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A model for landscape development in terms of shoreline displacement, sediment dynamics, lake formation, and lake choke-up processes

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Abstract

This project expands on the study "A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation" published in SKB TR-04-09. As the title suggests, this older model focuses on lakes (existing and future lakes). This newer study extends the model to examine progress of terrestrial objects such as mires or arable land. Furthermore, this newer model could simulate progress of the areas close to the objects. These areas are divided according to their watershed boundaries. If two or more objects are situated along the same brook, the lower situated area is defined as its catchments minus the catchments of the closest higher situated object.

The model encourages the study of an object situated in the sea from the time of deglaciation (c. 10,000 BP) to the time for the object due to positive shore displacement is situated on land or that a lake object has progressed to a wetland, however not longer than 18,000 AP. The model focuses on the object and its location in 100-year steps.

The model is written in VisualBasic and is divided into two modules, a marine module and a lake module. The marine module deals with shoreline displacement, erosion and accumulation of postglacial fine-grained sediments and erosion of glacial clay. Inputs to the marine module are a digital elevation model (DEM), a digital map showing the extension of the objects and a marine quaternary map. The two maps are in raster formats with exactly the same formats (extension and cell sizes) as the DEM. For each time step the water depths at each pixel are calculated using a shore displacement equation. Next, the water depth changes due to sediment dynamics are calculated using the following rules; accumulation of fine-grained sediments are allowed if the pixel is situated within a future lake object; erosion of fine-grained sediment is allowed if the pixel is not within a future lake object and the marine quaternary map shows occurrence of postglacial sediments and also that the total amount of erosion does not exceed the mean postglacial sediment thickness in the area and the water depths are deeper than 25 metres. If the water depth is less than 5 metres and the pixel is situated outside a future lake object, erosion of glacial clay is allowed with a value that corresponds to the mean thickness of glacial clay in the water depth interval 0–5 metres.

Output from the module is a text-file with values for each object for time step, water volume, water area and sea level. The module steps until a time when a future lake object is isolated or a terrestrial object is completely situated on land. The time for future lake isolation is calculated using the future lake threshold level and the shoreline displacement equation. When the module ends, the DEM at the actual time writes to a file in Asci-format that can be used as an input for the lake module.

Input to the lake module is either the DEM from the future lake isolation time or a DEM calculated from depth sounding data for an existing lake. The lake module simulates the progress from a newly isolated lake to a wetland considering accumulation of fine-grained sediments and choke-up processes. The accumulation of sediments at each time step is calculated using the actual lake water volume, a relationship that is calibrated using data from eight lakes in the Forsmark area. If the lake at actual time step has pixels that have water depths exceeding two metres, all new sediments are placed evenly over that area: otherwise, they are evenly distributed over the entire lake not occupied by vegetation. The choke-up rate is calculated using the area of the newly isolated lake, a relationship calibrated by data from 84 wetlands in the Forsmark area. The lake module calculates the number of pixels that will be occupied by vegetation at each time step. This process searches for the shallowest pixel in the lake not already occupied by vegetation and marks this pixel as vegetated. The process is repeated until the calculated number of pixels is marked. However, vegetation is only permitted to colonize on bottoms shallower than 2 metres. The lake module steps forward until the former lake basin is totally covered with vegetation. Outputs from the module are in text-file with following values; time, mean water depth, water area, added sediment volume since lake isolation, and area and volume of organic material.

The model is applied on a large number of objects in both the Forsmark and Oskarshamn sites. Most of the objects exists or are future lakes, but, also some terrestrial objects are processed. For future lakes in Forsmark, the results from the simulations show that the length of the lacustrine phase are 3,000–4,000 years for the small lakes and > 9,000 years for the large and deep lakes situated in the so-called Gräsörännan. Two of the future lakes in the Simpevarp area will also be long-lived (> 13,000 years); both will be formed in the existing Granholmsfjärden.

Sammanfattning

Det här projektet är en utvigdning av ”A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation” publicerad i SKB TR-04-09. Som titeln anger så låg focus på den äldre modellen på sjöobjekt (existerande och framtida). Den utvidgade modellen kan även simulera terrestra naturobjekt såsom myrar eller odlingsmarker. Vidare kan modellen simulera utvecklingen i objektens närområde. Närområdenas avgränsning sker med hjälp av vattendelare. Om två eller fler objekt är belägna längs samma vattendrag definieras den lägre belägna objektets närområde som dess avrinningsområde minus det närmast högre objektets avrinningsområde.

Modellen simulerar utvecklingen från deglaciationen (ca 10 000 BP) till dess att ett terrestriskt objekt hamnar på land eller ett sjöobjekt har utvecklats till en våtmark, dock inte längre än 18 000 AP. Modellen simulerar utvecklingen i 100-års steg.

Modellen är skriven i Visual Basic och är uppdelad i två moduler, en marin modul och en sjömodul. Den marina modulen beaktar strandlinjeförskjutning, erosion och accumulation av postglaciala finkorninga sediment och erosion av glaciallera. Indata till den marina modulen är en digital höjdmodell (DEM) över närområdet, en digital karta över objektets utbredning och en maringeologisk karta över närområdet. De två sista kartorna är i rasterformat med exakt samma format som höjdmodellen. För varje tidssteg beräknas aktuellt vattendjup i varje pixel med hjälp av tiden och en ekvation för strandlinjeförskjutningen. Därefter beräknas nya vattendjup orsakat av sedimentdynamik efter följande regler; accumulation av finkorniga sediment tillåts om pixeln ligger inom ett blivande sjöobjekt med ett genomsnittligt värde för sedimentationsgrad inom området, erosion av postglaciala sediment om pixeln inte är belägen inom ett sjöobjekt och den maringeologiska kartan visar förekomst av postglaciala sediment samt att den sammanlagda erosionen inte överstiger den genomsnittliga mäktigheten för postglaciala sediment i området samt att vattendjupet understiger 25 meter. Om vattendjupet understiger 5 meter och pixeln ligger utanför sjöobjektet tillåts erosion av glaciallera med ett värde som motsvarar den genomsnittliga mäktigheten för glaciallera i djupintervallet 0–5 meter för respektive område. Utdata från modulen är en textfil med värden för tidpunkt, vattenvolym, vattenarea, havsnivå och medelvattendjup för närområdet. Modulen stegar fram till den tidpunkt då ett sjöobjekt avsnörs eller ett terrestert objekt hamnar på land. Tidpunkten för avsnörning beräknas i modulen med hjälp av sjöobjektets tröskelnivå och ekvationen för strandlinjeförskjutningen. Modulen avslutas med att den aktuella höjdmodellen skrivs till en fil i Asci-format och som utgör indata till sjömodulen.

Indata till sjömodulen är alltså antingen höjdmodellen för avsnörningstidpunkten för framtida sjöar eller data från djuplodning av befintliga sjöar. Sjömodulen beaktar utvecklinen från sjö till våtmark utifrån sedimentation av finkorniga sediment och igenväxning. Sedimentationen beräknas med hjälp av aktuell bassängvolym, ett samband som är kalibrerat med data från åtta sjöar i Forsmarksområdet. Om sjön vid aktuell tidpunkt har pixlar som är djupare än två meter, placeras all sedimentmängd jämnt över den ytan, annars jämt över den del av sjön som inte har vegetation. Igenväxningshastigheten beräknas med den nybildade sjöns area, ett samband som tagits fram med data från 84 våtmarker i Forsmarksområdet. Sjömodulen beräknar hur många pixlar som skall fyllas med vegetation, letar rätt på den grundaste pixeln som inte har vegetation och markerar den pixeln som fylld med vegetation, upprepar det till dess att det beräknade antalet pixlar är fyllda. Dock tillåts igenväxning endast på bottnar grundare än två meter. Modellen stegar fram till dess att den forna bassängen är totalt igenväxt. Utdata från modulen är en textfil med värden för tid, vattendjup, vattenarea, sedimentvolym, area och volym av organisk material.

Modellen är applicerad på ett stort antal objekt i både Forsmark och Laxemar. De flesta objekten är befintliga eller blivande sjöobjekt, men även några terrestra objekt förekommer. Resultaten från simuleringarna visar att för blivande sjöar i Forsmark att längden på den lakustrina fasen är 3 000–4 000 år för de mindre sjöarna och > 9 000 år för de stora och djupa sjöar belägna i den s k. Gräsörännan. För de fyra blivande sjöarna i Laxemarområdet visar modellresultaten att de två som ligger i nuvarande Granholmsfjärden kommer att bli långlivade, längre än 13 000 år innan de har växt igen.

Contents

1 Introduction

This model is an extension of the study "A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation" published in SKB report TR-04-09 /Brydsten 2004b/, a model that focused on future lake ontogeny with modules for sea basin sedimentation, lake isolation and lake filling with sediments and vegetation. The extended model can handle other types of objects such as existing lakes, and terrestrial existing objects such as mires and arable land. Whereas the former model only examines the future lake object this extended model also examines the object's surroundings during the marine phase.

The model can only treat a single object in each run, so it is repeated with new input data until the whole study area is covered. The model is started soon after deglaciation (10,000 BP in Forsmark and 12,500 BP in Simpevarp) and stops when a lake object is completely filled or when a terrestrial object is formed.

The model consists of two modules, – a marine module and a lake module. The marine module runs from model start until lake isolation time and calculates change in bathymetry due to shoreline displacement and sediment dynamics (accumulation or erosion of postglacial fine-grained sediments). The lake module calculates change in water volume and water area due to sedimentation of inorganic material and colonization of macrophyte vegetation. Both modules runs in 100-year time steps.

In the marine module, sediment dynamics part uses new knowledge about both sediment properties and distribution of different sediment types /Elhammer and Sandkvist 2003, 2005, Ingvarson et al. 2004/.

The outputs from the modules are water volume, water area and postglacial fine-grained sediment volume for both sea basins and lakes, and organic volume and area for lakes. The model is applied to a large number of objects in both Forsmark and Simpevarp areas. The model's results will become input data for dose assessment models.

