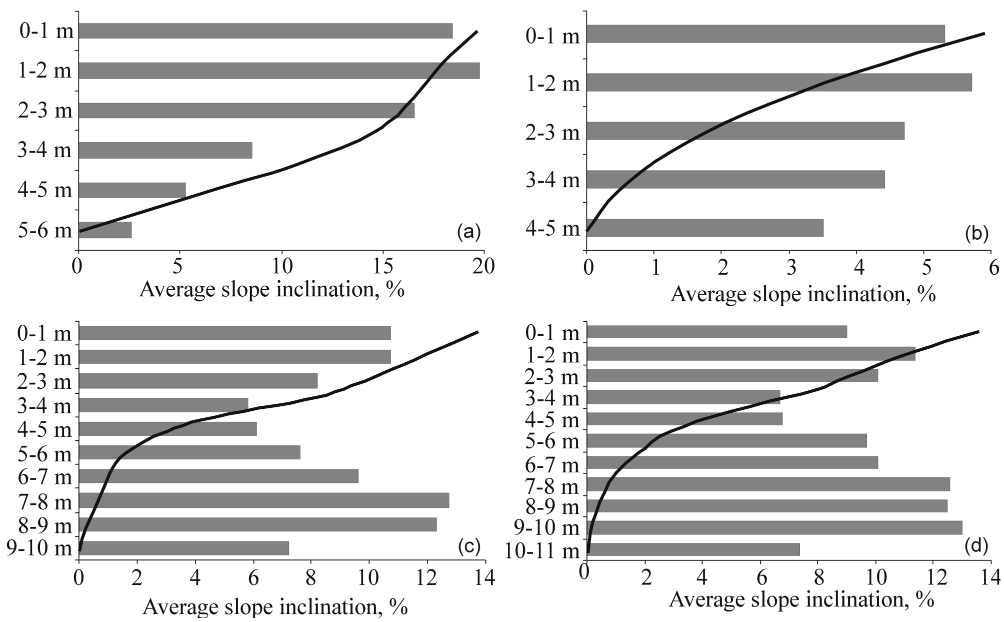

Figure 2. Average slope inclinations (grey columns) and bathymetric curves (black curve) of the studied lakes: Lake Juusa (a), Lake Linajärv (b), Lake Jussi (c), Lake Ruusmäe (d).

Lake Juusa is a mesotrophic-eutrophic dimictic lake with stratification (at depth's of about 2.5 to 3.5 m) during the spring and summer seasons. The near-bottom layers contain no oxygen during the whole year. The bottom sediments of Lake Juusa are up to 12 m thick in the deepest part of the lake. The upper sediments consist of brownish gyttja rich in water (on average 90%), LOI is quite low (on average 30%).

During the 20th century the trophic state of Lake Juusa has changed because of human impact. Near the lake are located three households. Until the 1950s the lake was used for flax retting.

In the period of collective farms fields near the lake were used intensively for agricultural purposes.

3.2. LAKE LINAJÄRV

Lake Linajärv (59^{o}27´ N, 25^{o}01´ E) is situated in Lahemaa National Park in northern Estonia (Fig. 1). The study area is located in the climatic zone of inner Estonia, which is a transition area with strong maritime features. Steep sloped eskers flank the lake to the west and south. On the east, a terraced fluvioglacial plain borders the lake and in the north is a small paludified area. The altitude of the catchment ranges from 75 to 95 m a.s.l. Lake Linajärv is in the region of glaciofluvial and limnoglacial sediments. The dominant soil type is *Podzols* on nutrient-poor sand. Pine forests with some other species, such as birch and alder, dominate on the poor sandy soils.

Lake Linajärv is a dimictic eutrophic lake. Its maximum depth (in the SW part of the lake) is 5 m (Fig. 1c, Table 1). The northern part of the lake is shallow with a mean depth of 1–2 m and forms a relatively separate system from which matter fluxes to other parts of the lake are apparently not very large. The lake is directed from south to north and has a convex hypsographic curve (approximately 80% of the total water mass in the lake is situated in the epilimnetic zone), in which the wind and wave have a rather modest impact on sedimentation (DR = 0.11) (Fig. 2b). The smallest slope inclinations in Lake Linajärv occur at depths of 4–5 m and 0–1 m; the largest ones at 1–2 m. The occurrence of largest slope inclinations at this depth is mainly due to the transition between the shallower northern part of the lake and deeper southern part and steeper slopes in the southwestern part.

Lake Linajärv is closed and mainly feeds from precipitation and groundwater (Mäemets, 1977). During the summer the lake is stratified (the thermocline is at depths between 2.5 and 3.5 m), during the whole year there is anoxia in the bottom layers. Surface sediments consist mainly of brownish gyttja with interbedded horizons of greyish gyttja. The sediment surface layer is extremely porous, its water content is 97–98%, and LOI is on average 80%.

There is no agricultural activity in the catchment of the lake. Lake Linajärv was oligotrophic, but its previous intensive use for flax retting since the 18th until the middle of the 20th century and the present use for swimming and recreation have led to eutrophication. In recent decades the human impact on the lake has been noticeable as a motel and saunas are situated near the lake. Since the 1980s, when road building nearby caused groundwater damming, the water-level fluctuation of the lake has been observed to reach 1 m.

3.3. LAKE JUSSI

Lake Jussi (59^{o}40´ N, 25^{o}45´ E) is situated in the central part on the North-Kõrvemaa Nature Reserve in northern Estonia (Fig. 1). The climate of the area is moderately continental belonging to the climatic zone of Inner Estonia; it is a transitional area with strong maritime characteristics. The Quaternary cover is of glacial genesis, N–S directed eskers border on the lake. The lake lies between hillocks and is surrounded by steep-sloped kames to the west, north and east. In the south it borders on ombotrophic mire. The altitude of the catchment ranges from 75 to 95 m a.s.l. The catchment area of the lake is characterised by limno- and fluvioglacial sediment and large peatland areas. The lake is surrounded by pine forest with some spruces and birches on poor sandy soils, mainly *Podzols* and *Cambisols*.

Lake Jussi is a mesotrophic lake, strongly elongated in N-S direction, its maximum depth is 9.8 m (near the eastern shore) (Fig. 1d, Table 1). The lake is characterised by a convex hypsographic curve (about 70% of the total water mass in the lake is in the epilimnion), DR is 0.08 (Fig. 2c). Slope inclinations are biggest at depths between 0–2 m and 7–9 m, the lake bottom is rather flat at depths of 3–7 m.

Lake Jussi is a mesotrophic lake with stratification during the summer period (Mäemets, 1977). Bottom layers suffer anoxia during the whole year. The thermocline lies at depths between 2 and 3 m. Surface sediments of the lake are brownish gyttja with a high water content and LOI (average 97% and 85%, respectively).

During recent times human impact on the lake has been small as the area was a gunnery practice ground for Soviet military and was thus closed to the general public. As far as is known, there has not been any permanent settlement in the area of the lake catchment, economic activity has been limited to logging. In recent decades the area has become an attractive tourism site.

3.4. LAKE RUUSMÄE

Lake Ruusmäe (57°38´ N, 27°05´ E) is situated in the Haanja Heights in southern Estonia (Fig. 1).The lake is situated in the part of Estonia with the most continental climate. The amount of precipitation and the number of rainy days are above average, the snow cover stays on the heights up to two weeks longer than in the neighbouring plains (Int & Karing, 1973; Arold, 1979). The landscape in the studied area is differentiated, the altitude of the catchment ranges from 228 to 270 m a.s.l. Geomorphologically the catchment represents a till plain where *Soddy-podzolic* soils predominate but also eroded and deluvial soils are represented. The vegetation consists of mixed and coniferous forest, meadow and paludified pasture communities and crop fields.

Lake Ruusmäe is directed SE–NW, the greatest depth (up to 11 m) is in the NW part on the lake (Fig. 1e, Table 1). The lake is closed and mainly feeds from precipitation and springs. The area of Lake Ruusmäe varies in time, according to different maps, from 3.9 to 4.7 ha, depending on water-level regulation and intensity of littoral vegetation.It is a lake with a convex hypsographic curve (up to 65% of water is lying above the thermocline) and small dynamic ratio (DR = 0.06), which indicates the importance of bottom topography to sedimentation (Fig. 2d). Greatest slope inclinations (on average up to 13%) occur at depths between 1–2 m and 7–10 m. Bottom topography is the flattest (average slope inclinations less than 7%) at depths between 3 and 5 m.

