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A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation

Lars Brydsten
Department of Biology and Environmental Science,
Umeå University

May 2004

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Lars Brydsten
Department of Biology and Environmental Science,
Umeå University

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

Abstract

A mathematical model for simulation of lake basin filling processes in areas with positive shore displacement was constructed. The model was calibrated using sediment and catchments data from eight existing lake basins situated in the northern coastal area of the province of Uppland, Sweden. The lake basin filling processes were separated into three phases: basin filling with wave-washed material (silt, silty sand or sand), filling with fine-grained material during the shallow gulf and lake stages, respectively, and filling with vegetation during the lake stage.

The basin filling rates for wave-washed material were generally low but varied considerably both between and within lakes. The mean basin filling rate of wave-washed material was 4.1%.

The volume of inorganic sediments produced, and basin filling rates during the shallow gulf and lake phases were determined for all the eight lakes. The relationship between basin filling rate and parameters describing the catchments, the former postglacial basins and the lakes, respectively, was determined using multiple regression analysis. The basin filling rate with inorganic sediments was best described by parameters related to former postglacial basin morphometry and current lake morphometry, e.g. basin volume, lake volume, and lake area. The goodness of fit (r^2) turned out to be 0.99 for a simple regression with basin volume as the sole independent variable.

The basin filling with vegetation (*Phragmites australis* followed by *Sphagnum spp.*) was treated as a 2-dimensional process. A dataset with 84 bogs was selected from a digital soil map. The ages of the bogs were calculated using a digital elevation map and an equation for shore displacement. The choke-up rate was then calculated by dividing the area of the bogs with their age. A strong exponential relationship exists between areas of the bogs and choke-up rat, and this relationship was then used in the model.

The resulting model starts by filling the former coastal basin with 4.1% wave-washed sand. Using time steps of 100 years, the sedimentation of inorganic material was then added according to the inorganic basin filling rate equation and the growth of vegetation using the choke-up rate. Growth of vegetation was only permitted on bottom areas shallower than 2 meters water depth. The model was then iterated until the former lake basin was totally filled with material.

The model was then used to predict the ontogeny of two future lakes, the “New Small Lake” and the “New Large Lake” situated close to the existing store for radioactive waste, SFR-1. According to the model, The “New Small Lake” will be completely filled with sediments and vegetation some 2500 years after isolation, while the “New Large Lake” will be completely filled 4000 years after isolation.

Sammanfattning

En matematisk model för simulering av igenväxning av sjöar i områden med possitiv strandförskjutning har konstruerats. Modellen kalibrerades med hjälp av data rörande sediment och avrinningsområden från åtta sjöbassänger belägna i Uppsala läns kustområde. Igenväxningsprocessen indelades i tre faser: sjöbassängen fylls med svallmaterial (silt, siltig sand eller sand), sedimentation med finkornigt material under en period då bassängen antingen var en grund havsvik eller en sjö samt fyllning med vegetation under sjöstadiet.

Fyllnadsgraden för svallmaterial var generellt låg men varierade avsevärt både mellan sjöar och inom enskilda sjöar. I medeltal utgjorde svallsedimentet 4.1% av den ursprungliga sjöbassängens volym.

Volymen av icke-organiska sediment avsatta under den period som bassängen var grund havsvik eller sjö beräknades för de åtta sjöarna. Sambandet mellan dessa sedimentvolymer och parametrar som beskriver avrinningsområdena, de ursprungliga postglaciala bassängerna och sjöarna bestämdes med multippel linjär regression. Volymen icke-organiska sediment befanns bäst beskrivas med parametrar relaterade till den postglaciala bassängen morfometri och den nuvarande sjöns morfometri, t.ex. bassängvolymen, sjöns vattenvolym och sjöns area. Regressionens förklaringsgrad (r^2) uppgick till 0.99 för en enkel regression med den forna bassängvolymen som enda oberoende variable.

Igenväxningen av bassängen (*Phragmites australis* följt av *Sphagnum spp.*) behandlades som en 2-dimensionell process. Ett dataset med 84 mossar valdes från den digitala jordartskartan. Åldern på varje mosse beräknades med hjälp av en digital höjddatabas och en ekvation för strandförskjutningen i området. Igenväxningshastigheten beräknades genom att dividera mossarnas areor med dess åldrar. Ett starkt exponentiellt samband föreligger mellan mossens area och igenväxningshastighet (r^2=0.99) och detta samband användes därefter i modellen.

Den slutgiltiga modellen startar med fyllning av bassängen med 4.1% svallmaterial. Med ett tidsteg om 100 år beräknas fyllningen av bassängen med ekvationerna för sedimentation och igenväxning. Igenväxningen tillåts endast på bottnar grundare än 2 meter. Modellen itererades tills dess att den forna bassängen blev totalt igenväxt.

Modellen applicerades på två blivande sjöar, den ”Nya lilla sjön” och den ”Nya stora sjön”, båda kommer att bildas nära det existerande förvaret för radioaktivt avfall, SFR. Modellen ger att den ”Nya lilla sjön” kommer att bli helt fylld med sediment och vegetation ungefär 2500 år efter isolering, medan den ”Nya stora sjön” kommer att vara totalt igenfylld 4000 år efter isolering.

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1 Introduction

In the coastal area of Forsmark (Figure 1-1), many lakes will be formed during the forthcoming 5000 years due to the positive shore displacement (Figure 1-2).

Two of these lakes have been considered important for the safety analysis of SFR-1. In this paper these two future lakes are called "New Small Lake" and "New Large Lake", respectively. The New Small Lake will be formed in 2000 years and the New Large Lake in 2800 years. In case of an accidental release of radionuclides from the repository after the lakes have been formed, it is probable that the groundwater that brings the radionuclides to the surface waters will discharge directly into or just upstream the New Small Lake /Holmén and Stigsson, 2001/. When it becomes isolated from the Sea, the New Large Lake will be located in the same drainage area and downstream the New Small Lake.

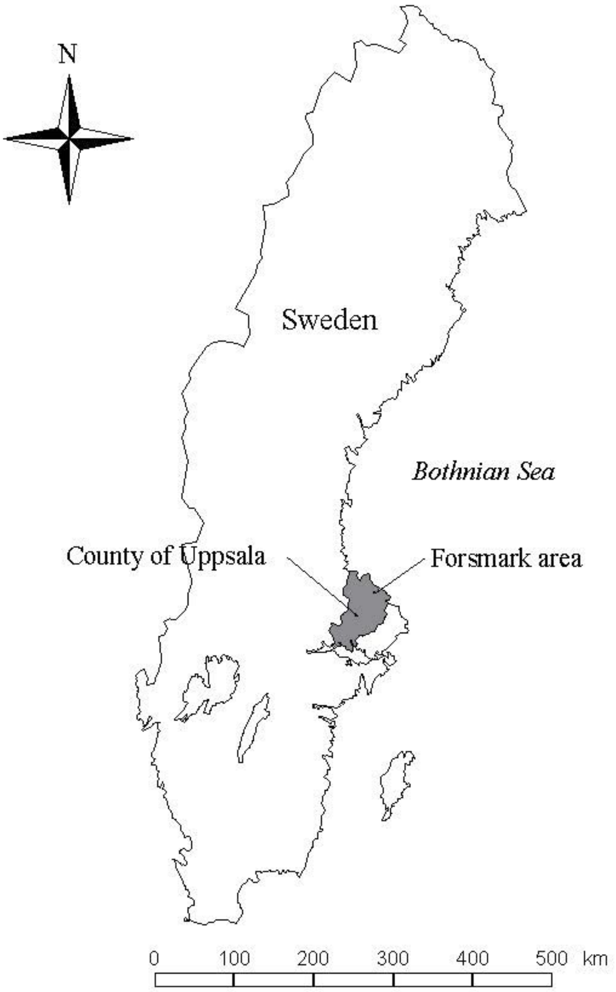

Figure 1-1. *The location of the investigation area in the northern part of the province of Uppland, Sweden.*