2 Material and methods

2.1 Delimitation of model basins

The study areas are divided into a large number of model basins based on drainage divides. Each model basin can only hold one single "object". Typical objects are lakes (existing or future) but terrestrial "objects" (such as mires or arable lands) are also frequent. The boundaries of the model basins are determined by using ArcGis hydrological tool with a DEM as input data. If multiple objects occur along a brook the model basin for the lowest situated object is defined as the catchment for this object minus the catchment for the next upstream object, so the only model basin that is determined directly by the hydrological tool is for the most upstream object.

For all objects in the Forsmark area, this method is used; however, for the Simpevarp area, four objects are identified using a combination of this method and earlier field-checked drainage divides /Brunberg et al. 2004ab/. The four objects are future lakes that will be formed in the inner bay areas in Simpevarp (Lake Id 31, 32, 33, and 34). Today, these four model basins are partly in the sea and partly on land. The method described above is used for the sea areas; field-checked drainage divides are used for the land areas. This combination of method was chosen because the model basin extension differs greatly between the modelled and the field-checked. The field-checked method are undoubtedly more accurate because man-made structure (such as ditches or road barrels) are often ignored when the modelled boundaries are established for the model basins.

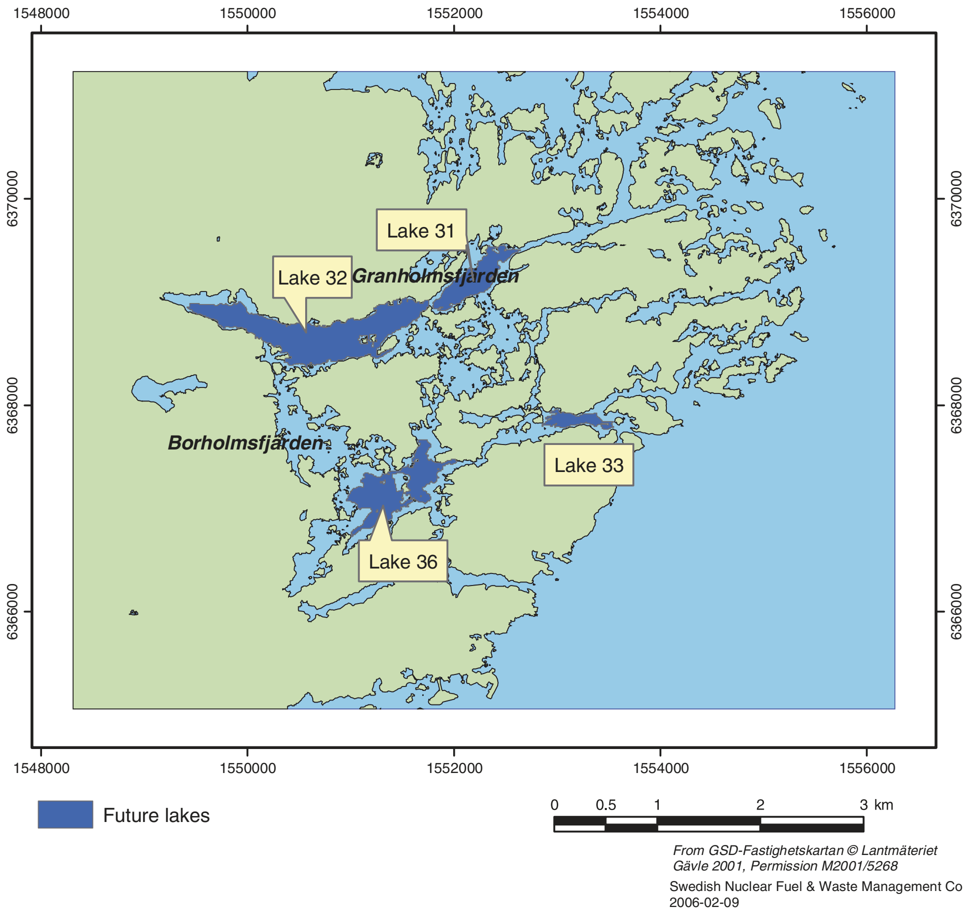


Figure 2-1. *Extension of future lakes in the Simpevarp area. All lakes (existing and future lakes) are numbered from north to south and in data delivered to SKB these numbers are identifications common for lake, catchments and sub-catchment.*

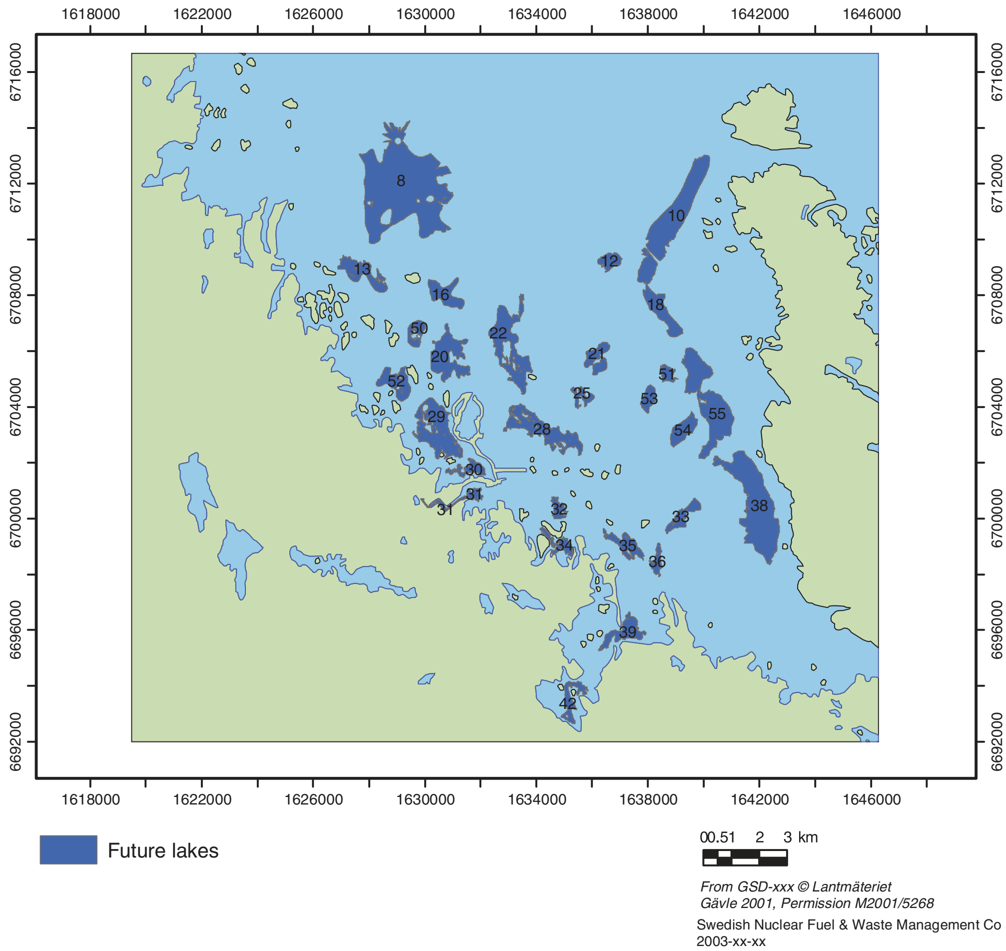


Figure 2-2. *Extension of future lakes in the Forsmark area. All lakes (existing and future lakes) are numbered from north to south and in data delivered to SKB these numbers are identifications common for lake, catchments and sub-catchment.*

2.2 Determining future lake boundaries

Future lake extensions are determined in the GIS-programme ArcGis using only the DEM as input data /Brydsten 2004a/. The method is follows this process:

- the DEM is added with a constant so all values are positive (due to a bug in the programme),
- with function *Fill* in the programme tool *Hydrological modelling*, all local depressions in the DEM are filled up to respective threshold level,
- this new filled DEM is subtracted with the original DEM, and this new DEM has values that shows the filling depths at each pixel,
- the subtracted grid is reclassified into two classes; filling depth is zero and filling depth is greater than zero,
- the reclassified grid is transformed to Shape-format (polygons) and all polygons with zero filling depths and polygons situated on land are deleted, and
- in a new table field the lake areas are calculated, and
- lakes smaller than a specified area are deleted and the result is a GIS-layer that shows the future lake extensions.

In both study areas, all future lakes smaller than 100,000 m^2 were deleted from the datasets. The 100,000 m^2 value is based on the size of small existing lakes in both areas.

The above method was applied to all future lakes in both areas except lakes 31, 32, 33 and 34 in the Simpevarp area. These thresholds were manually levelled during a field-campaign in August 2005 (see Table 3.5-2 in /Lindborg 2006/) and the threshold levels differ slightly between the two methods. Because the quality of the measured values are probably higher than the modelled values, these values were used.

2.3 The marine module

2.3.1 Geology

Since the old model was constructed new datasets for marine geology have been delivered to SKB for both the Forsmark and Simpevarp sites. This study uses four databases from the Geological survey of Sweden (SGU) /Elhammer and Sandkvist 2005/:

- a regional quaternary geological mapping of the outer (deeper) coastal areas with seven classes: crystalline bedrock, till, glacial clay, postglacial clay, postglacial silt, postglacial fine sand (wave washed sediment) and postglacial medium-coarse sand (wave washed sediment),
- a detailed quaternary geological map of the areas close to the shores with the same classes as the regional map,
- a large number of sediment profiles distributed over the same areas as the geological maps, and
- quaternary geological maps over land areas close to the coasts.

The company Marin Mätteknik (MMT) has delivered two datasets to SKB but only for the Simpevarp site /Ingvarson et al. 2004/:

- a detailed geological map over shallow coastal area and narrow bays with five classes: postglacial clay, postglacial fine sand, postglacial coarse sand and gravel, till and crystalline bedrock, and
- a GIS point layer showing the thickness of postglacial fine grained sediment (clay and silt)

In order to compare different geology units between the marine and land Quaternary deposit maps, the large numbers of units in the land maps (35) were merged into the same seven classes as the marine map: for example, Sandy Till and Silty Till were merged into Till.

Table 2-1 shows the areal distribution for different geological units and different geological maps. The most common units are crystalline bedrock, till, glacial clay and postglacial clay.