The water in this dimictic lake is stratified in summer (the thermocline is at a depth of 3.5–4 m) and during the winter season anoxia occurs in the full profile. The lake is hypertrophic. The sediment layer reaches up to 11 m, surface sediments of the lake are blackish-greyish gyttja with a high water content (over 90%); LOI reaches up to 60%.

The area around Lake Ruusmäe has been in agricultural use over centuries. With the establishment of a collective farm in 1948, more intensive husbandry started. Extensive cattle breeding and related activities during the las decade of Soviet time (1979–1990) caused high nutrient loading and the lake became hypertrophic. In the early 1990s, the collective farm was reorganised, land privatised and small-scale farming started again.

4. METHODS
4.1. FIELDWORK
4.1.1. Limnological studies

The bathymetry of all studied lakes was measured and mapped, in summertime from boat and in wintertime from ice. To measure the bathymetry, an echo sounder (Humminbird 100SX) and a measuring disk of 10 cm diameter were used. For the determination of the locations of sampling sites GPS Garmine 12 (maximum horizontal accuracy 3 m) and a measuring tape were used. Using the measurement results the digital height models of contemporary lake bottom topography were constructed. These models can be used to calculate the volume, average depth and slope inclinations of the lake.

The studied lakes were monitored and their oxygen content, temperature, pH and Secchi disk depth were measured (Table 2). For measuring temperature and oxygen, different instruments were used: oxygen analyser Marvet Junior, pH Meter Evikon 6115 and Multi Probe System YSI 556 MPS. From Viitna Linajärv water samples were taken periodically at depths 1, 2 and 3 m during the ice free periods in 1999 and 2000 to measure Chl *a*.

Table 2. Data used in the study. The sampled sediments are characterised by sampling depth. The sampling time is given in parenthesis. For locations of sampling sites and sediment traps see Fig. 1

Lake	Seston fluxes	Surface sediments (0–10 cm)	Short cores (0–110 cm)	Long cores (up to 1000 cm)	Lake monitoring period	Monitoring of Chl *a*
Lake Ruusmäe	–	–	1 (1998)	–	1998–1999	–
Lake Jussi	6 traps, 12 times (6 May 1997 – 5 May 1999)	–	1 (1997)	–	1997–1999	–
Lake Linajärv	2 traps, 6 times (9 March 1999 – 25 April 2000)	16 samples (2002)	14 (1999)	–	1999–2002	1999–2000
Lake Juusa	–	19 samples (2001–2002)	–	3 (2003–2004)	2001–2004	–

4.1.2. Sampling and bottom topography

For the description of the bottom topography of the lake and the distribution of its sediments a piston corer was used. Coring was done along a profile over the longitudinal axis of the lake and on two cross-profiles. Sediment samples were taken from ice cover in winter and from boat in summer. Long sediment cores were taken from ice cover, surface samples and short cores from boat and ice cover (Table 2, Fig. 1). Different sampling methods were used, considering the sediment composition (water content).

To study newly accumulated material, sixteen surface sediment samples (up to 10 cm in length) from Lake Linajärv and nineteen from Lake Juusa from different parts of the basin (Table 2, Fig. 1) were taken using a gravity corer modified by the author. In the field the sediment samples were packed into hermetic PVC boxes and refrigerated until analysis.

A modified Livingstone–Vallentyne piston corer was used to obtain up to 60 cm long short sediment cores (Table 2, Fig. 1). Commonly short cores were divided into 1 cm sections in the field and packed in PVC boxes. In Lake Linajärv, where the upper sediments were extremely soft, a freeze-coring method was applied to take a 110 cm long surface sediment core using dry ice and ethanol (Glew *et al.*, 2001). The freeze-core was sliced into subsamples in laboratory.

From Lake Juusa three long sediment cores (10, 9 and 4 m long) were taken from ice with a Belarus (Russian) peat sampler (**VI**). The cores were described in the field and then packed into bisected tubes for transportation.

4.1.3. Seston studies

To compile the seston budget sediment traps were used. The sediment trap consisted of five cylinders with aspect ratio of 5.6 (Håkanson & Jansson, 1983; Punning *et al.*, 2000). Depending on the bathymetry of lakes the study sites were selected and at every site two traps were deployed at different depths – the lower trap ca 1.0 m above the lake bottom and the upper trap ca 1.5 m below the water surface. The aim was to get a survey of the material settling in both the epilimnion and the hypolimnion and of the effect of the thermocline on seston fluxes in a lake. In Lake Jussi three pairs of traps were placed at three sites along the longest transect in the lake (Fig. 1), in Lake Linajärv one pair was placed in the deepest part of the lake (Fig. 1). The intervals of trap exposure were selected according to the seasons (Table 2). Upon removal of the traps, formalin was added to the cylinders to halt bacterial processes and photosynthesis. After removing the traps, the material in the traps was allowed to settle, water was decanted, and the residue was dried at 105 ^{o}C to constant weight.

4.2. LABORATORY ANALYSIS
4.2.1. Lithological analysis

All sediment samples were analysed for lithological composition (water, OM and MM content). The concentration of DM in sediment was determined by drying the samples at 105 ^{o}C to constant weight. OM was measured as loss-on-ignition (LOI) after heating the samples at 550 ^{o}C for 3.5 h. The $CaCO_3$ content was calculated as the loss of weight after burning the LOI residue at 950 ^{o}C for 2.5 h. The calculations were made by following generally used standard methods (Bengtsson & Enell, 1986; Boyle, 2001; Heiri *et al.*, 2001) (**II, V**, **VI**, **VII**, **VIII**).

The grain-size composition of sediment samples was determined by wet sieving. Four metallic woven mesh sieves (36, 63, 100 and 315 μm) were stacked vertically and placed in a Vibratory Sieve Shaker “Analysette 3” PRO. A weighted subsample of sediment was placed into the upper sieve and after a suitable period of shaking (generally 15–20 min), the content of each sieve was dried at 105 ^{o}C and weighted (Folk, 1980; Konert & Vandenberghe, 1997; Last, 2001; Vaasma, 2004). Particle size partitioning was determined from the amount of sediment remaining in each specific sieve. For generalisation grain-size fractions were amalgamated into two groups: sand (>63 μm) and silt and clay (<63 μm) according to the Udden–Wentworth grain-size scale (Last, 2001; Carmichael, 2005) (**VI**, **VII**). The objective was to obtain a good overview of the influx of mineral matter present in different fractions and to follow the proportion of the sand and the silt and clay fraction in the sediment composition.

4.2.2. Geochemical analysis

Different approaches were used to study the geochemical component of sediment. The content of fossil pigments was measured by K. Tõugu by the method described by Bengtsson & Enell (1986) (Punning & Tõugu, 2000). The measurement was carried out on a spectrophotometer "Cadas100". The same equipment was used to determine biogenic silica according to the method proposed by Enell & Larsson (1985) (**I, IV**).

The C and N contents were measured by L. Lahe with a Perkin Elmer-Analyser, type PE 2400/2 (**I, IV**) and with a Fison Element Analyser EA1108 (**V**) in the Institute of Chemistry at Tallinn University of Technology. The content of organic carbon was calculated as the difference between total carbon and inorganic carbon ($CaCO_3$) (Dean, 1999), and C/N ratios were calculated as weight ratios. The P-tot concentration was determined after hydrolysis of dried matter to P-PO_4 after ashing samples at 550 ^oC and extraction with 0.5 M HCl; from parallel samples extraction was performed according to Hieltijes & Lijklema (1980) (**I**, **IV**).

Chlorophyll *a* (Chl *a*) in the water samples was determined spectrophotometrically with 90% acetone or ethanol as the extraction solvent by A. Leeben. The concentration of Chl *a* was calculated using the appropriate equations by Arvola (1981).

Samples from the freeze-core were dated by the ^{210}Pb method in the Center for Environmental Monitoring and Technology, Ukrainian Hydrometeorological Research Institute, measuring direct gamma assay using an EG&G Ortec HPGe GWL series well type coaxial low background germanium detector (Appleby *et al.*, 1986) (**V**). Older samples were dated using the ^{14}C method in the Institute of Geology at Tallinn University of Technology (using the standard scintillation technique).

4.2.3. Palaeobiological analysis

For core correlations and the modelling of fluxes of various types of specific allochthonous particles (pollen and spherical fly-ash particles (SFAP)) was used. For the preparation of pollen samples dried samples were boiled in 10% KOH and treated with standard acetolysis (Moore & Webb, 1978). The samples were washed with distilled water and stained with safranin-stained glycerol. Pollen grains were determined by T. Koff under microscope. Pollen percentages were calculated using the sum of terrestrial pollen grains (**II, III**).