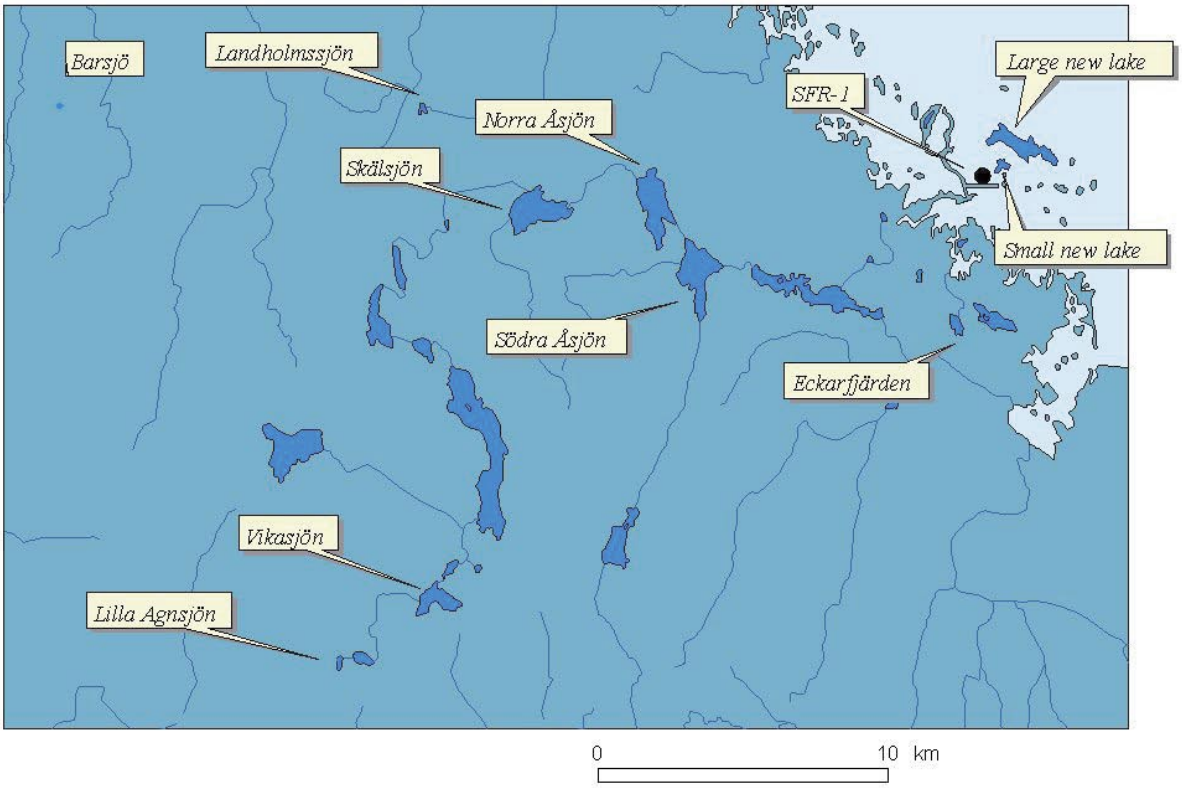

***Figure 1-2.** A detailed map over the investigation area, including the lake-rich catchment of River Forsmarksån. Adjacent catchment areas, and the coastal area of the Baltic Sea where new lake are being formed.*

The knowledge of how radionuclides will behave at the interface between groundwater and surface water in a lake is currently very limited. However, one factor which is most likely of great importance is in what stage of ontogeny the lake is. In newly formed lakes, the bottom sediments are thin and have low contents of organic particles. As a result, such lakes will lack compact bottom strata and the ground water will most likely discharge through the entire bottom of the basin into the lake. At the passage of the bottom interface, radionuclides may become adsorbed to minerogenic particles but total deposition will most likely be low. As the lake grows older, the sediment thickness increases and so does the content of organic material in the sediment. Successively the sediments will become impermeable to the groundwater and the sedimentation of material will increase. Radionuclides brought into the basin adsorbed to particles or as free ions taken up by biota, will settle out and subsequently be deposited in the sediments.

In lakes which are in late stages of their ontogeny, the near-shore vegetation is usually highly developed and consists of dense stands of emergent macrophytes and floating-leaved vegetation. In younger lakes, the vegetation is normally less well developed. In the area around Forsmark, there are currently many shallow lakes with dense belts of macrophyte vegetation, also in front of inlets and outlets. This circumstance is most likely of importance for the dynamics of radionuclides entering the lakes.

With increasing age, the share of the bottom covered by vegetation increases, and the lake is slowly transformed to a marsh. Later on in the ontogeny, the marsh is transformed to a bog, which is geohydrologically and hydrologically completely different from the previous systems. A bog is hydrologically a water recharge area, while the lake is a discharge area, a difference of great significance for the dynamics of the radionuclides. Radionuclides transported by the groundwater to the near surface ecosystem have a low probability to be trapped in a bog, but high probability to be trapped in a lake basin.

One effect of the positive shore displacement is that the groundwater discharge area is changing over time due to the decreased pressure from the lowered sea water surface. This could mean that at an early leakage from the repository, the discharge of ground water could be to surface water upstream the small lake, later on through the bottom of the lake, and even later on to the creek between the small and the large lake. In order to predict radionuclide dynamics in an area near a lake basin at different points of time, it is necessary to have knowledge of both variation in groundwater flow over time and the stage of ontogeny of the lake.

The variation in velocity of the lake basin filling process between basins with different characteristics is not well known. Obviously, there must be a large variation in velocity, since there are basins younger than 1000 years that are completely choked-up but also basins with the same size that are older than 10000 years were the choke-up process is in the initial stage. There are probably many causes for this large variation, e.g. differences in morphometry in the former basin, in catchments characteristics and in nutrient supply from the catchment area.

The aim of this study was to build a mathematical model describing the choke-up processes of lake basins, and to apply this model on the two future lakes close to SFR-1. Since the basin filling process consists of many sub-processes, many of which are difficult or impossible to describe in mathematical equations, only factors of major significance for the basin filling processes have been considered.

2 The basin fill process

With respect to filling with sediments and biota, the land-rise induced process during which a basin at the bottom of the sea successively turns a coastal shallow gulf, a lake, a fen (mire), and finally ends up as a bog, can be divided into five phases:

1. The postglacial sedimentation phase – a several thousand year period from the time when the inland ice left the area to the time when the water depth became so low that the wave wash process caused erosion at the basin bottom.
2. The wave wash phase – a several thousand years period with erosion of the postglacial clay and accumulation of silt, sand and occasionally also gravel.
3. The shallow gulf phase – an up to two thousand year period which starts when the wave wash process ceases due to that the wave energy filter effect dominates over the shelter effect and the water exchange with the sea decreases. The phase is characterized by sedimentation of gyttja-clay, clay-gyttja and gyttja.
4. The lake phase – continued sedimentation of clay gyttja and gyttja and successively choke-up with fen species and later with bryophytes.
5. The fen and bog phase – a phase where the former lake basin becomes dominated by organic soils and to a less degree by an open water surface.

A typical sediment profile from a basin in Roslagen that passed through all these phases may contain the following strata (data from /Bergström, 2001/ and /Ingmar, unpubl./):

0–100 cm	Moss peat	Phase 5
100–115 cm	Reed peat	Phase 4 or 5
115–190 cm	Algae gyttja, red	Phase 4
190–230 cm	Algae gyttja, green	Phase 4
230–270 cm	Clay gyttja	Phase 3 or 4
270–280 cm	Sandy clay gyttja	Phase 3
280–312 cm	Silty sand	Phase 2
312– cm	Postglacial clay	Phase 1

The postglacial clay is often placed on top of till.

The lake isolation level in the sediment profile (between phase 3 and 4) is difficult to determine by ocular inspection, and therefore requires diatom frustule analysis.

The thickness of each sediment stratum may vary considerably not only between but also within basins. The thickness of the postglacial clay will probably depend both on the length of the accumulation period and on the magnitude of the physical forces during the wave-wash erosion phase.

The wave-wash sediments (silty sand, sand or gravel) are often of limited thickness and of less importance for the basin filling process. The sedimentation during the shallow gulf phase is probably depending on the duration of the phase, which in turn depends on how fast the wave wash process declines. The latter is dependent on the bottom topography of the coastal area nearby the basin. A basin exposed to the open sea is expected to have less sediment volume accumulated during the shallow gulf phase than a basin not exposed to the open sea. A basin which is not sheltered by an archipelago rich in islands, is expected to have less sediment volume than an identical basin, which has a shallow coastal area rich in islands that provides a shelter from the physical forces of the open sea.