The postglacial clay is fluffy (non compacted) sediment that is easily re-suspended by wave action. At the Forsmark site it is quite common in the deeper regional area and almost wiped out at the shallower detailed area and on land. At the Simpevarp site both the regional and detailed area are highly exposed to waves from the northeast, so it is not surprising that even the deeper regional area lacks postglacial clay.

The glacial clay unit decrease drastically from the sea to land. The decrease is also almost the same for both sites. It is also interesting to note that there are no differences in glacial extension between the deeper regional area and the shallower detailed area. The differences between sea and land can be explained by the fact that glacial clay often is overlaid by peat or wave washed sediments and glacial clay are surficial lake sediment in young shallow lakes before postglacial clay sedimentation starts. The land map does not show the lake sediment but is classified as Water. Even if all lakes and all peat lands were glacial clay during the sea phase, this still represents a dramatic decrease in glacial clay extent.

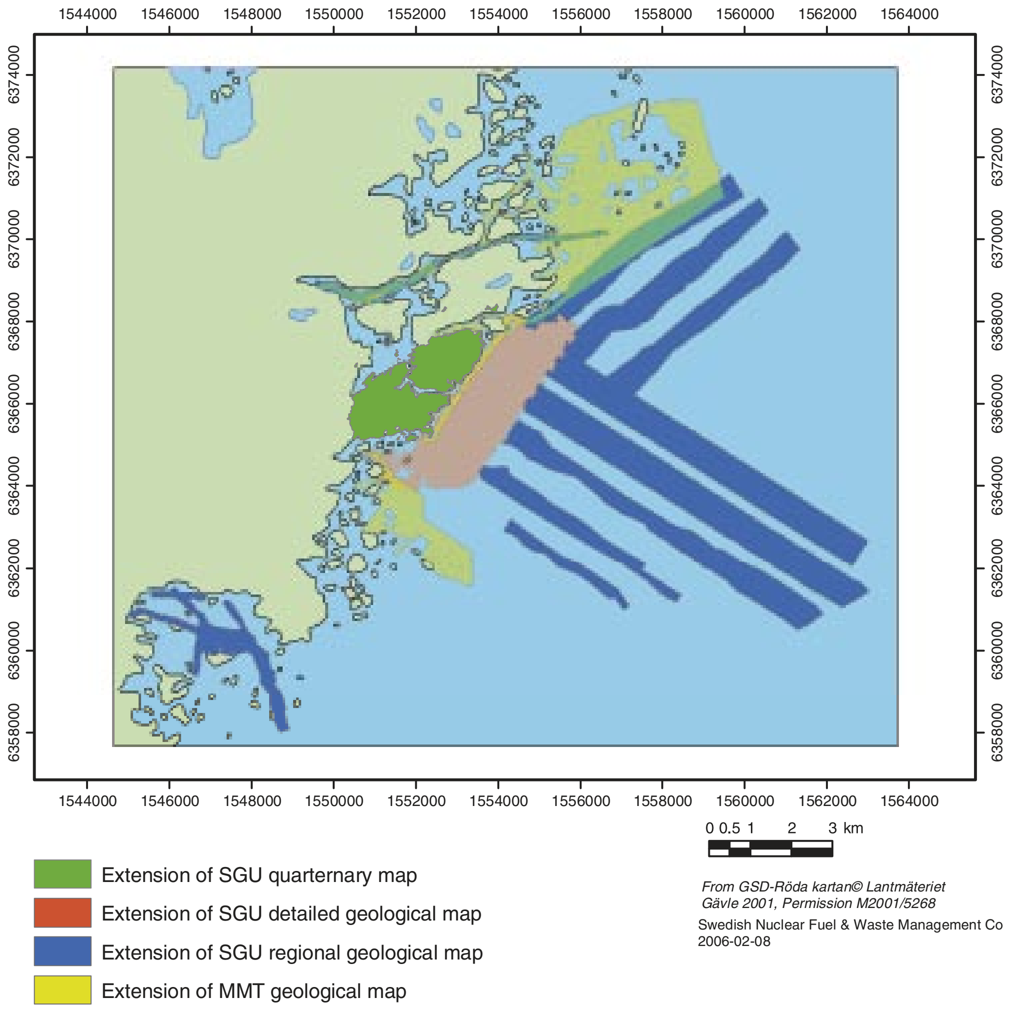


Figure 2-3. *Extensions of different marine geological investigations in the Simpevarp study site. Some areas are investigated both by the geological survey of Sweden (SGU) and Marin Mätteknik (MMT).*

Table 2-1. The area distribution for different geological units and different geological maps for the regional (Reg) and detailed (Det) areas.

Geological unit	Forsmark Reg area (%)	Det area (%)	Land (%)	Simpevarp Reg area (%)	Det area (%)	Land (%)
Glacial clay	40.7	40.8	3.9	37.5	42.5	1.3
Crystaline bedrock	7.8	1.7	4.8	55.1	53.5	46.5
Till	26.6	36.9	74.9	1.2	0.6	40.0
Postglacial clay	23.1	3.3	5.6	5.2	0.0	0.1
Postglacial fine sand	0.1	15.3	3.7	0.9	3.4	0.9
Postglacial medium-coarse sand	1.7	2.0	0.2	0.1	0.0	5.3
Peat			2.8			2.3
Water			6.1			3.6

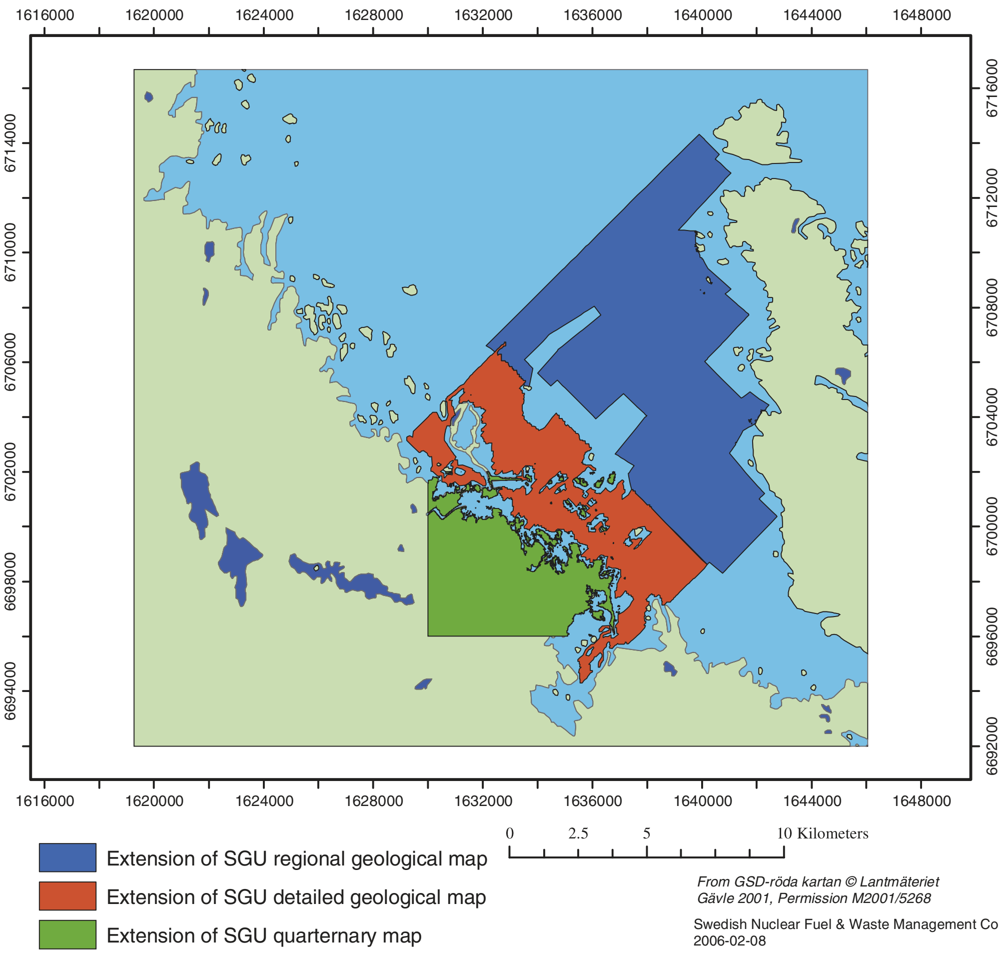


Figure 2-4. *Extension of different geological investigations in the Forsmark study site. The detailed marine geological survey (red) are mapped with 100 metres parallel traces while the regional survey (blue) has 1,000 metres between each trace, which makes the interpretation of the extension of different geological objects more uncertain.*

The extension of till increases in the transition from sea to land. The typical sediment profiles in the regional and detailed sea areas in Forsmark are shown in Figure 2-5.

The thickness of each layer is calculated as average values of about 500 sediment profiles from the central parts of each areas. When the postglacial clay is re-suspended and removed from the area the glacial clay extension increases. When the glacial clay is removed from the sea bottom, the till is exposed, explaining the increase in till extension from sea to land.

Table 2-2 shows the areal distribution of different geological units for shallow coast areas in Simpevarp calculated from the MMT data set. A comparison between SGU-data and MMT-data shows great differences. The glacial clay unit is totally missing in the MMT-data, whereas it is about 40% in the SGU data. Till is the dominating unit in MMT-data (about 50%) while it is only about 1% in the SGU-data. One explanation for these great differences is that SGU maps the geological unit at about 0.5 m depth in the profile, whereas MMT maps the surficial sediment even if it is only some decimetre thick. This could imply that all glacial clay in the Simpevarp area is overlaid with postglacial sediments (clay, sand or gravel).