For SFAP analysis a combined method (Renberg & Wik, 1985; Rose, 1990; Alliksaar, 2000) was used by T. Alliksaar. The OM was removed from samples using 32% H_2O_2; the biogenic silica was dissolved in 0.3 M solution of NaOH. A known amount of *Lycopodium* spores was added to the samples to calculate fly-ash particle concentration (**II, III, V**).

4.3. DATA ANALYSIS

To estimate the temporal dynamics of the intensity of human impact and analyse changes in lake catchments, different materials are in use (maps, archieve documents); in addition, information from interviews with local inhabitants is used. In this study topographic maps and aerial photographs from different times were used to identify changes in the catchments and lake contours. The maps and aerial photographs were digitised and analysed using *MapInfo Professional* and *VerticalMapper*. To analyse temporal and spatial changes GIS-based databases and digital height models were created for every lake and its catchment. Statistical analysis was made with help of *Microsoft Excel*, *SigmaPlot* and *SigmaStat*. For the generalisation of data different approaches are in use depending on the dataset – standard deviation or five-number summary for time series the is used. Five-number summary gives a complete description of the centre and spread of the data. For finding relationships and associations between variabilities, the Spearman correlation was used, as it is better for working with our datasets suiting also in the case of monotonous relationships.

To describe the basis of sediment composition and bottom morphometry of the sedimentology regimes the parameters of the sampling sites (water depth, slope inclinations and distance to shore) were transformed into dimensionless units to compare lakes of different size and shape in the same scale. Slope inclinations and distance to shore was found using previously compiled lake water–sediment surface morphometry digital height models. Slope inclination was determined as the mean value for an area with a diameter of 6 m surrounding the sampling site to reduce the effect of possible random variations in the course of interpolation on the determination of slope inclinations.

To estimate the combined effect of parameters describing different sampling sites a composite parameter CP was found (**VII, VIII**):

$$CP = \sqrt{\frac{D_r \times SI_r}{DS_r}} \qquad (1),$$

where D_r is the relative depth at the sampling site, SI_r is the relative slope inclination at the sampling site and DS_r is the relative distance of the sampling site to the shore. The relative depth (D_r) was found as:

$$D_r = \sqrt{D \times \frac{D_{max}}{D_{average} \times 3}} \qquad (2),$$

where D is the water depth at the sampling site (m) and $D_{average}$ is the average depth of the lake (m). The quotient of the maximum depth to the average depth multiplied by 3 is according to Håkanson & Jansson (1983) the so-called form factor V_d^{-1}. The relative slope inclination (SI_r) is found as:

$$SI_r = \sqrt{SI} \qquad (3),$$

where SI is the mean slope inclination in the area with a diameter of 6 m surrounding the sampling site (%). The relative distance to the shore DS_r is expressed as:

$$DS_r = \sqrt{\frac{DS \times L}{R_A \times W}} \qquad (4),$$

where DS is the distance of the sampling site to the nearest shore (m), L is the maximum length of the lake (m), R_A is the radius of a ring having an equal area with the lake (m) and W is the maximum width of the lake (m).

To estimate the distribution and proportion of areas of different sedimentation regimes in the lakes with the help of the composite parameter, a grid of 30 m steps was composed on the digital height model of every lake. From the grid nodes the depth, distance to the shore and slope inclinations in an area with a 6 m diameter of each point were found. The values of the relative parameters and the composite parameter were calculated using the above-given equations. Then, using the calculated values a model was built with the help of *VerticalMapper*. The model was used to delimit areas with different CP values.

5. RESULTS AND DISCUSSION

Today palaeolimnological investigations focus on estimating the reliability of palaeorecords and calibration of data with a spatio-temporal dimension. On the basis of calibration, it is possible to estimate how an accumulated sediment (and information stored in it) forms its pattern through time and space.

5.1. SESTON PATHWAYS IN THE LAKES

The study of seston pathways in lakes has great importance for understanding the matter circulation within lakes as well as the development of the lake ecosystems (Punning *et al.*, 2000). The intensity of seston fluxes and sediment resuspension and focusing were studied in Lake Jussi and Lake Linajärv. The seasonal fluxes of DM (MM, OM and C/N ratio in it), SFAP and pollen grains were studied in order to reveal the patterns of their spatio-temporal distribution in regard to seasonal variations. The idea to study the fluxes of SFAP and pollen grains was based on their pulsatory influx. A parallel upper sediment layer was studied to compare sedimentation rates and sediment composition. In Lake Linajärv also the distribution of Chl *a* in the lake water was studied, to understand the seasonal mechanism of the particles sedimentation.

5.1.1. Seasonal changes

The trapped matter in lakes consists mainly of newly produced planktonic matter, allochthonous MM and secondary flux of previously settled OM and MM. In Lake Jussi the total DM influx for the year 1997 was 1.6 times as high as for the year 1998, the largest variations were observed during summer and autumn. For both years, the difference in the content of DM between the upper traps within periods was small (up to 20%). At the same time essential variations were recorded in the lower traps depending on the exposure depth of the trap, the influx was the greatest in the deepest part of the lake (**III**). The annual influx also varied between the sites: the greatest flux was registered in traps placed in the area near steep slopes of the lake. Differences between the lower and upper traps were greater in the first year, maximum values occurred during the summer stratification and autumn in 1997.

The distribution of the SFAP in the traps in Lake Jussi reflects their different pathways into the lake – deposition from the atmosphere to the lake surface, inflow from the catchment, the discharge of snow water after ice-break, and particle distribution within the lake (**II**; **III**). As SFAP mainly are emitted in the heating period, then during the winter and spring a significant flux occurred, especially during a short period after ice-break and inflow of meltwater that includes winter deposition. In 1997 the spring was warmer than usual and thawing and runoff took place mainly before ice-break on the lake. In 1998 the spring was long and cool and the melting of snow was not so intensive (**III**). Pollen influxes are partly similar with SFAP influxes because of their strong dependence on seasonal changes and the temporal production of pollen, beside the influx of pollen grains into the sediment traps depends on weather conditions. In Estonia the highest atmospheric values of birch pollen occur from the middle of April until the first decade of May; pine pollen production reaches its peak a month later (Saar, 1996). In 1997 the flowering of birch was earlier than in 1998, when the influx maximum was in May and June.

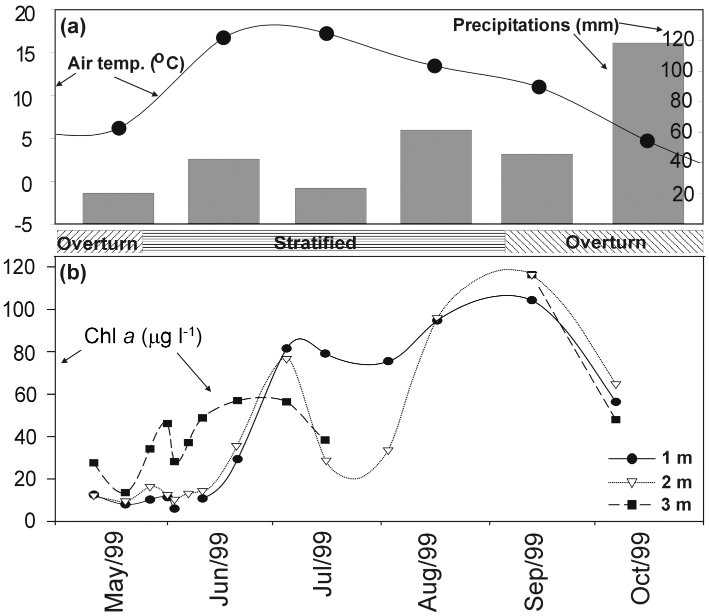

Figure 3. Air temperature and precipitation changes (a) and temporal changes in Chl *a* concentrations at depths 1, 2 and 3 m (b).

The distribution of Chl *a* in Lake Linajärv helps understand the role of OM in the seasonal variations of the fresh autochthonous biomass in the settling matter (Fig. 3b). As the Chl *a* and oxygen content in the vertical water profile indicates, the phytoplankton production began in April–May and was quite intensive in the hypolimnion until the end of June. In 1999 the summer was warm and dry, during the three summer months the total amount of precipitation was less than 140 mm. Studies (Cornett & Rigler, 1987) show that rates of seston respiration are proportional to the *in situ* water temperature and to the concentration of Chl *a*. In our work, the largest variations in Chl *a* concentration with depth were observed in July–August when the intensity of bioproduction was greater in the epilimnetic layers. In Lake Linajärv the particulate OM difference between the lower and upper traps peaked in May–June, simultaneously with the Chl *a* peak at a depth of 2–3 m.