The variation in sediment volume accumulated during the lake phase can be assumed to depend on the lake basin morphometry and on watershed characteristics such as the size and roughness of the drainage area, the lake water turnover time, the occurrence and on the distribution of fine-grained sediments in the watershed.

The growth of the organic sediments can be assumed to depend on how fast the inorganic sediments accumulates to create such a shallow water depth that colonization by macrophytes, (e.g. common reed; *Phramnites australis*) starts. Colonization by *Phragmites* is known only to proceed to a water depth of some two meters.

3 Material and methods

Two new lakes will be formed in the coastal area close to SFR /Brydsten, 1999/, they will hereafter be termed the "New Small Lake" and the "New Large Lake", respectively. The mathematical model will be applied to these future lakes to forecast the basin fill processes over time. The model will be built using sediment data from existing lakes in the area and from coastal basins close to SFR-1.

Data on lake morphometry and catchments characteristics were taken from /Brunberg and Blomqvist, 1988/. The GIS-application also contents digital elevation data from Lantmäteriet, a digital soil map from Geological Survey of Sweden, meteorological data from Swedish Meteorological and Hydrological Institute and sea depth data from Swedish Maritime Administration.

Existing sediment data from lakes close to Forsmark, available at the beginning of the study, were initially used in the model. These data consisted of sediment cores taken along transects in two lakes, Vikasjön och Lilla Agnsjön /Ingmar, unpubl./. The data describes the sediment structures from the sediment surface down to the underlying till or wave washed sand. In addition, the strata deposited during lake isolations had been determined. Hence, it was possible to determine the basin filling rate at time for lake isolation. These sediment data were then complemented with new data from other lakes in the Forsmark area presented by /Bergström, 2001/.

In order to analyze the assumed relationships between sedimentation and basin morphometry and watersheds characteristics, data from six lakes have been used. All these lakes are situated in the area close to SFR-1 (Figure 1-2). The lakes were selected so that their lake volumes range from smaller than the "New Small Lake" to larger than the "New Large Lake" and in an age structure from 900 to 3200 years (Figure 3-1).

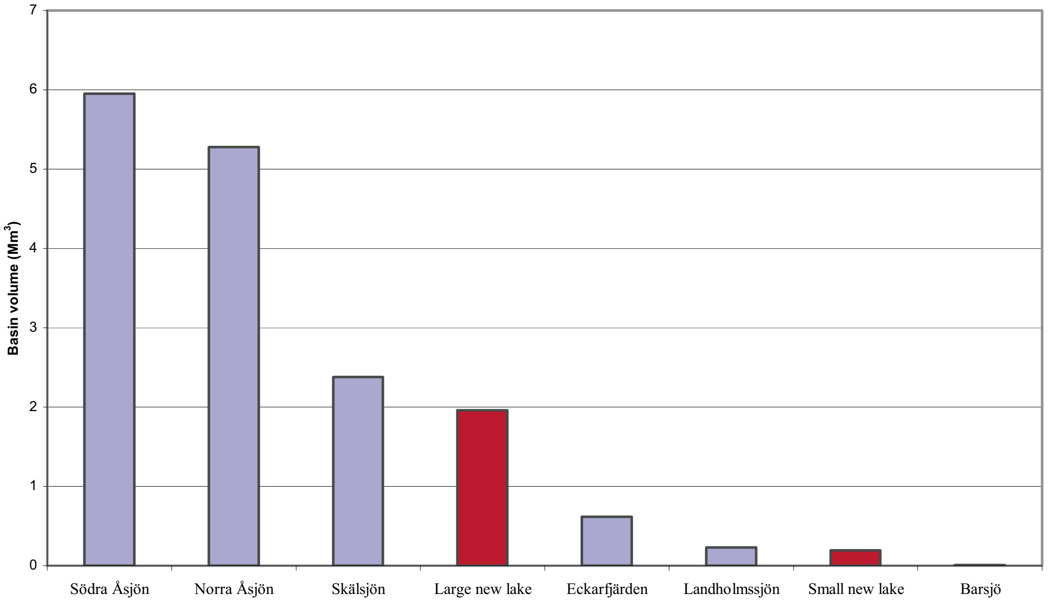

***Figure 3-1.** Basin volumes for lakes used for calibration of the model and basin volumes for future lakes.*

Morphometeric data for the existing lakes were taken from /Brunberg and Blomqvist, 1998/, while data for the future lakes originate from /Brydsten, 1999/. All morphometry data are presented in Table 3-1. The method for determining morphometric data for future lakes has been thoroughly described in /Brydsten, 1999/.

In a national perspective, all the lakes included in this study are small and shallow, which is typical for lakes in the province /Brunberg and Blomqvist, 1998/.

The sediment volumes for existing lakes were calculated from sediment data presented in /Bergström, 2001/. In each such lake a large number of sediment cores were collected and the sediment sequence was determined in the field. The sediment cores were collected in at least two transects, one along the maximum length of the lake and the second perpendicular to the first. All cores show the sediment sequence down to the wave washed material, but in addition some cores penetrated through the wave washed strata into the postglacial clay.

The sediment volume was calculated by multiplying the average sediment depth by the lake area. The former lake basin volume was calculated as the existing lake volume multiplied by the average quotient of water depth/sediment depth for all sediment cores in each lake.

The age of the lakes was calculated with the shore displacement equation presented in /Påsse, 1996/. The sedimentation rate during the shallow gulf and lake phases, expressed as m^3 $year^{-1}$, was calculated as the sediment volume above wave washed strata divided by the lake age.

The lake volumes were calculated using data from /Brunberg and Blomqvist, 1998/. The water depths are in Brunberg and Blomqvist presented in the form of isopleth maps. The maps were scanned and the images were rectified in the computer program ArcView Image Analysis. The water depth isoclines were digitized as points on the screen and the point elevation theme was extended with points along the shoreline and points from the nearest elevation line in the digital topographical map. A new TIN (triangular network) was constructed for each lake and the lake volumes were calculated using the computer program ArcView 3D Analyst.

Table 3-1. Morphometric data for lakes used in the analysis and for the future lakes that the mathematical model is applied on. Altitude is the lake elevation in meter above sea level. Lake length, width, maximum depth and mean depth are in the unit meters, lake area in m^2 and lake volume in m^3.

Name	Length	Width	Lake_area	Max_depth	Mean_depth	Volume	Altitude
Barsjö	145	62	6800	0.9	0.70	4800	23.0
Landholmssjön	430	270	83700	1.7	1.10	92100	16.0
Small new lake	496	458	128800	3.0	1.38	177800	–10.2
Eckarfjärden	870	410	230400	2.6	1.50	345500	6.0
Fiskarfjärden	1770	600	517900	2.0	0.70	362600	0.0
Skälsjön	2200	1400	1664300	1.5	0.80	1331400	13.3
Large new lake	2390	830	1176600	4.3	1.77	2082500	–15.0
Norra Åsjön	2890	1040	1834800	4.0	2.10	3853000	12.4
Södra Åsjön	2950	1550	1914600	3.8	2.30	4403700	12.4

The extensions of the watersheds were taken from /Brunberg and Blomqvist, 1998/. In that study, the water divides were determined and drawn on the topographic maps (scale 1:10000) and occasionally controlled in the field. These maps were scanned and the images were rectified within the computer program ArcView Image Analysis. The rectified maps were used as background for digitizing the lakes and their watersheds on the screen. A GIS-application with themes for watersheds and lakes was expanded with themes for land use from the red digital map and the digital elevation map, both from Lantmäteriet and the digital soil map from the Geological Survey of Sweden. Parameters for the lakes and the watersheds, presented in Table 3-2, were calculated with the GIS-program ArcView.

The sediment data in /Bergström, 2001/ lack a mark for the lake isolation level, so the data cannot be used to calculate the sediment rate for the shallow gulf and lake phases separately. The sediment data from cores in Lilla Agnsjön and Vikasjön /Ingmar, unpubl./ did, however, include both descriptions of the different strata and diatom analyses at a large number of levels in each core. Hence, Ingmar has with high accuracy determined the lake isolation level in each sediment core. These sediment data were used for determining the distribution of sediments accumulated during the shallow gulf phase and the lake phase, respectively.