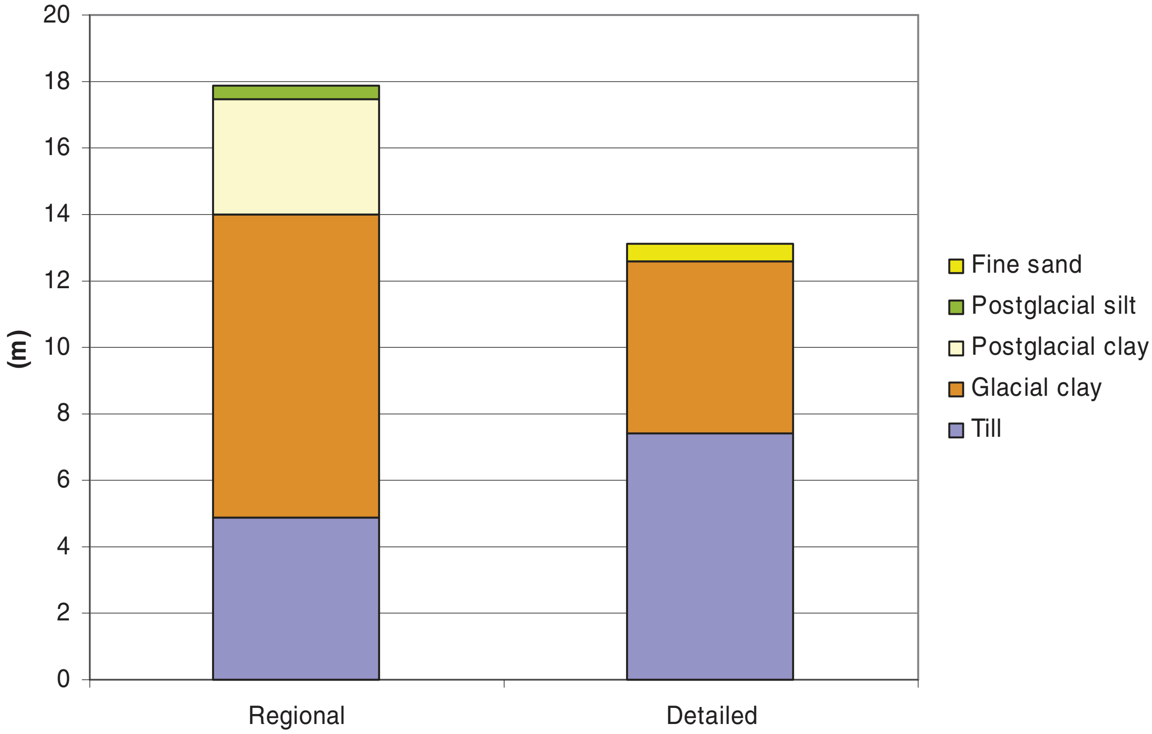


Figure 2-5. *Typical sediment profiles in the regional and detailed sea areas in Forsmark.*

Table 2-2. The area distribution for different geological units in MMT-data from the shallow coast and bays in Simpevarp.

Geological unit	Area (%)
Crystalline bedrock	17.3
Postglacial clay	11.6
Postglacial coarse sand, gravel	13.7
Postglacial fine sand	8.1
Till	49.3

2.3.2 Sediment profiles

The datasets holding the sediment profile data were delivered to SKB in two separate Asci-files. One file has fields for identification number of the track, running number for the profiles along the track and fields for X and Y coordinates (RT90 2.5 gon W). The second Asci-file has one record for each layer in the profiles with the same id-fields and one field for the top-level altitude (masl) for the layer and one field for the bottom level of the profile. Because the information is separated into two files, it is difficult to obtain an overview of the data and almost impossible to calculate total soil depth, etc. Therefore, the goal was to merge these files into one and transform it to a GIS-application so that the profiles could be displayed on a map and included in a searchable database. Another goal was to obtain one record for each profile; and attributes should be layer thickness instead of elevation of top and bottom of each layer. This was done using ArcView GIS program with repeated use of the join-function.

Table 2-3 shows summary statistics for sediment profiles (SGU) in Forsmark and Simpevarp sea areas. There are some similarities between the two areas, but there are also some pronounced differences. The numbers of sediment profiles with postglacial clay are about 20% in the regional areas at both sites and less than 2% in the detailed areas. The total soil depth and the numbers of profiles with till are much higher in the Forsmark area.

Table 2-3. Summary statistics for sediment profiles (SGU) in Forsmark and Simpevarp sea areas.

	Forsmark Regional area	Detailed area	Simpevarp Regional area	Detailed area
Area (km^2)	69.8	30.6	35.1	8.2
Average water depth (m)	20.6	10.7	17.4	13.6
Maximum water depth (m)	58.8	21.9	45.2	31.4
Number of profiles	28,865.0	1,103,949.0	71,805.0	205,339.0
Average soil depth (m)	8.4	8.5	2.5	1.7
Maximum soil depth (m)	43.3	43.8	27.7	16.4
Average till depth (m)	6.1	6.2	4.8	2.7
Maximum till depth (m)	22.3	33.2	23.8	14.6
Number of profiles with till (%)	67.0	98.5	10.2	22.9
Average glacial clay depth (m)	4.4	3.2	2.8	1.9
Maximum glacial clay depth (m)	37.8	19.8	30.7	22.0
Number of profiles with glacial clay (%)	79.8	64.8	63.9	52.7
Average postglacial clay depth (m)	2.1	0.5	1.1	0.7
Maximum postglacial clay depth (m)	7.4	2.5	5.3	1.3
Number of profiles with postglacial clay (%)	20.5	1.8	16.3	0.1
Average postglacial silt depth (m)	0.7	0.5	0	1.2
Maximum postglacial silt depth (m)	3.1	1.4	0	2.0
Number of profiles with postglacial silt (%)	16.6	0.01	0	0.1
Average postglacial fine sand depth (m)	0.9	0.9	0.6	0.6
Maximum postglacial fine sand depth (m)	2.7	8.5	1.9	12.4
Number of profiles with postglacial fine sand (%)	20.2	30.2	5.9	12.7
Average postglacial medium-coarse sand depth (m)	0.7	0.9	0.5	0.5
Maximum postglacial medium-coarse sand depth (m)	2.6	2.9	1.3	1.6
Number of profiles with postglacial medium-coarse sand (%)	12.4	1.2	2.4	4.1

The numbers of profiles with glacial clay is almost the same in both the regional and detailed areas, but the numbers of profiles with postglacial clay are much higher in the regional areas. This implies that the erosion of the postglacial clay starts earlier than the erosion of the glacial clay. To show this more clearly the relationship between layer thickness and water depth are illustrated in Figure 2-6.

The figure indicates that the re-suspension of the postglacial clay starts at a water depth of 20–25 metres and that all postglacial clays are eroded on bottoms shallower than about 5 metres. However, studies of lake sediments in the Forsmark area /Bergström 2001/ have shown that about 20% of the postglacial clay in the lake sediments are settled during a marine/brackish phase. In the Forsmark area there are no basins in the 0–5 metres of water depth interval that will later be lakes, so this phenomenon is not shown in the figure.

Within the SGU regional area in Forsmark there are 12 basins that later will become lakes. The average thicknesses of the postglacial clays layers in these basins are 2.38 metres while the average thickness within basins that not will become lakes are 1.65 metres. This indicates that the postglacial clays are re-suspended from non future lake basins and re-deposited within future lake basins or transported out of the area.

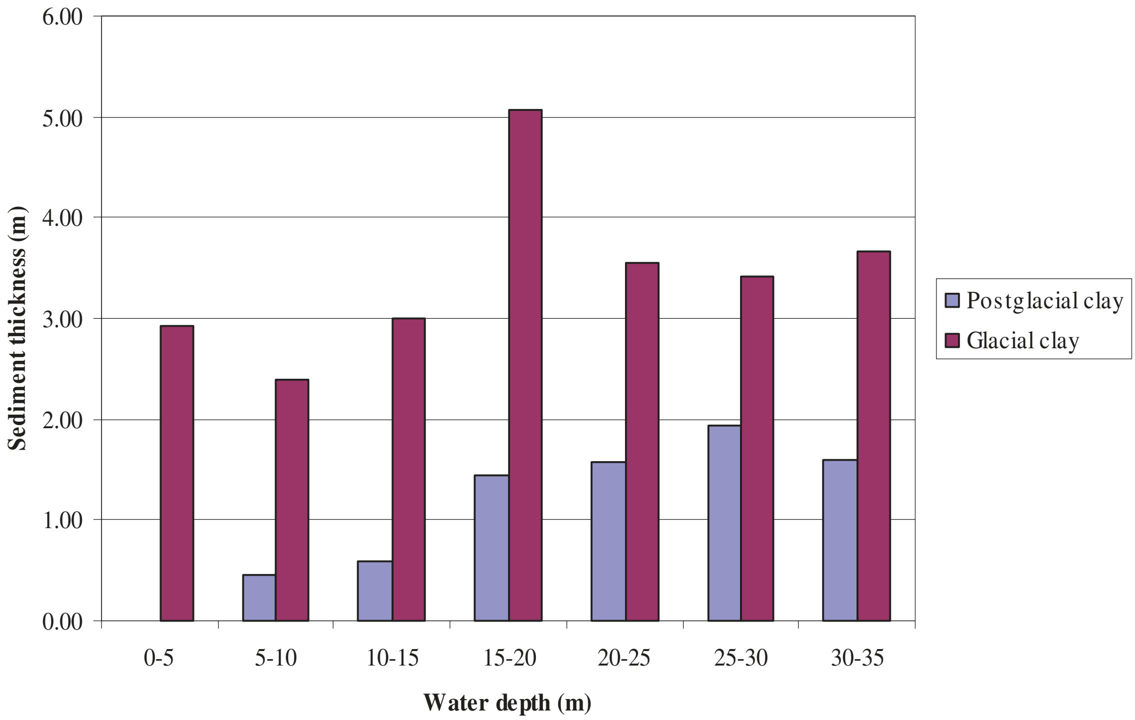


***Figure 2-6.** The relationship between layer thickness and water depth in Forsmark sea area.*

Figure 2-6 also shows that the erosion of glacial clay will probably take place close to the sea shore (glacial clay are almost absent on land, Table 2-1). As mentioned above, the glacial clay is highly compact and elastic sediment, so it seems unlikely that the water movement alone can cause an erosion of many metres of glacial clay in such a short period period. However, divers working in other SKB projects have observed that the glacial clay often is overlaid with a thin layer of wave washed sand or gravel. One explanation for the rapid erosion of the glacial clay is that the sand and gravel acts as blasting particles in the breaker and surf zones at the shore. The knowledge of this process is still deficient and must be verified with extended field studies.