Thus as our study shows, the particle fluxes in Lake Jussi and Lake Linajärv during the observed period could be assessed on the basis of meteorological conditions, the annual cycle of stratification in the lake, and the physical properties of particles. One of the most important factors augmenting the influx is intensive bioproduction in the lake. The intensity of bioproduction depends directly on temperature, oxygen and light conditions of the lake.

5.1.2. Spatial changes

During the exposure periods a direct relationship exists between the amount of DM in the lower traps and their depth in the water column. The differences between lower and upper traps can be caused by phytoplankton productivity in the water column below the upper trap. Results in Lake Linajärv confirm an essential share of planktonic material in the settled matter. An overview about seston pathways in a lake is given in Fig. 4. The difference between the influxes to the upper and lower traps is primarily due to the higher proportion of resuspended and autochthonous material in the lower trap. Weyhenmeyer (1996) found that plankton accounted for a major proportion of the material in traps of nine Swedish lakes; Veronesi *et al.* (1985) estimated that lateral transport and focusing prevail over pelagic resuspension. Therefore the highest influx of DM into the lower traps should not be connected only with sediment redeposition.

As our results show (**II, III**), in 1998 the bulk of birch pollen was produced before May; this was recorded in the upper traps. In the lower traps the maximum amount was reached at the beginning of stratification, mainly in June. A special case is represented by pine pollen grains due to their air sacks, because of which they may remain on the water surface for a long time. The differences of the values of pine pollen deposited into upper and lower traps show that it is after 1–2 months the signal in the lower traps has the same strength as it had initially in upper traps.

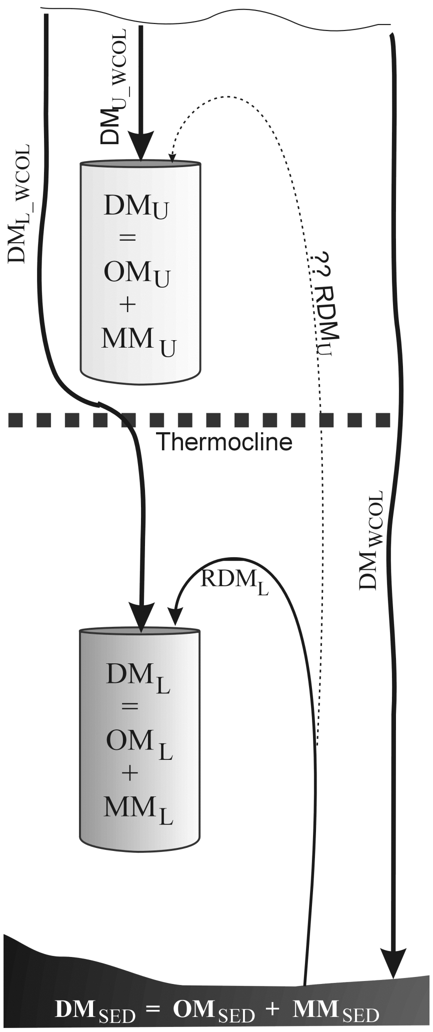

Figure 4. Seston pathways into the traps (DM – flux of dry matter, OM – flux of organic matter, MM – flux of mineral matter, RDM – resuspended dry matter, U – upper trap, L – lower trap, WCOL – flux from water column, SED – sediment).

The fact that during the autumn overturn the accumulation of birch pollen and SFAP was low and uniform indicates that resuspension and redistribution of particles within the lake are rather low in this period, as also described in some earlier papers (Davis, 1968; Pennington, 1974). This supports the hypothesis that the increase in the amount of deposited DM during early autumn is mainly caused by bioproduction.

The influx of SFAP can be considered an input surge because most particles enter the lake in spring. This enables to estimate the average sinking velocity of particles. The quantities of SFAP first increase in the upper traps (**III**), one month later in some lower traps and in the lowermost trap, located in the deepest area of the lake, the number of particles exceeds the one in the upper trap only at the end of the stratification period. Therefore, the calculated settling velocities of SFAP and pollen were comparable, but very low (6–8 cm d^{-1}), at least during the stratification period, when the thermocline might retard the sinking of some particles (Dean *et al.*, 1999). Sinking rates of 2–4 cm d^{-1} were also observed for natural phytoplankton assemblages in Lake Erken (Rodrigo *et al.*, 1998). Studies of Lake Maggiore indicate sinking velocities of 50 cm d^{-1} for particles <10 µm and 80 cm d^{-1} for particles 10–50 µm (Callieri, 1997).

Results from studies in Lake Linajärv indicate that the deposition of particulate matter is governed by particle aggregation, principally by the sinking planktonic matter with high sorption capacity. The settling material sinks as particles that together make up seston (Tartari & Biasci, 1997). Thus, the transport of fine-grained particles is affected greatly by capture of larger particles or aggretisation (especially particles <50 µm, Georgian *et al.*, 2003). The thermal regime and stratification also affect sinking velocity. The thermocline may not only reduce substantially the sinking velocity of smaller particles, but it also makes the flux of matter from the hypolimnion to the epilimnion very low or absent (Fig. 4). Studies confirm that the portion of redeposited material in the epilimnion trap is the lowest during stratification (Evans, 1994).

5.1.3. Redeposition and focusing

The influx into the trap in the deepest part of Lake Jussi was different from other lower traps mainly because of the thicker water layer above it (more bioproduction) and steep slopes near the trap, which caused more intensive sediment redeposition and focusing. The relatively similar amount of DM in all traps during summer and autumn in the second year (cold and rainy, with low production rates) suggests that the resuspension was low, not exceeding 30%. This conclusion is also supported by the influx of SFAP – similar influxes to upper and lower traps during the stratification period suggest an insignificant resuspension of particles. Studies (Weyhenmeyer *et al.*, 1996) in larger lakes with higher DR show that resuspended particulate matter may form up to 47–92% of the total flux. The mean influx of DM into sediments was much smaller than into traps (**II**). If it is caused by decomposition of OM during the sedimentation process while the influx of MM into sediment traps is the same as into bottom sediments, then ca 55% of OM must be decomposed.

Although pine pollen was mainly deposited in the traps during summer, considerable deposition also occurred in autumn. Autumn deposition is most probably the result of the redeposition or additional influx from the catchment and may be related to the sacked structure of the pine pollen grains. It took 1–2 months before the amount of pine pollen in the lower trap exceeded that in the upper traps. The influx of pine and birch pollen into the lake has temporal differences (**III**). During autumn the influx is very small, indicating a low rate of redeposition at this time. The amount of pollen in the upper and lower trap was uniform and temporal differences in the vertical distribution occurred only in the deepest area. To clarify principles of the formation of seston pathways and sediment deposition in small lakes we should consider the lake's bottom topography as an important factor in the process of sediment focusing and final accumulation.

5.2. BOTTOM TOPOGRAPHY AND SEDIMENT COMPOSITION

In the study of spatial variations in sediment composition a simplified approach was used, because our interest was focused mainly on the mineral component of sediments. Based on studies of Håkanson & Jansson (1983), we distinguish between sedimentation areas on the sediment–water surface: accumulation, transportation and erosion areas (with slope inclinations of <5%, 5–14% and >14%, respectively). Although the maximum depths and areas of the studied lakes are not very different, their bottom topographies differ greatly (Fig. 1; see also Fig. 2 and Table 1). As Fig. 1 shows, the distribution of areas with different slope inclinations (SI) is patchy, especially in Lake Ruusmäe and Lake Jussi, where areas with different SI are found at all depths. It is not possible to estimate the distribution of different sedimentation areas adequately only on the basis of SI as there are other parameters that affect the formation of sediment. In the current work we studied the impact of slope inclination, water depth (D) and distance to the shore (DS) on the sediment transport.

5.2.1. Spatial variations in the composition of accumulated sediment

Spatial variations in the composition of the surface layer of accumulated sediment were thoroughly studied in two lakes – Lake Linajärv and Lake Juusa (**VII**, **VIII**). Analysis of the spatial distribution of the components in surface sediment of Lake Linajärv revealed quite high variations of DM, allogenic MM and in grain-size composition of sediments (**VII**). The grain-size distribution of MM (**VII**) distinguishes clearly sites with a higher content of the sand fraction located on rather steep slopes and near the shore (see Fig. 1c). The sediments richer in OM and fine-grained fractions predominate mostly in the deepest part of the lake but also at the northern tip of the lake.