Possible relationships between sedimentation rates and parameters in Table 3-2, were statistically analyzed with partial correlations and multiple linear regressions. The regression equation was then used in the mathematical model.

Table 3-2. Lake and watershed parameters calculated in the GIS-application. Sub-watershed denotes the watershed from one lake to the nearest lake upstream.

Parameters for the watershed	
Max_Elev	Maximum elevation in the watershed (masl)
Mean_Elev	Average elevation in the watershed (masl)
Mean_Slope	Average slope gradient in the watershed (degrees)
WS_Area	Watershed area (km^2)
SubWS_Area	Sub watershed area (km^2)
Lake%	Lake area compared to watershed area in %
Sub_Lake%	Lake area compared to sub watershed area in %
Sub_Org	Area of organic material in % of sub watershed area
Sub_Fine	Area of fine-grained sediment in % of sub watershed area
Sub_Coarse	Area of coarse-grained sediment in % of sub watershed area
Parameters for the postglacial basin	
Bas_Volume	Basin volume (Mm^3)
Bas_Mean_Depth	Average basin depth (m)
Bas_Max_Depth	Maximum basin depth (m)
Parameters for the lake	
Lake_Area	Lake area (km^2)
Mean_Depth	Average water depth (m)
Max_Depth	Maximum water depth (m)
Lake_Length	The maximum length of the lake (m)
Lake_Width	The maximum lake width perpendicular to the maximum length line (m)
Lake_Elev	Lake elevation (masl)
Lake_Age	Lake age (years)
Turnover	Lake turnover time (days)

4 Results

4.1 Filling with wave-washed material

Some of the sediment cores in /Bergström, 2001/ (27 cores) did contain information about the thickness of the entire wave washed stratum (silty sand, sand or gravel) and reached into the postglacial clay, which forms the deepest stratum. These data were used to calculate the share of the total postglacial basin volume that consisted of wave-washed material. The calculated values range between 0.6 and 10.4%, with a large variance between as well as within lakes. The average value was calculated to 4.1% with a standard deviation of ± 2.4% (Table 4-1).

Table 4-1. The share of the distance between the deepest part of the wave washed stratum and the lake water surface that consisted of wave-washed material.

Lake	Core	Wave washed sediment (%)
Norra Åsjön	BP7	5.1
Södra Åsjön	BP6	3.8
Södra Åsjön	BP7	10.4
Södra Åsjön	BP8	3.2
Södra Åsjön	BP10	4.5
Södra Åsjön	BP11	3.7
Södra Åsjön	BP15	0.6
Barsjö	BP8	0.8
Landholmssjön	BP1	5.6
Skälsjön	BP2	5.2
Skälsjön	BP4	1.5
Skälsjön	BP5	7.0
Skälsjön	BP9	6.0
Skälsjön	BP11	2.6
Skälsjön	BP12	4.6
Skälsjön	BP13	7.3
Eckarfjärden	BP2	3.7
Eckarfjärden	BP4	3.4
Eckarfjärden	BP5	3.5
Eckarfjärden	BPD	1.4
Eckarfjärden	BPI	3.9
Eckarfjärden	BPJ	2.6
Fiskarfjärden	BP3	4.9
Fiskarfjärden	BP4	9.0
Fiskarfjärden	BP5	3.9
Fiskarfjärden	BP6	1.2
Fiskarfjärden	BP70	2.0
Average		4.1
Std		2.4

4.2 Sedimentation rates during the shallow gulf and lake phases

In the study of the sediments in Lake Vikasjön /Ingmar, unpubl./, the lake isolation level was determined in 27 cores along a transect over the basin. Sediments accumulated during the shallow gulf phase was found to constitute 37% of the total inorganic sediment volume and 21% of the postglacial basin volume.

The sediment data from lake Lilla Agnsjön /Ingmar, unpubl./, included data from 7 sediment cores. In this lake, the shallow gulf phase sediments constituted 41% of the inorganic sediment volume and filled up 15% of the postglacial basin volume.

/Bergström, 2001/ made one accurate study of the sediments of a basin, Vissomossen, that currently has been completely filled out with a bog. A total of 53 sediment cores were analyzed, and in this basin 6% of the volume of the postglacial basin was wave washed sediments, 34% inorganic fine-grained sediments (shallow gulf and lake phase sediments) and 60% organic material.

Pooling the sediment data from /Bergström, 2001/ and /Ingmar, unpubl./, a basin containing a completely developed bog in the Forsmark area should consist of:

0–10%	wave washed sediment (silty sand, sand or gravel)
15–25%	shallow gulf sediments (clay-gyttja, gyttja-clay or algal gyttja)
20–30%	lake sediments (clay-gyttja, gyttja-clay or algal gyttja)
40–65%	peat (moss-peat, reed-peat, sedge-peat or fen wood-peat)

Due to the difficulties to distinguish between sediments of shallow gulf phase and lake phase origin, the sedimentation rate was calculated as an average for both these phases. The rate (m^3 year^{-1}) was calculated as the measured sediment volume divided by the combined age of the lake and the shallow gulf phase. Using a mathematical model for simulating wave wash processes /Brydsten, 1999/, the time for shallow gulf phase was then estimated to be on average 2000 years for basins in the area close to SFR-1. The calculated sedimentation rates varied from 2–615 m^3 year^{-1} (Table 4-2).

Table 4-2. Sedimentation rate (m^3 year^{-1}) and (mm year^{-1}), postglacial basin volume (Mm^3) and sediment volume (Mm^3) for six lakes in the northern part of Uppsala County.

Lake	Sed. Rate (m^3 year^{-1})	Sed. Rate (mm year^{-1})	Volume basin	Volume sed.
Barsjö	2	0.45	0.014	0.010
Landholmssjön	42	0.72	0.230	0.138
Eckarfjärden	149	1.35	0.633	0.287
Skälsjön	386	0.35	2.466	1.134
Södra Åsjön	670	0.54	6.291	1.887
Norra Åsjön	615	0.52	5.584	1.731

An analysis of which lake and drainage area factors that best explained the sedimentation rates then performed. All data forming the basis for this analysis are presented in Appendix 1. The first step in the analysis was to calculate Spearmen's rho correlation coefficients between sedimentation rate (m^3 $year^{-1}$) and all parameters related to the lakes, the postglacial basins, and the watersheds. Lake morphometry parameters such as volume and area of the basins turned out to be strongly correlated to sedimentation rate (Table 4-3), while watershed parameters seemed to be of less importance. The relation between sediment rate and basin volume is illustrated in Figure 4-1.

A linear regression analysis was then used to obtain a mathematical relationship between sedimentation rate and basin volume. The relationship turned out to be exponential (Figure 4-1) and to be best described by a 2nd degree polynom:

$$\text{Sediment rate} = \text{Basin volume} + \text{Basin volume}^2$$

The goodness of fit for the regression was 0.998 and the model was significant at the $p< 0.001$ level. The intercept could be excluded. The resulting equation used in the mathematical model was:

$$\text{Sediment rate} = 193.024 \times \text{Basin volume} - 14.168 \times \text{Basin volume}^2 \qquad (1)$$

in which sedimentation rate is expressed as m^3 $year^{-1}$ and basin volume expressed as Mm^3.