In the Simpevarp area, 14 future lakes will be formed during the next 12,000 years, but only two lakes intersect with the SGU regional area and both are situated in the narrow longish bay Granholmsfjärden. Unfortunately, most of the SGU sediment profiles in these areas are blocked out due to gas in the sediment, but MMT's point map over postglacial sediment thickness covers these two future lakes in Granholmsfjärden. The SGU sediment profiles that were not blocked out are situated close to the future lakes shores and are probably not representative for the average postglacial sediment thickness in the basins. Some of the sediment thickness measurements in MMT's maps are also blocked out by gas, but many of the measurements are situated in the central parts of the basins. Therefore they are treated as more reliable than the SGU measurements.

The geology part of the marine module will extend the model in the following ways:

- allow sedimentation of postglacial clay within basins that later will become lakes with the mean sedimentation rate calculated with data from SGU sediment profiles for the Forsmark area (0.27 mm $year^{-1}$) and MMT data for the Simpevarp area (0.18 mm $year^{-1}$),
- allow resuspension of postglacial clay within basins that will not become lakes, start at 25 metres water depth and remove all postglacial clay before the sea bottom will become land, and decrease the DEM values at these sites with the average postglacial thickness at non future lake basins (0.9 metre in Forsmark and 1.7 metre in Simpevarp), and

- allow a total erosion of glacial clay from bottoms shallower than 5 metres and change the DEM value with the average glacial clay thickness on bottoms shallower than 5 metres (2.9 metres in Forsmark and 1.8 metres in Simpevarp).

2.3.3 Shore level displacement

The change in water depths in the sea is calculated using the shore level displacement equations published in /Påsse 1997/. The shore displacement is calculated as the glacio-isostatic uplift (U) minus the global eustatic sea level rise (E). The glacio-isostatic uplift is divided into a slow and fast component and is calculated as follows (with Microsoft Excel terminology):

$U = 0.6366 \cdot A_s \cdot (\text{ATAN}(12{,}500/B_s) - \text{ATAN}((12{,}500 - t)/B_s)) + A_f \cdot \text{EXP}(-0.5 \cdot (((t - 11{,}500)/B_f) \cdot (t - 11{,}500)/B_f))$ (Equation 1)

where A (m) is a download factor (m), B (y^{-1}) is an inertia factor, and t is the time in calendar years, and the subscripts S is for the slow component and F for the fast component.

The eustatic sea level rise is calculated as follows:

$E = 0.6366 \cdot 50 \cdot (\text{ATAN}(9{,}350/1{,}375) - \text{ATAN}((9{,}350 - t)/1{,}375))$ (Equation 2)

The factors A_s, B_s, A_f and B_f are all site dependent. For the Oskarshamn site, Påsse used data from /Svensson 1989/ to calibrate the model and find values for the four factors, but no calibrations were made for the Forsmark site in the 1997 publication. The three nearest sites are Stockholm area, Gästrikland and Åland. Each site had different values for the factors, especially for the A_s and B_s factors. In earlier studies about the Forsmark site investigations, the average values from the three sites were used /Brydsten 1999/. Within the Formark site investigation programme new shore level datings were performed and using also older datings a new shore level curve was constructed /Hedenström and Risberg 2003/. Using values from this curve, the four factors in the shore level equation were calculated using the Excel solver add-in. Table 2-4 shows the values for the four factors used in this model.

2.4 The lake module

The lake module is identical to the module presented in /Brydsten 2004b/. A brief summary will be presented here. For detailed information about calibration and validation of the module see /Brydsten 2004b/.

The lake basin filling processes were separated in two parallel processes; filling with fine-grained material (clay and/or silt) and filling with vegetation. The sedimentation rate in a lake depends on the lake water volume and can be expressed as follows /Brydsten 2004b/:

$\text{Sediment rate} = 193.024 \cdot \text{Water volume} - 14.168 \cdot \text{Water volume}^2$ (Equation 3)

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

Table 2-4. Values of four factors used in the shore level displacement equation. The Simpevarp site has no fast glacio-isostatic uplift component and these values are set to zero.

Factor	Forsmark	Simpevarp	Unit
A_s	304	177	m
B_s	6,986	3,200	Year $^{-1}$
A_f	81	0	m
B_f	1,144	0	Year $^{-1}$

This means that the sedimentation rate decreases over time as the water volume decreases due to the two filling processes.

The choke-up of the lake with vegetation starts with colonization by littoral plants, followed by invasion of bryophytes when the resulting wetland becomes a bog. The colonization of littoral plants requires shallow water (< 2 metres), a shore with a low slope, and a shore without a wave-breaking zone. Wave breaking that causes erosion of vegetation close to the shore is not common in small lakes, because the short fetch produces low wave power. There are no visible signs of erosion of the littoral vegetation in any of the orthophotos covering the lakes in Forsmark or Simpevarp, therefore, the non wave-breaking zone criteria is not considered in the lake module. The low slope criterion is also not considered in the lake module because of the uncommon steep shores at both sites. The "Choke-up rate" in lakes depends on lake area and can be expressed as follows /Brydsten 2004b/:

"Choke-up rate" = 16.53 + 2.41E–4 · "Basin area" (Equation 4)

in which choke-up rate is expressed as m^2 $year^{-1}$ and basin area as m^2. The choke-up rate is a maximum value that can be lower because the area of the bottom is shallower than 2 metres, a depth that's limits the colonization.

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.

2.5 A mathematical model for simulation of landscape evolution processes

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

1. change in bathymetry due to sedimentation of postglacial clay or silt in sea areas that later will be lake basins,
2. change in bathymetry due to erosion of postglacial clay or silt from sea areas that will later not be lake basins,
3. change in bathymetry due to erosion or glacial clay from sea areas that will later not be lake basins,
4. change in bathymetry due to shore displacement,
5. change in lake bathymetry due to sedimentation of organic rich sediments, and
6. change in lake bathymetry due to lake choke-up process by colonization of marsh and bog vegetation.

The marine module starts soon after deglaciation of the areas (10,000 BP in Forsmark and 12,500 BP in Simpevarp) and stops at lake isolation time and requires the following input data:

- a DEM covering the catchment (or sub catchment) and only the catchment (no data value outside the catchment) for the future lake in Asci raster format,
- a map showing potential accumulation bottoms, bottoms that have been or will be influenced by accumulation of fine-grained postglacial material. These bottoms are defined as areas with existing or future lakes, existing organic sediment in the quaternary map, existing postglacial fine-grained sediment in both the quaternary and marine geological map and bottoms deeper than 50 metres (hereafter called ACC). The map is used for calculation of the fraction of potential accumulation bottoms,

- a combination of the marine geological map and future lake extension (hereafter called Combo) with codes for the first three processes listed above in exactly the same format as the DEM (cell size and extension), and
- the lake isolation time.

The marine module does not involve any change in bathymetry due to sedimentation/erosion processes for the former sea basins (from deglaciation to today), but only calculates change in bathymetry due to shoreline displacement. The sedimentation/erosion sub-module starts at year 2000 and has steps of 100 years until the lake isolation time is reached.

Step 1: The DEM is read and transformed to a two-dimensional array.

Step 2: The Acc and Combo is read and transformed to two-dimensional arrays with exactly the same indexing as the DEM-array.

Step 3: The module makes a two-dimensional array with the same indexing as the DEM-array that will hold the postglacial clay thickness (hereafter called SED-array). It is assumed that the initial sediment thickness is the average values for postglacial clay in future lake basins or in non-future lake basins, respectively. If the Combo-array says that the cell is till, crystalline bedrock or glacial clay the value is set to zero.

Step 4: At each time step after 2,000 AD the module is runs through the three arrays in parallel, if the following conditions are met:

(i) if Combo-array shows a future lake basin, both the Sed-array and DEM-array are added with 0.027 m for Forsmark and 0.018 m for Simpevarp,

(ii) if Combo-array shows a non-future lake basin and the SED-array shows sediment thickness greater than zero and the DEM-array shows water depth shallower than 25 metres both the DEM-array and the SED-array are decreased with 0.14 metres (the minimum value to remove all postglacial sediment before reaching 5 metres water depth), and

(iii) if Combo-array shows and DEM-array shows water depth shallower than 5 metres, all glacial clay is removed and the DEM-array is decreased with 2.9 metres for the Forsmark site and 1.8 metres for the Simpevarp site (average values of glacial clay thickness in the 0–5 metres depth interval).

Step 5: The module runs through the DEM-array and calculates the basin water volume and basin water area and runs through the Sed-array and calculates the postglacial sediment volume. These parameters are written to a comma-separated text file.

Step 6: Step 4 and 5 were repeated until the lake isolation time is reached.

Step 7: The DEM-array is written to a text file with Asci raster format and the output text file is closed.

The lake module is separated from the marine module in order to run the module on existing lakes where the sedimentation and choke-up processes already are ongoing.

The only input to the lake module is the output DEM from the marine module or for existing lakes a DEM made from echo sounding data.

Step 1: The lake DEM is read and transformed to a two-dimensional array.

Step 2: Three 2-dimensional arrays are constructed; one for holding information on occurrence of organic material, one to store information on the water depth when the cells are occupied by organic material (hereafter called Org-array and Orgdepth-array, respectively), and one for holding information on postglacial sediment thickness (Sed-array). These arrays have exactly the same format as the DEM-array.

Step 3: The lake water volume is calculated using the DEM-array and the Org-array by adding all negative values in the DEM-array that in Org-array are not marked as organic material and this value is divided by the number of non-organic cells in the Org-array and multiplied by the square of the DEM cell size. The cell size is automatically read in from the header of the asci raster file, so it is possible to use different cell sizes for different lakes (for large lakes and small cell size the module runs extremely slow).