The variations of the lithological composition of the surface sediments of Lake Juusa (**VII**) are less conspicuous than in Lake Linajärv. The content of DM and MM is higher in the nearshore areas where slopes are steep. The slope inclinations in Lake Juusa are higher through the whole shoreline (see Fig. 1b), therefore the area of shallow water is smaller and with steeper slopes. The proportion of the sand fraction varied more notably with higher values occurring mainly in the near-shore sampling sites, lower values in deeper areas. The sediments in the eastern and northeastern parts of the lake have a coarser MM fraction than the western and southwestern parts, where OM and fine-grained fractions in MM predominating. Such distribution is probably caused by characteristics of the landscape around the lake. The same pattern was outlined by Genereux & Bandopadayay (2001).

In small lakes the dynamics of sedimentation is significantly determined by bottom topography. Bottom topography in simplified form could be described by the hypsographic curve (see Fig. 2). The type of hypsographic curve enables to draw some general conclusions about the location of different sedimentation areas. To compare lakes with different size and shape a limited number of rather easily observable parameters of the location of the sampling site (slope inclinations, water depth, and distance to the shore) was transformed to a dimensionless (relative) form and a composite parameter (CP) was compiled by author (see equations 1–4) (**VII**). In both lakes, Lake Linajärv and Lake Juusa, CP was strongly related with the relative slope inclinations (SI_r), for Lake Juusa the correlation was good also with the relative depth (D_r) and relative distance to the shore (DS_r) (Table 3) (**VII**). For Lake Linajärv practically no correlation was found between CP and the relative depth (D_r), which is due to the characteristics of the lake bottom.

Table. 3. Spearman correlations between relative parameters of sampling sites and sediment composition in Lake Linajärv and Lake Juusa. P-values are given in parentheses, NS – not significant

	Lake Linajärv						**Lake Juusa**				
	SI_r	**DS_r**	**CP**	**DM, %**	**Sand (>63 µm), %**		**SI_r**	**DS_r**	**CP**	**DM, %**	**Sand (>63 µm), %**
D_r	0.04 (NS)	0.44 (NS)	0.13 (NS)	–0.45 (NS)	–0.37 (NS)	**D_r**	–0.78 (<.01)	0.91 (<.01)	–0.80 (<.01)	–0.52 (<.05)	–0.66 (<.01)
SI_r		–0.77 (<.01)	0.99 (<.01)	0.54 (<.05)	0.54 (<.05)	**SI_r**		–0.85 (<.01)	0.99 (<.01)	0.75 (<.01)	0.86 (<.01)
DS_r			–0.75 (<.01)	–0.71 (<.01)	–0.66 (<.01)	**DS_r**			–0.89 (<.01)	–0.56 (<.05)	–0.67 (<.01)
CP				0.49 (NS)	0.51 (<.05)	**CP**				0.77 (<.01)	0.86 (<.01)
DM, %					0.91 (<.01)	**DM, %**					0.72 (<.01)

Regression analysis of the lithological composition of sediment and the parameters of the location of the sampling sites show that these variabilities are related (Table 3). Correlations in Lake Linajärv show that the sediment composition is more strongly related with the DS and

SI than with the D. In Lake Juusa the sediment lithological composition is strongly related with SI, but other two parameters also show statistically significant relations. A positive correlation between the content of DM and the grain-size distribution with SI_r means that in an area with higher slope inclinations the sediment contains less water, OM and fine-grained material has been transported to deeper places with gentle slopes. The determination coefficient (R^2) between SI_r and the sediment composition was in both lakes on average 0.3, which means that nearly 1/3 of the sediment content is determined by slope inclinations.

Sampling sites situated in the accumulation area (A area) and in the erosion and transportation area (E+T area) were distinguished using the CP values (**VII**). With the help of CP it is possible to estimate whether a certain spot in the lake sediment surface is situated in an A area or in an E+T area. To generalise the results of the studied lakes we can say that the transition from the A area to the E+T area takes place at CP value of 2.5±0.5. Grain-size composition of samples can be divided into two groups (A area and E+T area) on the basis of CP values (**VII**). In Lake Linajärv the content of the sand fraction in the samples in the E+T area is more than 68% and in the A area less than 57% at 0.95 confidence level. For Lake Juusa the difference between the content of sand between the sampling sites in the E+T area was greater, apparently due to less stable sedimentation conditions prevailing on steep slopes near the shore. In Lake Juusa the content of the sand fraction is more than 42% in the E+T area and less than 29% in the A area, with confidence level of 0.95.

Thus, it can be said that in Lake Linajärv accumulation generally takes place at greater depths than 1.3–2.3 m, slope inclinations are less than 5% and the border of the A area is about 20 m from the shore. In Lake Juusa the accumulation area begins from a depth of ca 3.5–4 m; slope inclinations are less than 5% and the distance to the shore should be not less than about 20 m.

5.2.2. Sedimentation zones and bottom topography

On the basis of studies of the composition of surface sediments of Lake Linajärv and Lake Juusa and the impact of bottom topography on it, models describing the water-sediment surface were built for all the studied lakes with the help of *VerticalMapper*. Using the model, areas with different CP values were found, and the vertical model characterising the digital water-sediment surface of the lakes was divided into three parts: CP < 2.0 (rather an A area than an E+T area), CP = 2.0–3.0 (transition area, may be one or the other), CP > 3.0 (rather an E+T area than an A area) (Fig. 5).

Such an approach notably generalises and improves the division based on SI alone (compare Fig. 1 and Fig. 5), including in the model the role played by all parameters characterising a sampling site. However, also this approach has certain drawbacks, primarily because the E+T area starts to dominate, especially so in the case of Lake Ruusmäe and Lake Jussi, where the results show as if there was no accumulation area in the deepest part of the lake. However, it should be taken into consideration here that the division shown in the figure 5 is based on points of a certain spacing (after every 30 m), and thus the deepest parts of the lake with their rather small areas proved to be too small to be clearly differentiated by this analysis. Still, a general comparison of the lakes will give quite a truthful picture, which coincides with the results of earlier analysis. The distribution of sedimentation areas is the most uniform in the case of Lake Juusa; it coincides with the course of the bathymetric curve and the general topography of the lake. The A area is the largest (45%) and the E+T area is the smallest (19%) in Lake Linajärv, which has the gentlest bottom. In the case of Lake Jussi the A area is mostly at a depth of 2–4 m, and the E+T area is determined mainly by location on steep slopes and in the nearshore area. As to Lake Ruusmäe, it stands out as the lake with an especially small proportion of the A area (5%), which can be explained by its shape and rather large slope inclinations. The largest proportion of the E+T area (56%) is found in Lake Ruusmäe; this area is especially dominant in the southwestern part of the lake where also the deepest point of the lake with steep slopes can be found. The deepest part in the lake should obviously be partially an A area due to the focusing effect; however, the resolution used in the present analysis did not show it.

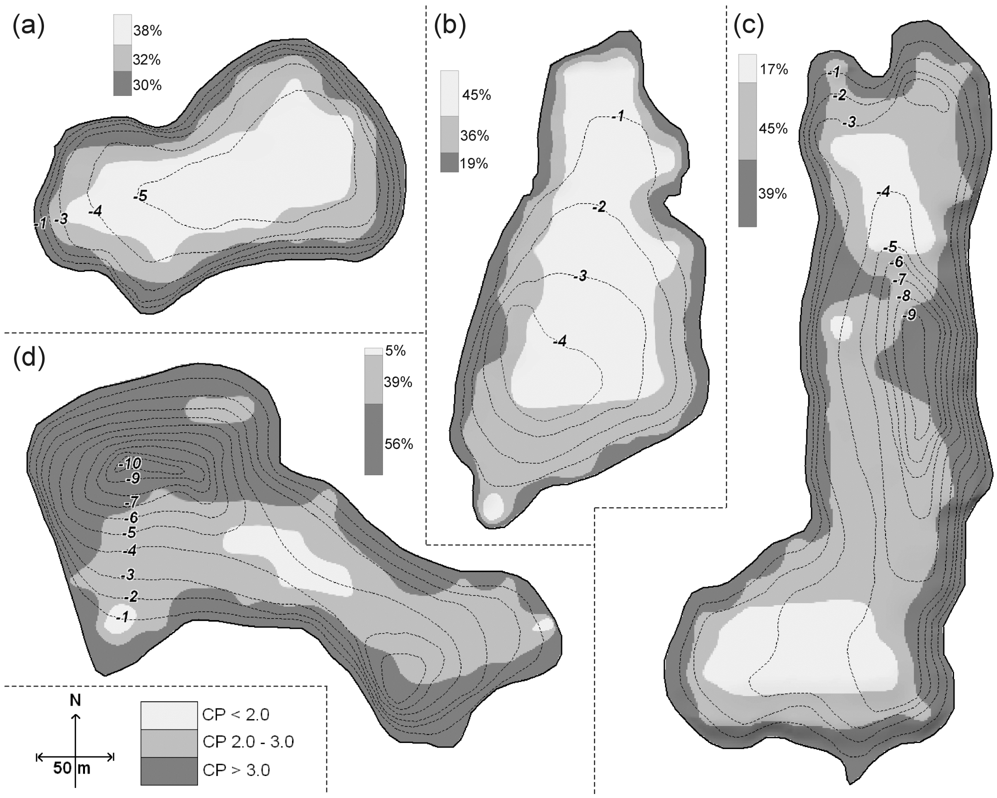

Figure 5. Areas with different CP values (CP < 2.0 – accumulation area; CP >3.0 – erosion and transportation area): Lake Juusa (a), Lake Linajärv (b), Lake Jussi (c), Lake Ruusmäe (d) on the sediment surface. The columns show the percentage of respective areas.