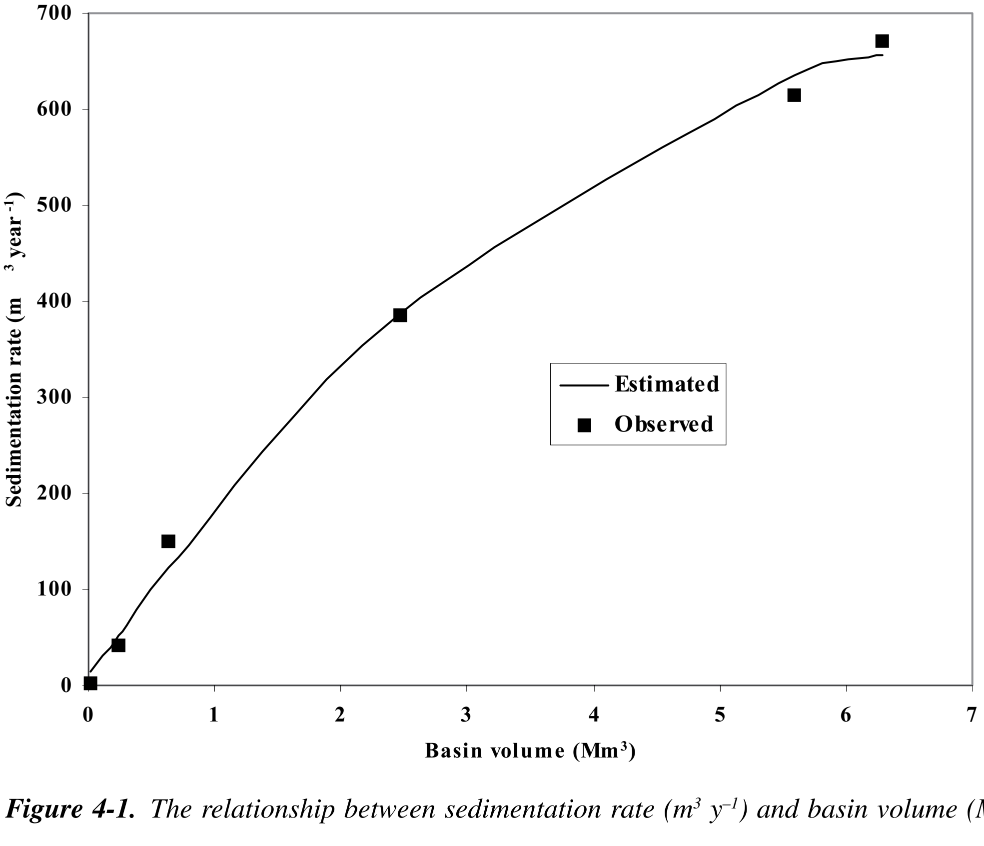

Figure 4-1. *The relationship between sedimentation rate (m^3 y^{-1}) and basin volume (Mm^3).*

Table 4-3. Spearmen's rho values for correlation with sedimentation rate (m³ year⁻¹). The table is sorted on the absolute values of correlation coefficients.

Spearman's rho correlation Variable	Correlation Coefficient	Sig. (2-tailed)
Basin volume	1.00	
Water volume	0.94	0.005
Lake length	0.94	0.005
Lake area	0.94	0.005
Maximum basin depth	0.89	0.019
Watershed area	0.89	0.019
Lake width	0.83	0.042
Maximum lake depth	0.83	0.042
Mean lake depth	0.77	0.072
Calcium content in till near the lake	0.77	0.072
Sub watershed area	0.77	0.072
Maximum elevation in watershed	0.76	0.080
Lake%	–0.67	0.148
Lake elevation	–0.64	0.173
Lake age	–0.64	0.173
Lake% in sub watershed	0.60	0.208
Mean basin depth	0.31	0.544
Mean watershed elevation	0.26	0.623
Mean slope in the watershed	0.17	0.749
Calcium content in till in watershed	0.09	0.872
Turnover time for lake water	–0.03	0.957

4.3 Determination of the organic basin fill process rate

The choke-up of the lake with vegetation starts with colonization by littoral plants, followed by invasion of bryophytes when the resulting wetland is transferred to a bog. The colonization of the littoral zone requires shallow water, that the slope of the shore is low a low, and that the shore is lacking a wave-breaking zone.

Sediment data from /Bergström, 2001/ show that the water depth must be lower than approximately 2 meters before the littoral vegetation start to colonize. /Brunberg and Blomqvist, 1998/ also mention that the zone with helophytes as a rule extends to approximately 2 meters water depth.

The critical slope of the shore for marsh colonization was determined using the GIS-application. A digital slope gradient map was made from the digital elevation model (DEM). Three types of shore soils was selected from the digital soil map (in raster format), marsh, till, and bedrock. Each soil type was converted to vector-format.

The lakes from the raster soil map were converted to vector-format, and the lakes were buffered with a surrounding 20 meter zone. The three soil maps where intersected with the map of buffered lakes and the gradients were determined using the function Summarize zones in ArcView Spatial Analyst (Table 4-4).

Table 4-4. Slope gradients (degrees) for three typical shore materials for 80 lakes in the studied area.

Material	Min	Max	Mean	STD
Peat	0.0	5.2	0.5	0.6
Till	0.0	9.0	1.3	1.4
Bedrock	0.0	10.7	1.6	1.5

The mean gradient values in the table show that colonization by littoral plants is more common on low gradient lake shores, and that colonization very seldom takes place on shores which have a slope steeper than 2 degrees (mean values ± 2 standard deviations).

Wave breaking causing erosion of vegetation close to the shore is not common in small lakes, mainly due to the short fetch and therefore low wave power. There were no visible signs of erosion of the littoral vegetation in any of the orthophotos covering the lakes in the Forsmark area.

In order to get a value of the choke-up rate (m^2 $year^{-1}$) with bog, the digital soil map was used. All bogs were selected and converted to a vector format. The area of each bog was then possible to calculate. Underneath each bog, the DEM was subtracted by 2 meters and this new DEM was then filled. Only bogs situated in depressions were used in the analysis. The ages of the bogs were calculated using the DEM and the equation for shore displacement. The choke-up rates (m^2 $year^{-1}$) were then calculated by dividing the bog areas with the bog ages.

One great source of error in the calculation of the choke-up rates is the age estimates of the bogs. It is unknown for how long time the bogs have completely filled up the basins, and therefore the choke-up rates should be considered as minimum values. Due to this fact, all older bogs situated above 30 meters above sea level and all bogs smaller than the "New Small Lake" basin, were excluded from the analysis. After this exclusion, 84 bogs remained in the dataset.

The relationship between choke-up rates and morphometry parameters of the former lake basins, such as basin area, shore length and basin perimeter irregularity was analyzed using multiple linear regression. The "Basin area" was the single best explainable independent variable. The theoretically most significant variable, "Length of the shoreline with gradient lower than 2 degrees", had lower goodness of fit than the "Basin area".

The simple linear regression with "Choke-up rate" as dependent variable and "Basin area" as independent variable resulted in a high degree of explanation, R Square = 0.92 and $p < 0.001$. Figure 4-2 shows the relationship between "Choke-up rate" and the former "Basin area". Certainly, the outlier point with a choke-up rate of more than 450 m^2 $year^{-1}$, is one explanation to the very high R^2-value, but even with that point excluded, the R^2-value was as high as 0.88.

The resulting equation used in the mathematical model then became:

$$\text{"Choke-up rate"} = 16.53 + 2.41\text{E}{-4} \times \text{"Basin area"} \qquad (2)$$

The choke-up rate should be regarded as an average value over the entire process of filling the basin with a bog. In reality, the rate is higher at the beginning of the process and then successively decreases over time.

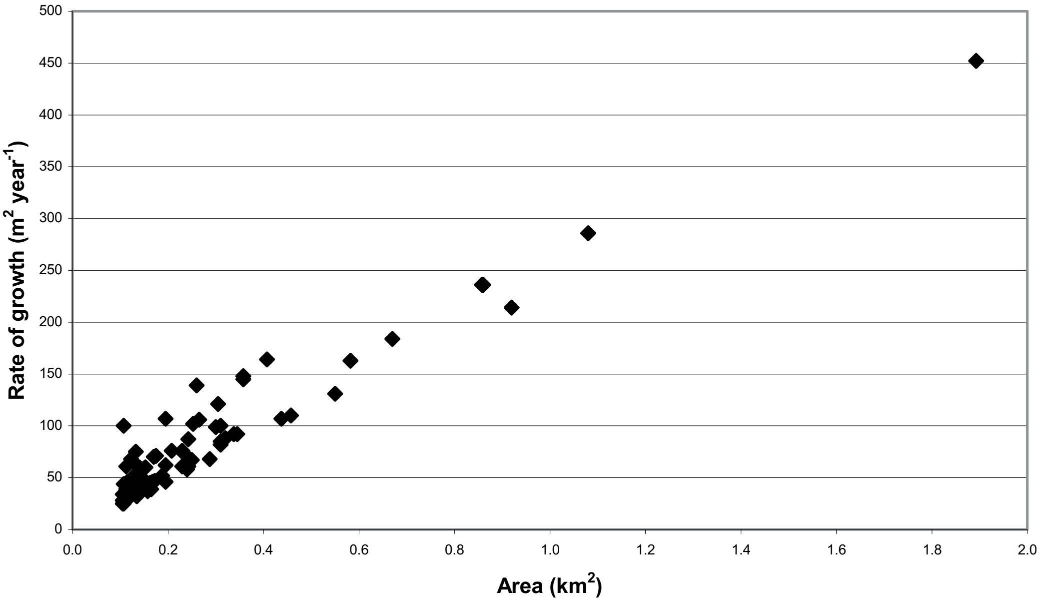

Figure 4-2. *The relationship between choke-up rate and area of 84 bogs situated in the Forsmark region.*

5 A mathematical model for simulation of the lake choke-up processes

Three processes will be mathematically described in the model presented below:

1. The sedimentation of silty sand, sand, or gravel by wave wash processes.
2. The sedimentation of inorganic sediments during the shallow gulf and lake phases.
3. The lake choke-up process by colonization of marsh and bog vegetation.