Step 4: The basin is supplied with fine-grained inorganic sediments with a volume calculated using Equation 3 and actual water volume calculated in step 3. If the basin has bottom areas located below two metres water depth, all new sediments are placed there, otherwise the new sediments are spread evenly over the entire lake not occupied by organic material. The DEM-array values are increased with a value calculated by the quota between new sediment volume and area, only some values when the maximum water depth is below two meters or all values when maximum water depth is shallower than two meters (bottom area beneath two metres water depth or basin area not occupied by organic material). Equation 3 is calibrated using sediment data from six lakes in Forsmark area with water volume lower than 6 Mm^3. Because two future lakes in the Forsmark area have initially larger water volumes and the sediment rate calculated with Equation 3 is not appropriate. For these two lakes (Id = 10 and 55), the average sediment rate for the six lakes are used (0.665 mm $year^{-1}$) as long as the lakes water volumes exceeds 6 Mm^3; thereafter, Equation 3 is used.

Step 5: For bottom areas shallower than 2 metres water depth, the choke-up rate is calculated using Equation 4. In cases when choke-up area exceeds the area calculated to be shallower than 2 meters, growth of the bog is only permitted to proceed out to two metres water depth. The growth is allowed to proceed on the shallowest part of the basin not already occupied by organic material.

Step 6: Step 3 is repeated in order to calculate water volume after the latest sedimentation and choke-up processes. The water area is calculated as the number of non-organic cells in Org-array multiplied by the square of the cell size. The volume of the organic material is calculated as the average water depth in the Orgdepth-array multiplied by the growth area. These parameters are written as a comma-separated text file.

Step 7: Step 4, 5 and 6 are repeated until the entire former basin area consists of a bog or the time step exceeds 20,000 AD. At each time step, there is an opportunity to obtain a copy of the Org-array written to an Asci raster file easily imported to the GIS program. This opportunity makes it possible to see how the choke-up process proceeds over time.

Finally, the three text-files (output from the marine former sea basin module, the marine sedimentation module, and the lake module) are imported to MS Excel spreadsheet program and merged into a single spreadsheet.

3 Results

For the Forsmark site, 21 future lakes and 20 existing lakes were modelled and all results are merged into a single Excel-file. Of the future lakes simulations, 17 runs ended normally (100% bog), 3 ended due to the 20,000 AD rule (Id 10, 18 and 55), and one was totally filled with inorganic sediments at the isolation time (Id 12).

Table 3-1 shows a summary of the results from the Forsmark site. The lakes can be classified into three classes based on the length of the lacustrine phase (the time between lake isolation and totally filled basin): four future lakes that are both large and deep and will have a long lacustrine phases, the rest of the future lakes and the medium sized existing lakes -Bolundsfjärden, Fiskarfjärden and Eckarfjärden – that will have a lacustrine phases between about 3,000–6,000 years, and small and shallow existing lakes that will have lacustrine phases shorter than 1,800 years.

The absence of small future lakes are due to the method used to determine the extension of future lakes, were the accuracy of the extensions are controlled by the accuracy of the DEM. It was decided that future lakes smaller than 0.1 km^2 are not accurately determined.

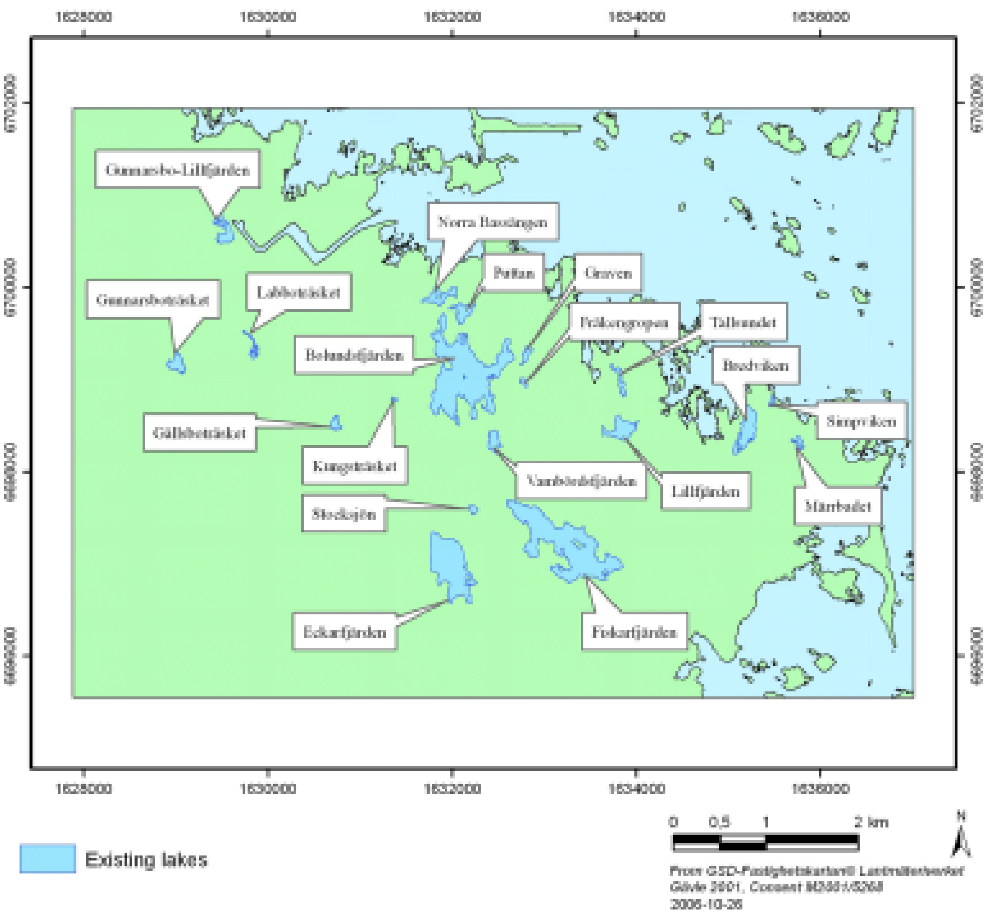


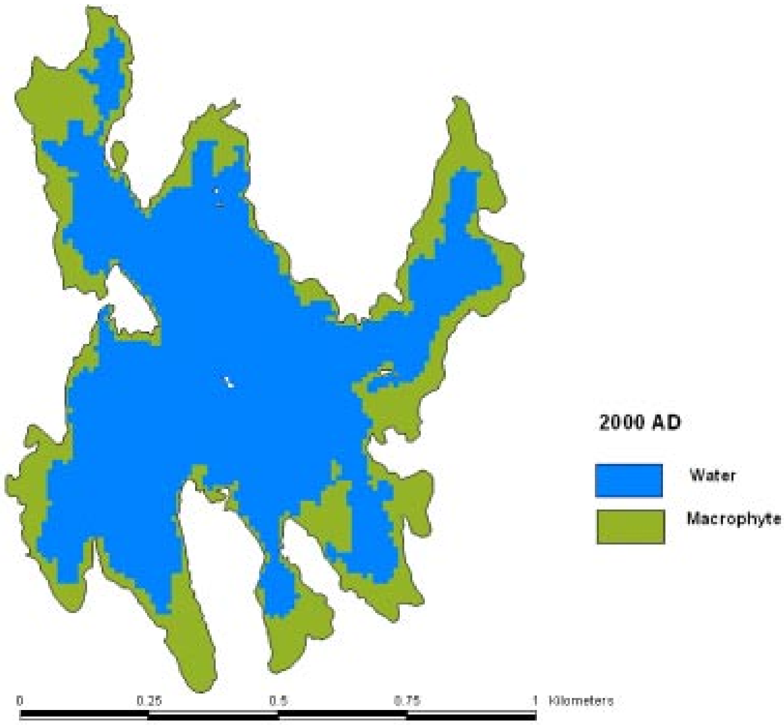
Figure 3-1. *Existing lakes at the Forsmark site.*

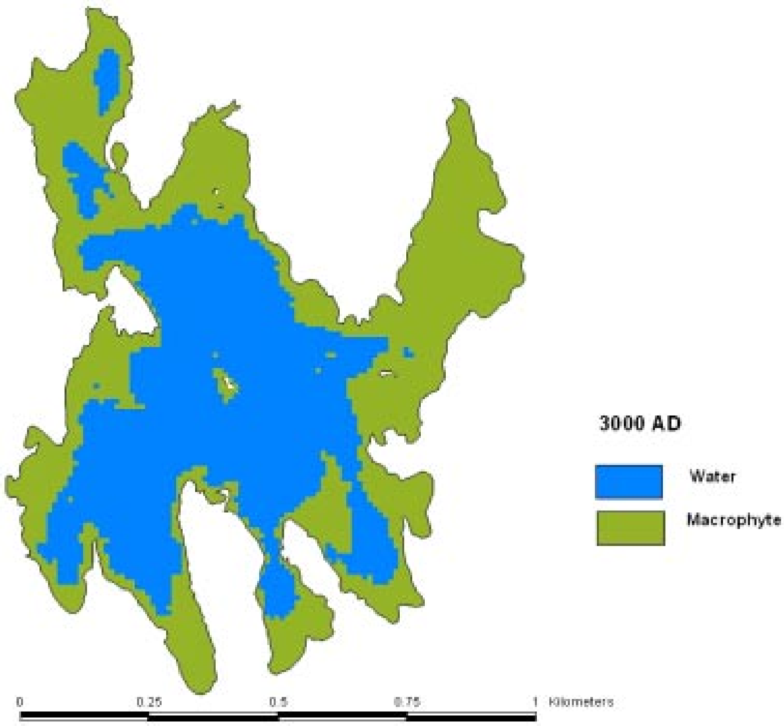
Table 3-1. Summary results from evolution of future and existing lakes at the Forsmark site. For the length of the marine phase it is assumed that the deglaciation took place for 10,000 years ago /Fredén 1994/.