Thus, the described analysis of CP values provides an opportunity to delimit with certain accuracy areas of different sedimentation regimes. However, depending on the generalisation level, it may happen that small though important areas are not differentiated. Naturally, this depends also on the size and shape of the lake.

5.3. HUMAN IMPACT ON LAKE ECOSYSTEM AND ITS REFLECTION IN PALAEORECORDS

During the last century lakes in Estonia have been affected by the intensification of human activity, especially by the increased pollution load and altered water regime. An important question here is the tolerance and inertia of lakes – what is the intensity of human activity that exerts unrecoverable effect on the lake, what is the load under which no self-recovery takes place? Changes in human influence cause changes in the ecosystem, which in turn affect the composition and structure of the settling material. The aim of the study was to find out whether and to what extent documented past events in the catchment area of the lake and the response of the lake to these can be established. If palaeoecological data can be correlated to specific events, it will be possible to establish the cause–effect relationship and to model the dynamics of landscape and ecosystem. Analogous work (Engstrom *et al.*, 1985) in larger lakes about signals of changes in human impact and lake limnological conditions in lake sediment have shown good results.

5.3.1. Impact of land-use changes on the sediment composition

The most detailed study of human impact on the structure and composition of sediments was conducted in Lake Ruusmäe. For that area we have rich historical documentation showing that human impact was rather modest there before World War II and then increased continuously because near the lake a cattle farm and new apartment houses were created, and Ruusmäe became the centre of the collective farm. For gathering factual material about human impact maps were compared and materials from archives were used. (**I**).

The historical documents for the years before 1948 demonstrate that the most intensive activity on the catchment was connected with agriculture in private farms. The share of arable land nearby the lake was 39%, built-up area made about 10%. In the nearest vicinity of the lake paludified grassland with a good filtering capacity for infiltrating nutrients predominated. The period from 1948 to 1978 is characterised by a sharp increase in the human load on the lake. In 1948 the village of Ruusmäe became the centre of a collective farm, which specialised in animal husbandry (cattle shed for 500 head was built), the share of arable land decreased and that of grassland increased. Due to land amelioration, the share of paludified grassland decreased; at the same time settled areas in the nearest vicinity of the lake increased from 10% to 22% (**IV,** Fig. 2). In the third period, in the early 1980s, the intensity of land use around the lake reached its maximum level. At the beginning of 1990s, after Estonia regained its independence, the intensity of agricultural activities and cattle breading decreased.

The palaeorecords of the sediment core from Lake Ruusmäe show certain variations (**IV**). The core of the studied surface sediment (65 cm) consists of blackish-grey homogeneous gyttja. The water content increases from 86% at a depth of 65 cm to 95–97% in surface layers; the concentration of OM is increasing upward rather uniformly, having a sharp decline at a depth of 30 cm.

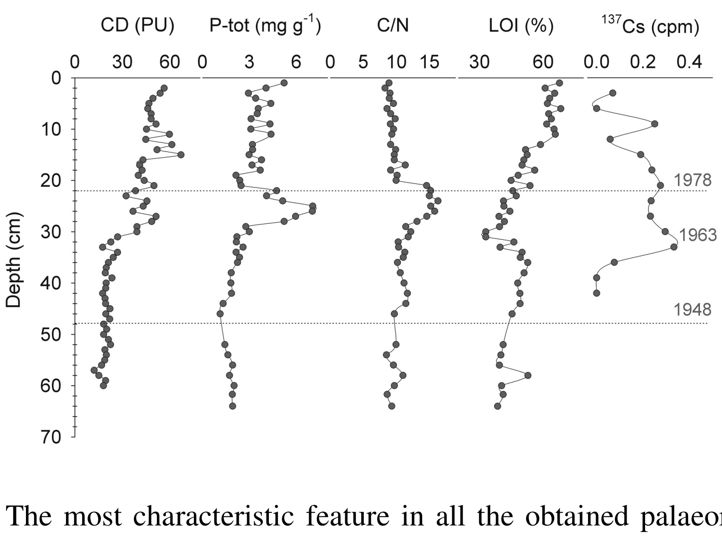

Figure 6. Variations in the content of palaeoindicators in the sediment core of Lake Ruusmäe – chlorophyll (CD), total phosphorous (P-tot), C/N ratio, loss-on-ignition at 550 °C (LOI). Stratification based on the historical data (1948 and 1978) and ^{137}Cs peak (Punning *et al.*, 1999).

The most characteristic feature in all the obtained palaeorecords is presence of two clearly distinct parts (Fig. 6). In the lower (65–30 cm) part of the studied core the records of OM and MM, concentrations of fossil pigments and phosphorus and the C/N ratio are rather even within the whole interval. These layers accumulated from the beginning of the 1940s up to the beginning of the 1970s. Although at the end of this period an essential and continuous increase of human load occurred on the catchment of Lake Ruusmäe, it did not cause principal changes in the matter cycling.

Sharp changes began from a depth of 30–29 cm upwards where practically all analysed parameters show drastic alterations, especially P-tot, which increases three-fold during a very short interval (P-NaOH is dominating). The concentration of P-org increases within this interval continuously, reaching its maximum value at 24 cm (**IV**). Such changes in the phosphorus fractions in the sediments are caused by the variations of the rate of organic sediment mineralisation and oxygen content in the lake (Enell & Löfgren, 1998; Harry *et al.,* 1992; Istvanovics *et al.,* 1992; Huttula & Nõges, 1998). The increase of fossil pigments and chlorophyll from a depth of 29 cm upwards reflects a drastic increase in the nutrient load on the lake and oxygen demand of the settled OM in the hypolimnion (Fig. 6).

Those regularities speak about major changes in the internal biogeochemical matter cycles in the lake. Diatom analysis confirms quick changes occurred in the lake ecosystem in the time period covered in sediment at a depth around 30 cm, where mesoeutrophic species are displaced by more hypertrophic species (**IV**).

While an accelerated growth of the load on the lake started already at the end of the 1950s, a clear response as noteworthy changes in carbon, phosphorus, fossil pigments and diatoms is evident only in the layers accumulated at the end of the 1960s. These fundamental changes in the ecosystem, clearly recorded in the sediment core, caused the transition of the lake from (meso)eutrophic condition to the hypertrophic state. Since 1990, after land privatisation, there has been practically no more external load, but due to the permanent anoxic condition in the hypolimnion, the lake has retained its hypertrophic state and the sedimentation regime has not changed essentially These results have been confirmed by other studies (Punning & Tõugu, 2000). It is known (Wetzel, 1983) that recycling of nutrients from internal sources in the sediments can sustain a high rate of production for many years after the influence of loading has been reduced. This, of course, makes finding exact temporal correlation between the impact of a single event and changes in the composition of sediments especially complicated. Our studies showed that in a hypertrophic lake the magnitude of seston fluxes and resedimentation is not large enough to affect the preservation of the initial information.

5.3.2. Impact of lake-level changes on the sediment composition

The sedimentation pattern can change through time for a variety of reasons, one being lake-level changes (Verschuren, 1999; Punning *et al.*, 2003; Punning *et al.*, 2005). The fluctuations of water-level alert the lake morphometry and sedimentation zones on the lake bed, thereby directly influencing sedimentation and resuspension. This may change properties of sediments accumulating in the lake, their MM content, grain-size distribution and will lead to increasing rates of MM delivery (Shteinman & Parparov, 1997).