The first process is independent of the other two, but the choke-up processes require that the inorganic sedimentation proceeds long enough to make the water depth smaller than 2 meters.

The model starts with a basin that exists before the wave wash phase starts, i.e. a basin with a bottom consisting of till or postglacial clay.

Step 1: The basin fills up with 4% of the former volume by silty sand (the average filling in the 27 cores in /Bergström, 2001/).

Step 2: Each year the basin is supplied with fine-grained inorganic sediments with a volume calculated using equation 1. If the basin has bottom areas located below two meters water depth, all new sediments are placed there, otherwise the new sediments are spread evenly over the entire lake. The successive shallowing is calculated by dividing the sediment volume with the open water area.

Step 3: Step 2 is repeated until at least 18% of the former basin volume consists of fine-grained shallow gulf sediments, then it is assumed that lake isolation takes place (18% is the average value of shallow gulf sediment filling in Vikasjön and Lilla Agnsjön).

Step 4: For bottom areas shallower than 2 meters water depth, the choke-up rate was calculated using equation 2. In cases when the choke-up area exceeded the area calculated to be shallower than 2 meters, growth of the bog was only permitted to proceed out to two meters water depth. The growth was allowed to proceed on the shallowest part of the basin not already occupied by organic material. The volume of the organic material was calculated as the average depth multiplied by the growth area

Step 5: Step 2 and 4 were repeated until the entire former basin area consists of a bog.

The results from the model simulations are presented as volumes of wave wash sediment, shallow gulf- and lake sediments, organic sediment, and lake water for each time step in the model.

The model only requires a DEM covering the basin and the threshold level for the future lake as input data. So, only morphometrical data for the basin are required to run the model, and this means that it can be applied to future basins in the province, provided that an accurate depth sounding has been carried out.

The model is written in Visual Basic. Using the DEM, the model calculates the initial area, the mean water depth, and the volume of the basin. With the information about the threshold level, the model calculates the lake isolation time using the shoreline displacement equation. For each time step, the model transfers to a text file the following columns:

1. Time.
2. Total inorganic sediment volume produced during earlier time steps.
3. Water volume.
4. Water volume below 2 meters water depth.
5. Total organic sediment volume produced during earlier time steps.
6. Water area.

In addition, the model writes a summary of model results to a separate text file with the following parameters:

1 Initial lake area.

2 Initial lake volume.

3 Initial mean water depth.

4 Initial maximum water depth.

5 Initial lake length.

6 Initial lake width.

7 Initial lake perimeter.

8 % wave washed material in the completely filled basin.

9 % inorganic sediment in the completely filled basin.

10 % organic material in the completely filled basin.

11 Time for the start of the shallow gulf phase.

12 Time for lake isolation.

13 Time for completely filled basin.

6 The model applied to the future lakes

The morphometry of the former lakes was calculated in the GIS-application. The basis for this calculation was a DEM with an accuracy of 25 meters. The DEM has been built from many sources of elevation data; the DEM over land from Lantmäteriet (50 meters resolution), elevation curves from the topographic map (5 meters resolution), the digital nautical chart from the Swedish Maritime Administration, manually digitized point depths from the paper nautical chart, and manually digitized depth values from the original nautical chart maps. All sources were converted to point themes and merged to form a new DEM using Kriging as the interpolation method.

The new DEM was then used for calculation of the input data to the model using the GIS-program ArcView. In the program extension "Hydrologic modelling" the DEM was filled, that is all depressions in the DEM were filled up to each depression threshold value. Then the difference between original DEM and the filled DEM were calculated with the function "Map calculator". The result is the filled volume in raster format. The filled DEM was reclassified into two classes; filled or not filled. The reclassified raster map was then converted to vector-format. This new map shows the two-dimensional extension of the future lakes.

With the function "Summarize zones" applied to the filled DEM with the "Future lake shape-theme" for defining the zones, the threshold elevation values for each lake were determined. Using the equation for shore displacement /Påsse, 1996/, the isolation time for each former lake was calculated.

The morphometric data, such as basin area, maximum basin depth, average basin depth, of the future lakes were calculated using "Summarize zones" applied to the original DEM,

The original DEM was clipped for the two lakes that were modeled using the Avenue-script "Grid_Clip_2_Polygon" and the vector-theme for future lakes. The clipped DEM was converted to ASCII-format. This new dataset was imported to the model.

The elevation (Z) were recalculated to water depths using the known lake water surface threshold levels. Each depth value represents an area of 625 m^2 (25 × 25 m), and this is the size of the areas used in the model for calculation of the area occupied by organic sediments.

Time steps of 100 years were chosen and the model was applied to both the "New Large Lake" and the "New Small Lake".

In Table 6-1, some basic data for the future lakes are presented and Figure 6-1 shows a comparison between basin volumes in the future lakes and in the lakes used in the statistical analysis.

The model was applied on the two future lakes with the starting parameters presented in Table 6-1. The model outputs for the "New Large Lake" are shown in Figures 6-1 and 6-2. The entire lake basin filling process, from the shallow gulf phase to a bog, was predicted to take approximately 5200 years, and during this period the basin has been in a shallow gulf phase for approximately 25% of the time. The shallow gulf phase will start 3600 AD and the lake isolation will occur at 4800 AD.

Table 6-1. Morphometry and other data for the future lakes and their watersheds.

	Small lake	Large lake
Maximum basin depth (m)	2.9	4.2
Average basin depth (m)	1.4	1.7
Basin area (km²)	0.134	1.134
Basin volume (Mm³)	0.192	1.961
Basin area where basin depth exceeds 2 meters (km²)	0.034	0.376
Basin volume beneath 2 meter basin depth (Mm³)	0.082	0.35
Basin length (m)	500	2400
Basin width (m)	460	830
Threshold level (masl)	–10.2	–15.0
Lake isolation date (AD)	3800	4800
Watershed area (km²)	0.975	29
Lake%	13.2	4.0
Lake water turnover time (days)	264	102
Mean water discharge (m³ s⁻¹)	0.01	0.24

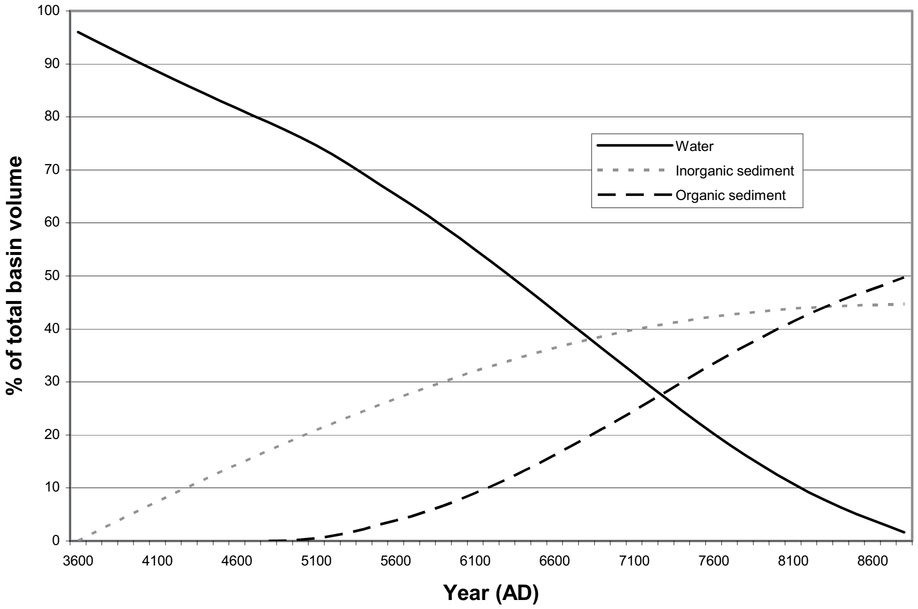

Figure 6-1. Modelling results concerning the filling of the "New Large Lake" with sediments and vegetation.