Lake	Baltic Basin phase (years)	Lacustrine phase (years)	Lake isolation time (Year AP)
Lake 10	20,600	> 9,400	8,700
Lake 12	17,600	0	5,700
Lake 18	20,500	> 9,500	8,500
Lake 21	15,700	3,700	3,700
Lake 22	14,800	4,000	2,900
Lake 25	14,200	3,300	2,200
Lake 28	14,600	4,000	2,700
Lake 29	12,900	4,100	1,000
Lake 30	12,800	3,500	800
Lake 31	12,400	12,700	400
Lake 32	13,900	3,200	1,900
Lake 33	16,200	3,700	4,200
Lake 34	12,200	3,500	200
Lake 35	14,300	3,600	2,300
Lake 36	14,600	3,300	2,600
Lake 39	13,400	3,800	1,400
Lake 51	16,600	3,300	4,700
Lake 52	13,000	3,800	1,100
Lake 53	15,200	3,500	3,300
Lake 54	16,300	3,700	4,400
Lake 55	18,100	> 11,900	6,100
Bolundsfjärden	9,900	5,700	–100
Bredviken	10,000	3,900	0
Eckarfjärden	9,200	5,900	–800
Fiskarfjärden	9,900	5,700	–100
Fräkengropen	9,800	400	–200
Graven	9,900	600	–100
Gunnarbo-Lillfjärden (the north side)	9,700	600	–300
Gunnarbo-Lillfjärden (the south side)	9,700	1,200	–300
Gunnarsboträsket	9,100	1,800	–900
Gällsboträsket	9,700	800	–300
Kungsträsket	9,600	600	–400
Labboträsket	9,400	800	–600
Lillfjärden	10,000	1,700	0
Norra Bassängen	9,900	1,500	–100
Märrbadet	10,000	300	0
Puttan	9,900	1,300	–100
Simpviken	10,000	200	0
Stocksjön	9,500	900	–500
Tallsundet	10,000	600	0
Vambördsfjärden	9,800	1,200	–200

Figure 3-2 shows an example of lake choke-up process for the lake Bolundsfjärden at the Formark site. The vegetation colonization occurs from the shore against the deepest central part of the lake, but, small ponds are isolated at peripheral parts of the lake.

For the Simpevarp site, 4 future lakes and 4 existing lakes were modelled and all results are merged into a single Excel-file. Of the future lakes simulations, 3 runs ended normally (100% bog), and one ended due to the 20,000 AD rule (Id 32).





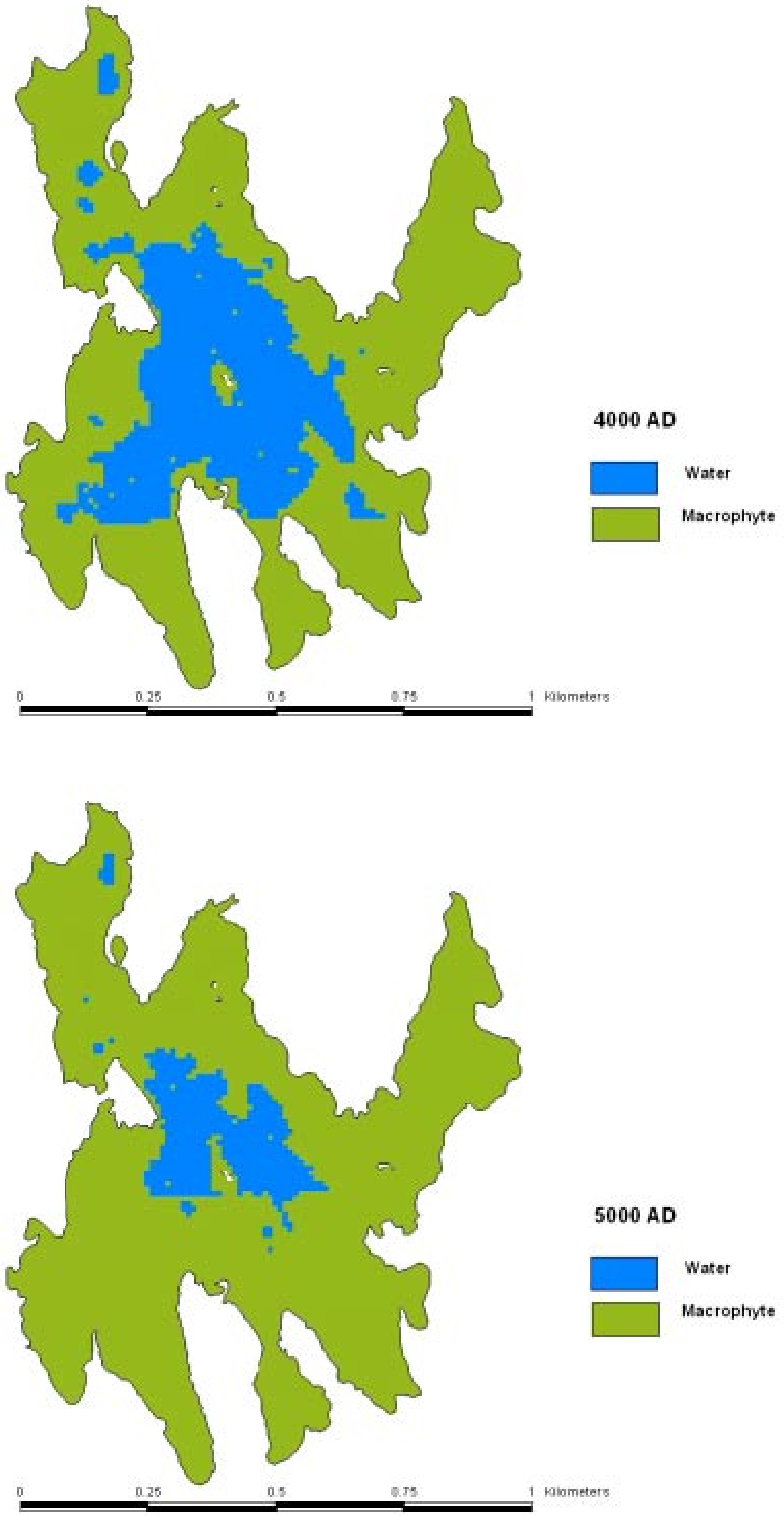


Figure 3-2. *The progress of lake choke-up process for the lake Bolundsfjärden at the Formark site.*

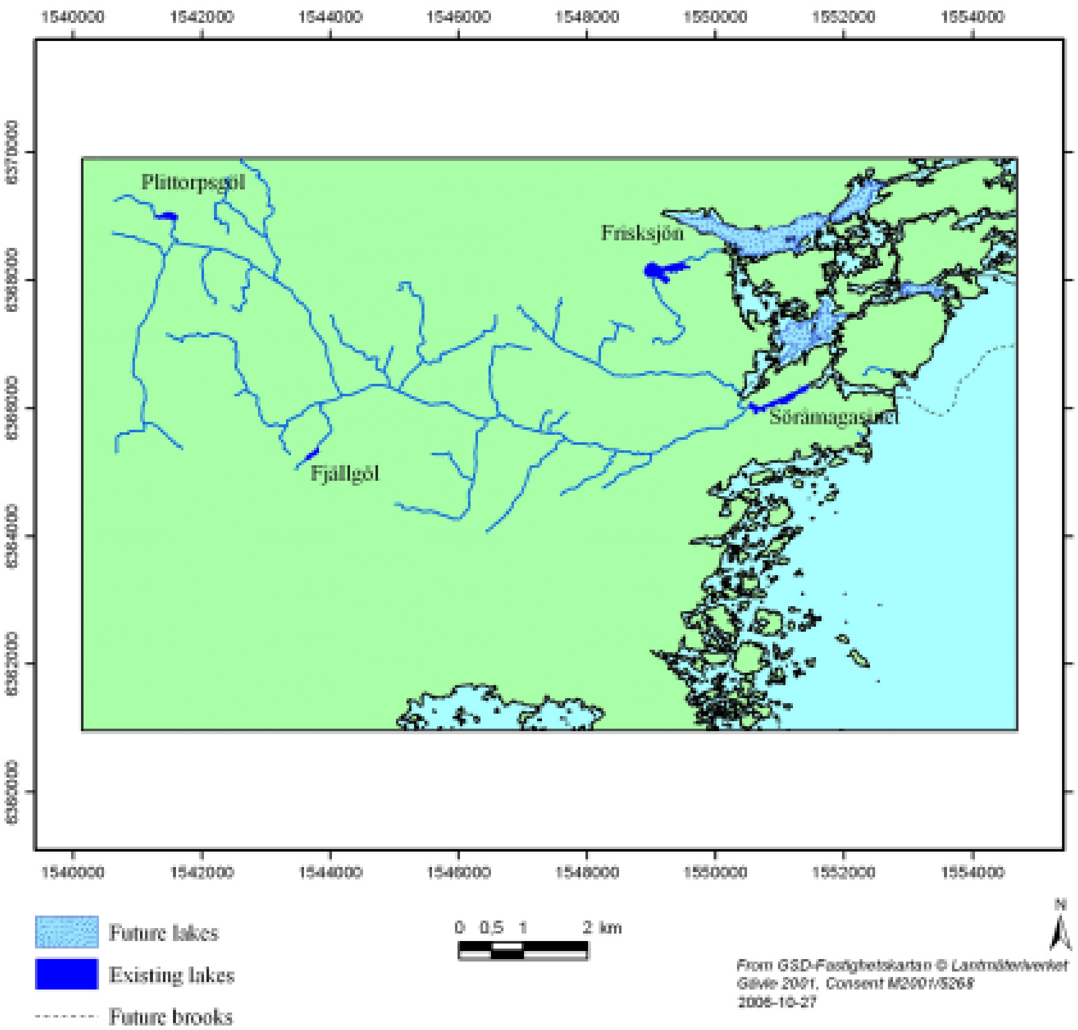


Figure 3-3. *Exstensions of existing and future lakes at the Simpevarp site. The two northernmost future lakes will be a part of the brook from Lake Frisksjön and the two southernmost will be a part of the River Laxemarån.*

Table 3-2. Summary results from evolution of future and existing lakes at the Simpevarp site. For the length of the Baltic Basin phase, it is assumed that the deglaciation took place for 12,500 years ago /Fredén 1994/. Note that Söråmagasinet is highly manipulated by humans so the figures are not correct.