A detailed study of the impact of the lake-level fluctuation on the sediment composition was conducted in Lake Linajärv. In the 1980s, when road building nearby caused groundwater damming, the water-level fluctuations in this lake reached up to 1 m (**V**). As studies show (Punning & Leeben, 2003), at the same time great changes in the lake ecosystem took place and the lake ecosystem became more eutrophic, fluctuations in LOI and C concentrations also point out rise of water-level in this period.

To study the impact of water-level changes on sediment composition, 13 sediment cores (up to 60 cm) and one freeze core (up to 110 cm) were used. The OM and MM concentrations, and their ratio and relationships were studied to find out changes in sedimentation for the determination of cores in the sphere of influence of water-level changes (**V**). Sedimentation was rather stable in the deeper basin of the lake, where the water depth was more than 3 m and the slope inclination was small. Using the data obtained sedimentation patterns in Lake Linajärv was examined in relation to basin morphometry. The results suggested strong links between the temporal changes in sediment composition in single cores and lake bottom topography. In the cores taken from deeper water or from areas with moderate underwater slopes, the concentration of both OM and MM increased downward rather uniformly, but in the cores that were taken from shallower areas of the lake, the concentration curves had larger variations (**V**). Most probably sediment cores from shallower areas reflect changes in sedimentation dynamics caused by water-level fluctuations during the last decades (**V**).

The cores taken from deeper areas (V4, V7) have quite uniform MM/OM ratios that decrease slowly upwards. The cores taken from shallow water or deep slopes (V8, V14) show the opposite tendency with the change being especially significant in the upper sediment layer, which may indicate a change in the water-level (Fig. 7). The variation of MM/OM in the core taken from the shallowest part of the lake that is almost overgrown (V2) is rather similar to those in the core from the deepest part (which is likewise an accumulation rather than an erosion and transportation area); however, in the upper part of the core the change from one regime into the other is more abrupt.

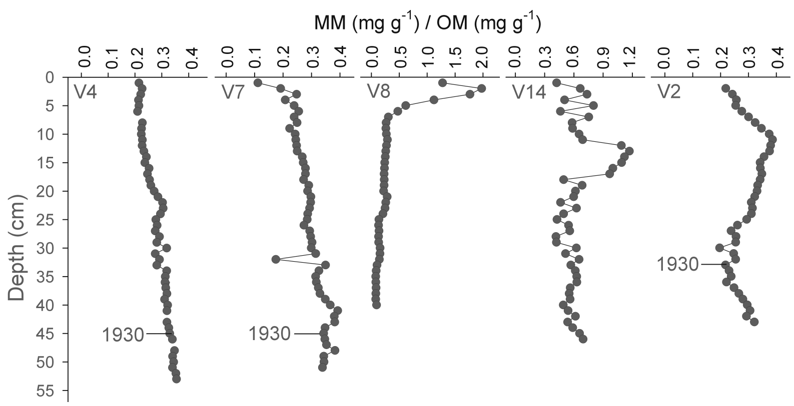

Figure 7. Changes in the MM and OM concentration ratios (mg g^{-1} / mg g^{-1}) in different cores. Year 1930 was dated using SFAP.

Results showed that the sediment accumulation, redistribution and composition are linked to the bottom topography. These results are in good accordance with previous results about the role of CP in sediment composition. The firmest evidence of water-level fluctuations is recorded in the marginal areas, in the transition zone, in the steep slopes and in the littoral zone where the water depth is less than 3 m.

5.4. TEMPORAL VARIATION IN SEDIMENT GRAIN-SIZE COMPOSITION

As previous analysis has shown, lake depth, slope inclination and distance to the shore determine up to half of the variations in the composition of sediments (**VII**). With knowledge from upper sediment analyses we can give estimations about reasons of changes that have occurred in lake sediment composition (**V**).

Grain-size analyses of samples were performed in 19 surface sediment samples and 3 sediment cores to determine the relationships between grain-size and topography of the different sedimentation areas (**VI**). On the basis of these data it is possible to reconstruct changes in lake water-level in the past and their impact on the grain-size distribution of sediment. To generalise data, the parameter F_{36} is in use, which shows the proportion of the finest fraction (36 μm) in the sediment composition among all other fractions (**VI**).

Analysis of grain-size data of surface sediments (Fig. 8) shows that the F_{36} value fits well with previous results about the lithological data of surface sediments in Lake Juusa (**VII**). The grain-size composition is given in a generalised way; the boundary is drawn between the fractions less or more than 36 μm. The points located at greater depths where the sediment is finer with the >36 μm fraction dominating are visually well distinguishable. We can assume that the boundary between the erosion and transportation area and the accumulation area lies approximately at a water depth of 3.5–4.0 m (**VII**). Analysis of diatoms and C/N in surface samples shows a clear sift in data at the same depth (Punning *et al.*, 2004). This assumption is in good accordance with the F_{36} value of 0.9 as a boundary between different sedimentation conditions. Analysis shows that the F_{36} value has a strong relationship with the water depth at sampling points (R=0.81, p<0.01). If F_{36}>0.9, the sedimentation conditions have been rather characteristic of an accumulation area.

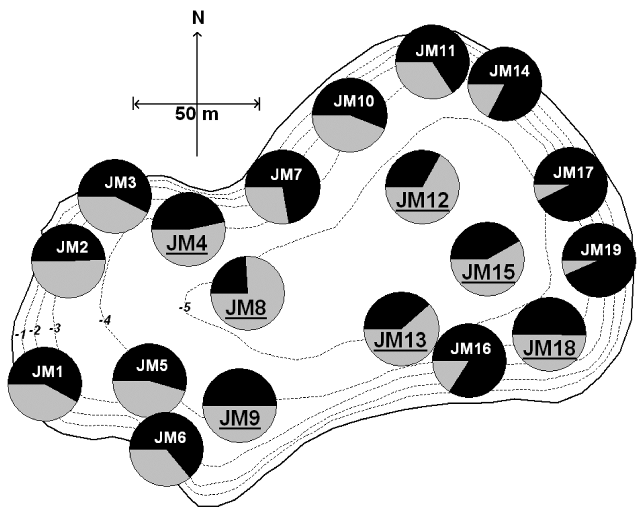

Figure 8. Grain-size composition of surface sediments of Lake Juusa (black <36 μm; gray > 36 μm). Underlined sampling sites indexes denote values of F_{36}>0.9.

The grain-size analysis of the samples from the deep core of Lake Juusa allows distinguishing several cycles (**VI**). Assuming that the F_{36} values characterise the different sedimentation areas, it is possible to estimate the intervals when the coring site was situated within the accumulation areas (**VI**). The content of coarser and finer fractions in these cycles varies periodically, especially in deep cores J31 and J20 (**VI**), where the basal layer shows the domination of the silt and clay fractions (<63 μm), and at depths of 10 m in core J20 and at 8.6 m in core J31 the content of the <36 μm fraction is over 80%. According to the variation of F_{36} it is possible to define and correlate certain depth intervals in all cores. Two intervals of cores J20 and J31 display higher values of F_{36}, showing the prevalence of finer particles. In core J30 only the lower layers have elevated values of F_{36}, while in the upper layers variations are rather occasional due to unstable accumulation conditions. Comparison of the results of cores with the depth distribution of grain-size of surface sediments suggests that at F_{36}>0.9 the lake had a regression period while F_{36}<0.9 indicates a transgression period of the lake. These results are in good agreement with the results obtained using the transect method for the same lake (Punning *et al.*, 2005).

Based on the results obtained, we can reconstruct the history of the lake in the past, including the individual sedimentation zones and amplitude of single lake-level fluctuations. It facilitates understanding the functioning of the ecosystem during different hydrothermal regimes, which is necessary for palaeolimnological studies and modelling of the processes in the future.

6. CONCLUSIONS

The aim of this thesis was to find out regularities in sedimentation patterns and seston pathways in small lakes. That is the reason why four Estonian lakes were studied during several years. As a result of this work some general conclusions can be made to clarify sedimentation processes in small lakes.