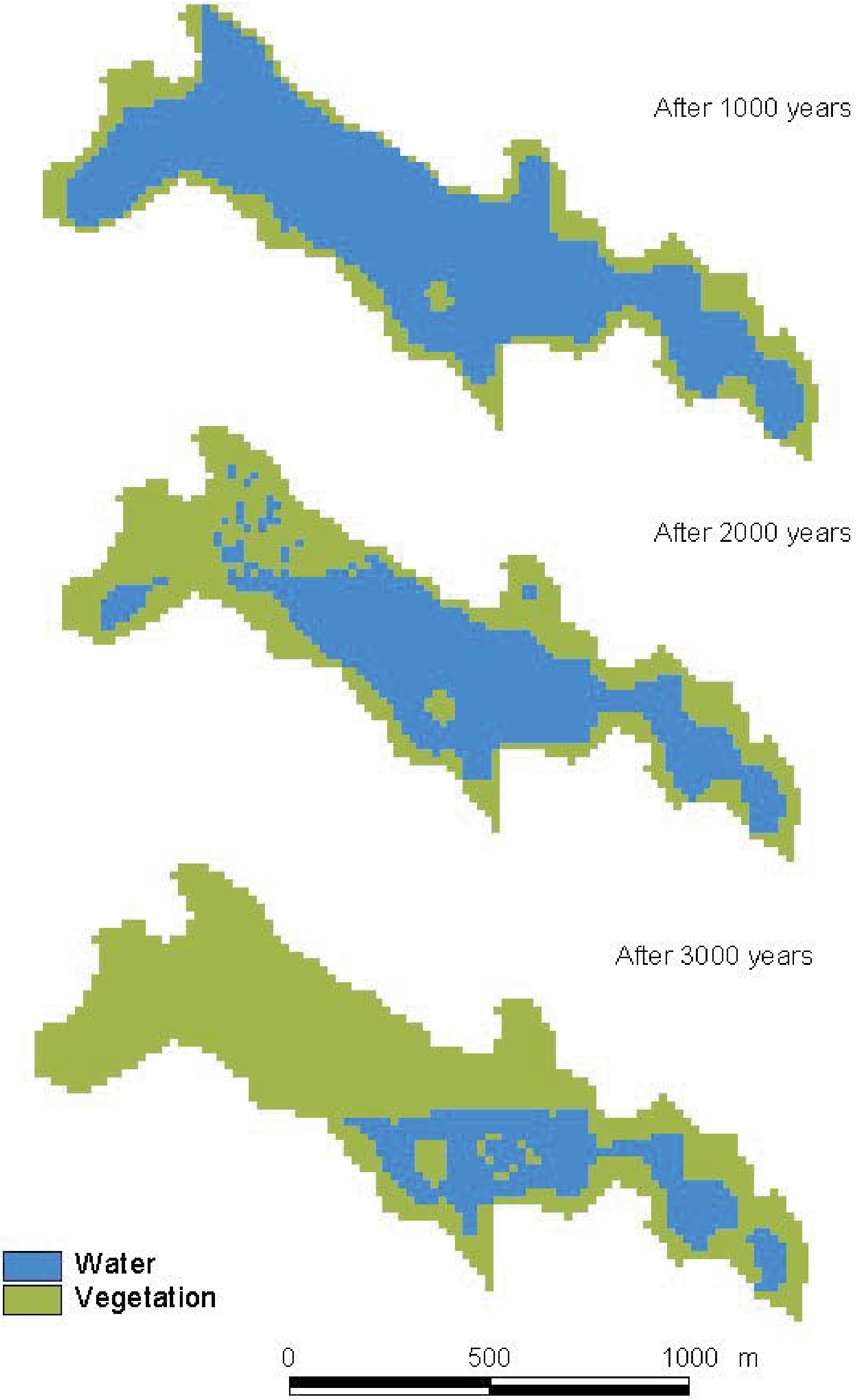

Figure 6-2. *The distribution of vegetation and water in the "New Large Lake" at different stages of its ontogeny towards a bog.*

According to the model, the growth of the organic sediments will start slowly. This is mainly due to large bottom areas in the lake which first have to be colonized by vegetation before the organic material will start to accumulate. Half of the former basin will be filled with sediments in year 6200, i.e. 1400 years after the lake isolation. At the end of the lake basin filling process, the former basin will consist of approximately 50% organic material, 46% inorganic material and 4% wave-washed sediment.

The model results for the small lake are summarized in Figure 6-3. The basin will, according to model, be totally filled 2500 years after isolation. For the "New Small Lake", the filling process was never delayed by the 2 meter water depth restriction rule and, therefore, the percentage volume of the organic sediment is higher in the "New Small Lake", compared to the "New Large Lake" (Figure 6-3).

In cases when the lake basin filling process is not affected by water depth, the filling time can be calculated with equation 2. The filling time for a small basin (< 0.15 km^2) was estimated to 2000–2500 years and for a large basin (> 1 km^2) 3900–4200 years.

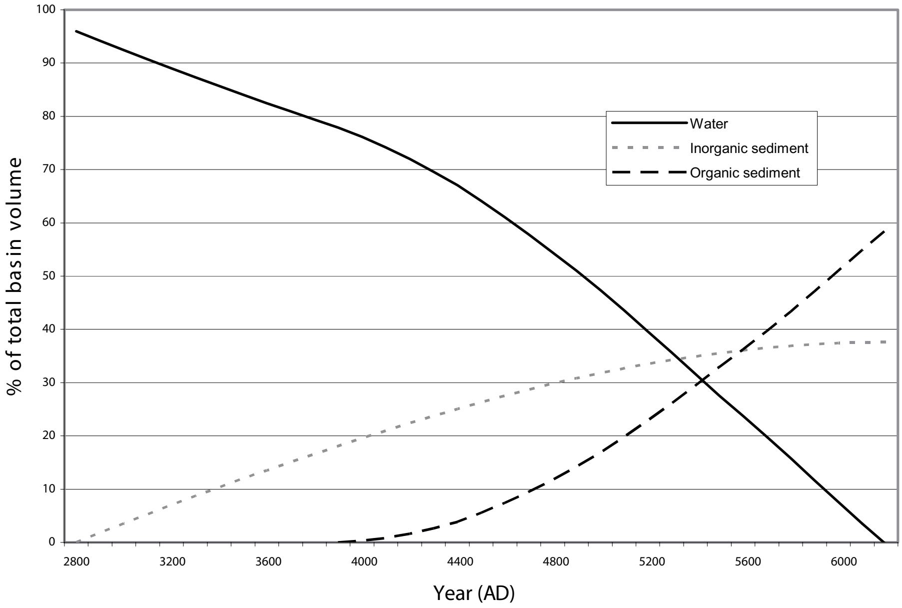

Figure 6-3. *Modelling results concerning the filling of the "New Small Lake" with sediments and vegetation.*

7 Discussion

Several earlier studies have shown strong correlations between sedimentation rates in lakes and characteristics of their catchments /e. g. Håkanson, 1981, Leeder, 1985, Pye, 1994/. The results in this study differ from these of the earlier studies since the statistical analysis showed that the lake morphometry parameters are of greater importance for explaining the variation in sedimentations rates than catchment parameters (Table 4-3). This implies that the sediments in these lakes have a higher degree of autochtonous origin compared to many other lakes. Several factors imply that this could be correct.