Lake	Baltic Basin phase (years)	Lacustrine phase (years)	Lake isolation time (Year AP)
Lake 31 (Outher Granholmsfjärden)	17,900	13,900	3,500
Lake 32 (Inner Granholmsfjärden)	16,300	> 18,200	1,800
Lake 33	18,700	5,800	4,200
Lake 34 (Borholmsfjärden)	16,100	3,400	1,700
Fjällgöl	4,500	8,300	–8,000
Frisksjön	11,700	5,400	–800
Plittorpsgöl	4,500	18,500	–8,000
Söråmagasinet	11,400	11,600	–1,100

Table 3-3 is an example of merged output from the two modules. The example is for the future lake Borholmsfjärden in the Simpevarp area. The marine phase from 9,000 BC to today is excluded from the table. As shown in the table the water volume and water area decreases drastically during the marine phase while the sediment volume only increases slowly. These are general results for all model basins: the change in water volume and area during the marine phase are much more dependent on shoreline displacement than different sedimentation processes. It is even more accentuated in the Forsmark area where the shoreline displacement rate is more rapid.

When the whole future basin is filled with organic material (7,000 AD), the basin is filled with 17% organic material and 83% inorganic sediment. These figures differ greatly between different future lakes, but it is unusual that the organic material would be in majority.

Table 3-3. Results from the simulation of the basin filling processes of Borholmsfjärden in the Simpevarp area.

Year AD	Water volume Mm^3	Water area m^2	Sed volume Mm^3	Volume organic Mm^3	Area organic m^2
2,000	2.295	1,425,400	0.673	0	0
2,100	2.066	1,282,800	0.679	0	0
2,200	1.857	1,200,100	0.684	0	0
2,300	1.663	1,124,600	0.690	0	0
2,400	1.484	1,047,800	0.695	0	0
2,500	1.319	970,100	0.700	0	0
2,600	1.168	894,600	0.706	0	0
2,700	1.032	813,000	0.711	0	0
2,800	0.909	736,200	0.716	0	0
2,900	0.799	668,100	0.721	0	0
3,000	0.700	603,500	0.726	0	0
3,100	0.611	550,000	0.731	0	0
3,200	0.530	500,700	0.736	0	0
3,300	0.457	456,200	0.741	0	0
3,400	0.391	409,600	0.745	0	0
3,500	0.332	372,900	0.750	0	0
3,600	0.279	338,600	0.755	0	0
3,700	0.269	297,000	0.760	0.001	9,000
3,800	0.262	288,000	0.765	0.002	18,000
3,900	0.255	279,000	0.770	0.004	27,000
4,000	0.249	270,000	0.775	0.005	36,000
4,100	0.242	261,000	0.780	0.007	45,000
4,200	0.236	252,000	0.784	0.009	54,000
4,300	0.230	243,000	0.789	0.011	63,000
4,400	0.224	234,000	0.793	0.013	72,000
4,500	0.220	225,000	0.794	0.014	81,000
4,600	0.214	216,000	0.799	0.017	90,000
4,700	0.208	207,000	0.803	0.019	99,000
4,800	0.202	198,000	0.806	0.021	108,000
4,900	0.196	189,000	0.810	0.024	117,000
5,000	0.190	180,000	0.814	0.025	126,000
5,100	0.184	171,000	0.817	0.028	135,000
5,200	0.178	162,000	0.820	0.031	144,000
5,300	0.172	153,000	0.824	0.034	153,000

Year AD	Water volume Mm³	Water area m²	Sed volume Mm³	Volume organic Mm³	Area organic m²
5,400	0.163	144,000	0.827	0.039	162,000
5,500	0.154	135,000	0.830	0.045	171,000
5,600	0.145	126,000	0.833	0.051	180,000
5,700	0.136	117,000	0.836	0.058	189,000
5,800	0.127	108,000	0.839	0.064	198,000
5,900	0.118	99,000	0.841	0.070	207,000
6,000	0.109	90,000	0.843	0.077	216,000
6,100	0.100	81,000	0.845	0.084	225,000
6,200	0.091	72,000	0.847	0.091	234,000
6,300	0.082	63,000	0.849	0.098	243,000
6,400	0.073	54,000	0.851	0.106	252,000
6,500	0.060	45,000	0.852	0.117	261,000
6,600	0.048	36,000	0.853	0.128	270,000
6,700	0.036	27,000	0.854	0.139	279,000
6,800	0.024	18,000	0.855	0.150	288,000
6,900	0.012	9,000	0.855	0.162	297,000
7,000	0.000	0	0.855	0.174	306,000

4 Discussion and further improvement of the model

For some of the model objects in Forsmark, the models end up at 18,000 AP and are still within the marine phase. This implies that the shoreline displacement equation is used through the whole time period 8,000 BC to 18,000 AP. For the past, the equation is calibrated against dating of isolation times in lake sediments, but for the future there are of course no possibilities for any validations. It can be supposed that the equation precision is decreases over time, and therefore the shoreline displacement model can not be used beyond a certain time and probably not as long as until 18,000 AP. This can cause misleading model results for late time steps.

The parameters for the shoreline displacement equation for Oskarshamn are the parameters published by /Påsse 1997/, but recently Påsse updated these parameters /Påsse and Andersson 2005/. These parameters will be used in next version of the model.

The age of existing lakes is calculated using the lake elevations and the shoreline displacement equations. Most of the lakes in both Forsmark and Simpevarp areas are lowered by human activities in order to recover extended arable land. For these lakes, the calculated ages are underestimated; for example, if the lake Frisksjön in the Simpevarp area is lowered by one metre the underestimation of the age is about 500 years.

The elevations of future lakes are determined using the DEM and the hydrological extension in ArcGis. If the future lake outlet is narrow there is a risk that the outlet is not correctly described in the DEM and the result that the elevation is overestimated. This will also result in overstimations for future lake area and water volume. These possible errors can be corrected by accurate echo soundings of the determined outlet areas.

The choke-up process in lakes is supposed to start at isolation time, but at many places the process starts as early as in the shallow gulf phase. The criteria that determines whether the choke-up process starts or not in the shallow gulf phase are not known, so in the model the process always starts at isolation tim; therefore, the calculation of vegetated area will therefore be underestimated for some lakes.

In the model the choke-up rate is supposed to be constant over time. In reality, the rate is higher in the beginning of the process and successively decreases over time. In future versions of the model, this will be considered.

In the marine module it is assumed that sedimentation of fine-grained particles are ongoing constantly on bottoms that later will be lakes. This is probably correct for deep lake basins but not for shallow basins where wave generated processes causes resuspension of these particles. One example from the Forsmark area, future lake 28 ("Charlies Lake") has a threshold level of – 14 metres, a maximum depth of 4.79 m and a mean depth of 1.37 m. The bottom is highly exposed against waves from north and is probably influenced of wave-generated re-suspension. According to the marine geological map /Elhammer and Sandkvist 2003/, the bottom material is dominated by till and glacial clay and the only postglacial material is fine sand (wave washed material). On the other hand, lake 39 (situated inside the esker in Kallrigafjärden) will have almost the same area and the same mean water depth, but with the postglacial clay as dominating bottom material. The difference between these two basins is the exposure against waves, where lake 39 is sheltered against waves by the narrow outlet of the Kallrigafjärden. If it is only the depths of the future lakes that determine whether the lakes should have accumulation bottoms or not, it could easily be incorporated in the marine module, but not the combination of exposure and basin depths. This problem requires an additional wave re-suspension module. In the available version of the module the results overestimate postglacial sedimentation for some future lakes.

5 References

Bergström E, 2001. Late Holocene distribution of lake sediment and peat in NE Uppland, Sweden**.** SKB R-01-12. Svensk Kärnbränslehantering AB.

Brunberg A-K, Carlsson T, Brydsten L, Strömgren M, 2004a. Identification of catchments, lake-related drainage parameters and lake habitats. Oskarshamn site investigation. SKB P-04-242. Svensk Kärnbränslehantering AB.

Brunberg A-K, Carlsson T, Blomqvist P, Brydsten L, Strömgren M, 2004b. Identification of catchments, lake-related drainage parameters and lake habitats. Forsmark site investigation. SKB P-04-25. Svensk Kärnbränslehantering AB.

Brydsten L, 1999. Shore line displacement in Öregrundsgrepen. SKB TR-99-16. Svensk Kärnbränslehantering AB.

Brydsten L, 2004a. A method for construction of digital elevation models for site investigation program at Forsmark and Simpevarp. SKB P-04-03. Svensk Kärnbränslehantering AB.

Brydsten L, 2004b. A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation. SKB TR-04-09. Svensk Kärnbränslehantering AB.

Elhammer A, Sandkvist Å, 2003. Detailed marine geological survey of the sea bottom outside Forsmark. SKB P-03-101. Svensk Kärnbränslehantering AB.

Elhammer A, Sandkvist Å, 2005. Detailed marine geological survey of the sea bottom outside Simpevarp. Oskarshamn site investigation. SKB P-05-35. Svensk Kärnbränslehantering AB.

Fredén C, 1994. Berg och jord. Sveriges nationalatlas.

Hedenström A, Risberg J, 2003. Shore displacement in northern Uppland during the last 6,500 calender years. SKB TR-03-17. Svensk Kärnbränslehantering AB.

Ingvarson N, Palmeby S, Svensson O, Nilsson O, Ekfeldt T, 2004. Marine survey in shallow coastal waters. Bathymetric and geophysical investigation 2004. Oskarshamn site invsestigation. SKB P-04-254. Svensk Kärnbränslehantering AB.

Lindborg T, (ed), 2006. Description of surface systems. Preliminary site description Laxemar subarea – version 1.2 SKB R-06-11. Svensk Kärnbränslehantering AB.

Påsse T, 1997. A mathematical model of past, present and future shore level displacement in Fennoscandia. SKB TR 97-28. Svensk Kärnbränslehantering AB.

Påsse T, Andersson L, 2005. Shore-level displacement in Fennoscandia calculated from empirical data. GFF, Vol. 127 (Pt. 4, December), pp 253–268. Stockholm.

Svensson N-O, 1989. Late Weichselian and Early Holocene shore displacement in the Central Baltic, based on stratigraphical and morphological records from Eastern Småland and Gotland, Sweden. Lund University, Department of Quaternary Geology 25, 1–195

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