The comprehensive studies gave the following major results:

- Complex methods were developed and applied for the description of the dynamics of bottom sediments of small lakes and for analysing seston fluxes and spatial and temporal dynamics in the variation of sediment formation. Results demonstrate a relatively slow resedimentation rate of settled particles, in the case of total DM resedimentation involved up to a third of all the material. Resedimentation of particles is strongly dependent on meteorological conditions, at the same time it is greater in the traps exposed below the thermocline and near the steep slopes. In the movement of seston from the epilimnion to the hypolimnion the thremocline is a sufficient barrier to reduce the sinking velocity of particles, except in the case of small particle aggregation (mainly with planktonic matter with high sorption capacity).
- In small lakes the sedimentation is determined by lake bottom topography, which in a simplified form could be described by the hypsographic curve. Analysis of the composition of surface sediments and parameters describing the sampling site made it possible to determine certain regularities and construct a composite parameter (CP), which describes slope inclinations, distance to shore and water depth in a dimensionless way. Up to half of the variations in the composition of sediments are determined by those parameters.
- Reflection of well-documented changes in the lake catchment in the sediments gave an opportunity to estimate the effect of different disturbances on the composition of sediment and the preservation of signals of these changes in the lake sediment. As the eutrophic (hypertrophic) lakes have a strong tolerance and inertness, their response to external disturbances is lower. The influence of water-level changes on sediment composition is manifested through changes in the shape and depth of the lake, exerting thus the greatest effect on the sediment in transitional areas in the lake, especially so in areas near the shore and on steep slopes.
- The relationship between grain-size distribution of surface sediment and water depth showed that the proportion of the finest fraction in the total sample is a good indicator for estimating whether the sedimentation conditions are characteristic of an accumulation or an erosion and transportation area. This relationship was used in the case of a Holocene core and periods that coincided with those distinguished with the help of other methods were delimited.

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My thanks are due to Tiia Kaare for revising the English language of the thesis.

As the collection of material that by now has become a dissertation started already during my early university years, the importance of friends is worth special mentioning. Here I would like to thank Krister and Kalvi, who volunteered to help me during their free time. Special thanks are due to persons, who live in the neighbourhood of the lakes studied (especially villagers from Ruusmäe), who were ready to offer us lodging for the night and who patiently answered our endless questions about the history of the neighbourhood.

I warmly thank my family – my wife Aet and son Karl Joonas, who had to spend days, nights and weekends alone when I was busy with my research work. And last but not least – I am grateful to my parents, sisters and brother, who gave me an opportunity to get a good education and have always supported my research career.

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SESTONIVOOD JA SETTIMISE DÜNAAMIKA EESTI VÄIKEJÄRVEDES

Kokkuvõte (eesti keeles)

Järvesetteid võib vaadelda kui looduslikku arhiivi, kuhu salvestub informatsioon nii järves, valgalal kui ka keskkonnafaktoritega toimunud muutuste kohta ning järve reaktsioon nendele muutustele. Selleks, et ajas toimunud muutusi mõista, tuleb esmalt mõista setete kujunemise dünaamikat ning sedimentatsiooniprotsessi tervikuna. Iga osake, mis jõuab järve või tekib kohapeal ning akumuleerub settesse, kannab infot enda tekkeloo ning teekonna kohta settesse. Kuid loomulikult on see info loetav vaid teatud üldistusastme korral, kui sarnast infot kandvaid osakesi on piisavalt.

Käesoleva töö olulisus seisneb väikejärvedes toimuvate settimisprotsesside selgitamises, sest maailmas seni tehtud töödes on vaatluse all peamiselt suurjärved, milles toimuvaid protsesse mõjutavad paljuski teised faktorid, kui väikejärvedes. Rea aastate jooksul on autori poolt uuringuid läbi viidud mitmes Eesti väikejärves, milledest nelja kohta saadud tulemuste analüüs ja üldistused esitatakse käesolevas dissertatsioonis.

Töö põhieesmärkideks oli töötada välja metoodika sestonivoogude ja sette kujunemise uurimiseks väikejärvedes, luua mudel sette koostist mõjutavate järve topograafiga seotud faktorite kirjeldamiseks. Oluline oli leida ka kinnitust väljastpoolt tulevate mõjurite (maakasutusest, veetaseme kõikumisest tingitud muutused järves) kajastumise ja säilimise kohta järvesettes ning luua sette litoloogilise koostise varieerumisel põhinev üleminek pindmiste setete uurimisest paleoinformatsiooni interpreteerimiseks.

Peamiseks sestonivoogude uurimise objektiks oli Jussi Pikkjärv, seda nii tänu oma asukohale küllaltki vähese inimtegevusega regioonis kui ka varieeruvale põhjatopograafiale, mis pakkus laialdasi võimalusi settelõksude eksponeerimiseks erinevatel sügavustel ja erineva põhjakonfiguratsiooniga aladel. Lühemaajaline settelõksueksperiment leidis aset Viitna Linajärves, kus viidi läbi sestonivoogude bilansside koostamine ning paralleelselt keskenduti settinud materjali uuringutele, et leida põhjuseid ja tagajärgi, mis kaasnevad erinevate järvesiseste protsessidega ja meteoroloogiliste tingimuste muutustega. Sette litoloogilise koostise ruumilist kujunemist üle terve järvepõhja uuriti kahes järves – Viitna Linajärves ja Väike Juusa järves.

Et rakendada saadud teadmisi paleoandmestiku interpretatsioonil, on oluline tulemuste kalibratsioon ning põhjus-tagajärg seoste uurimine. Parim moodus selleks on ajaloolisele andmestikule tuginemine ja mõju ning vastaval ajal moodustunud settekihtide muutuste võrdlus. Vastavad uuringud viidi läbi Ruusmäe järve setetes, mille valgalal ja järves endas toimunud inimmõjulised muutused viimastel aastakümnetel on hästi dokumenteeritud. Lisaks uuriti veetaseme muutuste mõju sette kujunemisele Viitna Linajärves, et selgitada selle kajastumist muutustes setete litoloogilises koostises. Pindmiste setete ja sestonivoogude uurimisest saadud teadmiste rakendamine vanemate setete uurimiseks viidi läbi Väike Juusa järves. Selleks kasutati leitud seaduspärasusi setete granulomeetrilises koostises pikkade kernide tsoneerimiseks ja erinevate settimistingimustega perioodide leidmiseks.

Töö tulemustena saab välja tuua:

- Töötati välja ning aprobeeriti kompleksne metoodika väikejärve põhjasetete dünaamika kirjeldamiseks sestonivoogude ja sette kujunemise ruumilise ja ajalise varieerumise analüüsimiseks. Tulemused näitasid, et ümbersettiva materjali osakaal on kuni kolmandik kogumaterjalist; ühtlasi on ümbersettimine tugevalt seotud valitsevate

meteoroloogiliste tingimustega ning järve põhjatopograafiaga. Stratifitseerunud järves osutus termokliin piisavalt oluliseks barjääriks, et mõjutada nii sestoni langemiskiirust liikumisel epilimnionist hüpolimnionisse kui ka takistada ümbersettiva materjali taasjõudmist pindmistesse veekihtidesse.

- Väikejärvedes on sette kujunemine määratud ära põhjatopograafia poolt, mida lihtsustatud kujul kirjeldab batümeetriline kõver. Settepinna saab jaotada erineva settimisrežiimiga aladeks, pindmiste setete koostise ja proovivõtukohta kirjeldavate parameetrite (veerukalded, veesügavus, kaugus kaldast) uurimine võimaldas koostada koondparameetri (CP). CP määrab ära kuni poole sette koostise ruumilisest varieerumisest. Settimisalade jaotus CP väärtuste abil langes uuritud järvedes kokku erinevatele settimistingimustele viitavatele suurematele erinevustele setete litoloogilises koostises.
- Hästi dokumenteeritud (inimmõjuliste) muutuste kajastuvus järvesettes andis võimaluse hinnata erinevate häiringute mõju sette koostisele ja nende muutuste säilumist järvesettes. Intensiivse põllumajandustegevuse läbi toimunud muutused järve ökosüsteemis kajastusid ka erinevates settest määratud paleoindikaatorites. Veetaseme muutuste mõju sette koostisele avaldub läbi muutuste järve kujus ja veesügavuses ning on seetõttu suurima mõjuga üleminekualadele jäävale settele, seda peamiselt kaldalähedastel või järsematel veerudel paiknevatel aladel.
- Seosed pindmistes setetes osakeste suuruse jaotuse ja veesügavuse vahel võimaldasid leida algoritmi ning sette litoloogilise koostise muutuste põhjal Holotseeni puursüdamikust välja eraldada erinevate valitsevate settimistingimustega perioodi, mis langesid kokku teistel meetoditel saaduga. Heaks indikaatoriks oli peenterise fraktsiooni suhe ülejäänud fraktsioonidega, mis olenevalt väärtusest (rohkem või vähem kui 0,9) on iseloomulik vastavalt kas akumulatsiooni- või erosiooni- ja transpordialale.

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