The area around Forsmark has extremely small topographic variations, which probably will give a proportionately lower transport of sediments of allochtonous origin to the lakes in comparison with lakes situated in more hilly landscapes. In addition, the sources to allochtonous material are few since the catchments are dominated by wave-washed till or wetlands (70–90%) and fine-grained sediments only cover up to 1% of the catchment areas. Further on, extensive littoral vegetation fields cover all inlets of the lakes in the study. With low current velocities (due to the levelled landscape), these littoral vegetation fields will probably act as filters for particles transported with the running water and, hence, the lakes are supplied with only small amounts of allochtonous material. Consequently, there is strong indication that the basin filling process is dominated by autochtonous processes.

Is it then likely that the production of biota in the lakes is high enough to explain the measured sediment volumes? A rough estimate of the combined primary production of phytoplankton and microphytobenthos in the new basins can be obtained using existing data on the production of these organisms from Lake Eckarfjärden /Blomqvist et al, 2002/. Lake Eckarfjärden has an age of ca. 930 years /Brydsten 1999/, is located in the same watershed as the two new lakes, and is currently in the oligotrophic hardwater stage that follows directly after the shallow gulf stage. The estimated combined average primary production during the open water season in that lake amounts roughly to 50 mg $C \times m^{-2} \times h^{-1}$. Assuming a day length of 12 hours and a production period of 6 months, this results in an annual production of 108 $g\ C \times m^{2} \times yr^{-1}$. Multiplying this value with the lake area (0.23 km^{2}=230 000 m^{2}) yields a total within-lake production of almost 25 000 $kg\ C \times yr^{-1}$. The carbon to fresh weight ratio in phytoplankton and microphytobenthos is approximately 11% /Olrik et al, 1998/. In terms of fresh weight biomass the organic primary production alone in Lake Eckarfjärden corresponds to 226 000 kg.

To this primary production by microorganisms should also be added the part of the total production of heterotrophic bacteria which is based on imported (allochtonous) organic carbon and which often exceeds the primary production in lakes rich in dissolved organic matter /e.g. Jansson et al, 2000/. In addition the production of submersed macrophytes (e.g. the Characeans which dominate large areas of the soft sediments). Assuming that all other biota other than the phytoplankton and microphytobenthos contributeas much biomass as these primary producers, the total organic production in the lake would be some 450 tonnes fresh weight, which is likely a conservative estimate. This production corresponds to ca. 450 m^{3} of living material which, if completely settled, covers the bottoms with 450 000 mm of sediments or approximately 2 mm of sediment per m^{2} of lake area.

The question is then how much of this material that ends up in the sediments. Since the turnover time of the water is rather long, losses via the outlet are most likely negligible. Hence, the major loss processes that will affect the amount of material finally deposited is decomposition of the organic material. A minimum estimate of the deposition of material can be obtained from the assumption that only the inorganic constituents of the organisms are finally deposited. The ash content of phytoplankton and microphytobenthos is highly variable depending on group of organisms and species. /Nalewajko, 1966/ found that ash accounted for between 5 and 20% (mean 10%) of the dry weight of 16 planktonic green algae, but for between 27 and 55% (mean 40%) of 11 diatoms (which posess a silica frustule). Assuming 10% to be valid for all other organisms, 40% to be valid for diatoms, and diatoms to constitute 25% of the total biomass, the average value of ash content for phytoplankton and microphytobenthos would be 17.5% of the dry weight. Assuming the dry weight to be 20% of the fresh weight /Reynolds, 1984/, the 450 m^3 (or 450 tonnes assuming a density of 1 of the organisms) corresponds to approximately 15 tonnes of inorganic material. Assuming this material to have the density of e.g. quartz (2.65) this corresponds to 6 m^3 of inorganic material. If these 6 m^3 of inorganic material are evenly distributed over 226 000 m^2 of lake bottom, this corresponds to a 0.03 mm thick "sediment". Altogether, the organic production within the lake can be estimated to contribute between 0.07 and 2 mm of sediment per year. Since the average water content of the sediments in Lake Eckarfjärden is around 90% (96% at the surface and 89% at one meters depth in the sediment, /Brunberg pers. comm./, the higher value is more reasonable than the lower. Hence, the calculated mean sedimentation rate in Lake Eckarfjärden (Table 4-2) seem quite reasonable. Furthermore, in addition to these values, and particularly in the oligotrophic hardwater lakes in the Forsmark area, there are also large amounts of biogenic $CaCO_3$ precipitated by the organisms that contributes to build up the sediments /e.g. Brunberg et al, 2002/. Hence, the answer to the question if internal production processes can contribute all of the sediments in the lakes in the Forsmark area is yes.

Concerning the calculation of the choke-up rate there are several potential sources of error. As mentioned earlier, the age of the bogs was calculated using a DEM and the choke-up rate was calculated as the quotient between the area and the age of the bogs. However, the choke-up may have been completed for many years, so the filling rate of the bogs could be higher than calculated. In addition, the basin filling process for some of the basins may have been delayed by the 2-meter restriction rule, which also may give a lower value of the choke-up rate. A third possible source of error is climatic changes. The climatic conditions during the time when these bogs were in the most expansive phase may differ, both with the climatic conditions today, and with the conditions when the future lake basins will be filled with bogs. The two first sources of error could be reduced by a study with the same approach as /Bergström, 2001/, but focused on bogs instead of lakes.

One method for validation of the model is to make a comparison between model results and basin filling grade for existing lake basins with approximately the same basin area. To do this, the "New Large Lake" was compared with Lake Landholmssjön and the "New Small Lake" with Lake Skälsjön. The basin areas for the former postglacial lake basins were determined using the digital soil map and the DEM. The bogs that are bounded to the lakes and not elevated more than one meter above the lake level were defined to be a part of the former basins. The former basin of Lake Skälsjön is currently choked-up with sediments and vegetation to 36%. The lake is 1935 years old and the "New Large Lake" will have the same age at year 6700 AD. The comparison shows that the future large lake will be choked-up to 44% at that time. In a similar comparison between the "New Small Lake" and Lake Landholmssjön, which at present is choked-up to 75%, the model indicates that the "New Small Lake" will be choked-up to 77% at equivalent age. Even if the determinations of the extensions of the former lake basins were difficult to do without extensive field work, the comparison shows that the model gives reasonable results.

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Appendix 1

Data for watersheds used in the statistical analysis

Data for the watersheds

Lake	Max_Elev	Mean_Elev	Mean_Slope	WS_Area	SubWS_Area	Lake%	Sub_Lake%	Sub_Org	Sub_Fine	Sub_Coarse	Sub_Till
Barsjö	29.0	24.2	1.0	0.27	0.27	2.5	2.5	n.a	n.a	n.a	n.a
Landholmssjön	41.0	29.2	0.7	2.28	2.28	3.7	3.7	38.5	0.0	0.0	51.1
Eckarfjärden	16.0	8.8	1.2	1.47	1.47	15.7	15.7	8.0	0.0	0.1	56.8
Skälsjön	56.0	30.0	1.0	180.67	24.00	0.9	6.9	22.6	0.4	1.4	52.9
Södra Åsjön	56.0	27.7	1.0	267.14	38.04	0.7	5.0	19.3	0.5	2.7	47.8
Norra Åsjön	56.0	28.6	1.0	197.67	17.00	0.9	10.8	29.4	0.6	7.9	39.7

Appendix 2

Data for postglacial basins and lakes used in the statistical analysis

Data for the postglacial basins

Lake	Bas_Volume	Bas_Mean_Depth	Bas_Max_Depth
Barsjö	0.009	1.30	2.60
Landholmssjön	0.230	2.75	3.35
Eckarfjärden	0.617	2.68	3.92
Skälsjön	2.378	1.43	3.38
Södra Åsjön	5.951	3.11	4.67
Norra Åsjön	5.278	2.88	4.30

Data for the lakes

Lake	Lake_Area	Lake_Volume	Lake_Length	Lake_Width	Max_Depth	Mean_Depth	Turnover	Lake_Elev	Lake_Age
Barsjö	0.007	0.005	145	62	0.9	0.7	25	23.0	3160
Landholmssjön	0.084	0.092	430	270	1.7	1.1	58	16.0	2280
Eckarfjärden	0.230	0.346	870	410	2.6	1.5	383	6.0	925
Skälsjön	1.664	1.331	2200	1400	1.5	0.8	14	13.3	1935
Södra Åsjön	1.915	4.404	2950	1550	3.8	2.3	28	12.4	1815
Norra Åsjön	1.835	3.853	2890	1040	4.0	2.1	31	12.4	1815

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