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A coupled regolith-lake development model applied to the Forsmark site

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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 authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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Extended summary

The Swedish Nuclear Fuel and Waste Management Co. (SKB) has been conducting site investigations at two sites in Sweden, the Laxemar area and Forsmark, to find a suitable geological repository for spent nuclear fuel. These site investigations, which began in 2002 and finished in 2007, provide information about the site and its regional setting, including the geosphere, the biosphere, and natural processes that may influence long-term safety. These site investigations should provide parameters and models to be used in analyses conducted by the Safety Assessment, Repository Design and Environmental Impact Assessment.

The Quaternary geology at the Forsmark site has been characterized using both a map of Quaternary deposits /Hedenström and Sohlenius 2008/ and a regolith depth model (RDM) that show the stratigraphy and thickness of different deposits /Hedenström et al. 2008/. Regolith refers to all the unconsolidated deposits overlying the bedrock. The surface geology and regolith depth are important parameters for hydrogeological and geochemical modelling and for the overall understanding of the area. The safety assessment analysis should focus on processes involved during a period of 120,000 years, which includes a full glacial cycle; however, the investigations within the site description model do not cover the temporal change of the regolith, a limitation that does not fulfil the requirements for the safety assessment. To this end, this study constructs a model that can predict the surface geology, stratigraphy, and thickness of different strata at any time during a glacial cycle and applies this model to the Forsmark site.

The Weichselian ice sheet covered the study area until around 9500 BC. The deglaciation revealed a marine landscape with bedrock, till and glacial clay. The water depth was about 145 to 230 meters, well below the wave base, so postglacial clay and silt started to settle and covered glacial sediments or bedrock where sediments were absent. Regression of the sea brought the shallowest part above the wave base and caused glacial and postglacial sediments to resuspend. These particles were transported out of the area into the Bothnian Sea or re-settled on deeper bottoms within the study area. As regression of the sea continued, more and more bottoms were situated above the wave base and the wave resuspension of sediments gradually exposed more of the pre-glacial sea bottom. When the area became even shallower, the wave power decreased. This was partly caused by a decreased extension of the Baltic Sea. The decreased fetch led to lower wave power in the open sea. Bottom friction or wave breaking before the wave entered the study area decreased wave power. The wave base was raised and in some parts of the study area fine-grained particles started to deposit on the lea-sides of hills. Finally, some parts of the area were situated in the littoral zone with strong erosion in the breaker zone and long-shore transportation. At these areas, part of the postglacial clay was eroded when the sea bottom became land.

For the safety assessment, the most important unconsolidated strata are clay or silt: these small grains can bind nuclear elements more easily than coarser sediment particles. Thick layers of clay can be found where post-glacial clay settled on top of glacial clay, especially where the middle-aged erosion of postglacial clay is missing and where there is an uninterrupted sequence of accumulation of fine-grained particles. Such areas could be found in deep marine basins that later become lakes when raised into a supra-marine position.

The coupled regolith-lake development model (RLDM) predicts the course of events described above during an interglacial, especially the dynamics of the clay and silt particles. The RLDM is divided into two modules: a marine module that predicts the sediment dynamics caused by wind waves and a lake module that predicts the lake infill processes.

The RLDM marine module starts at the time when the area has recently been deglaciated and the local Quaternary geology consist of glacial sediments only (surface geology, stratigraphy, and thickness around 9500 BC). These conditions are generated using the regolith depth model (RDM) /Hedenström et al. 2008/. The RDM is a model in raster format with seven layers where each layer is presented as a digital elevation model (DEM) for the upper surface of that particular layer. The top three layers in the RDM are formed during the postglacial period, so the bottom four layers represent the stratigraphy as it existed around 9500 BC. Because the RDM is in a raster format with a cell size of 20 meters, the RLDM is in the same extension and resolution as the RDM.

Between 9000 BC and 11,500 AD (with 500 year time steps), postglacial clay/silt are added or removed in each raster cell based on the sediment dynamic environment for that date. This sediment dynamic data is output from the sediment dynamic model (SDM) as presented by /Brydsten 2009/. In a cell where erosion is the predominant process, all postglacial accumulation is resuspended and transported out of the cell. Cells dominated of accumulation get a contribution of 0.06–0.39 m postglacial clay in each time step. The net sedimentation rate (m $500a^{-1}$) varies over time and is calibrated using the SDM and measured postglacial clay thickness from the marine geological survey /Elhammer and Sandkvist 2005/. For each time step, the RLDM marine module outputs are raster maps of surface geology, thickness of postglacial clay, and DEM.

The lakes are modelled with a module within the RLDM based on an equation for net sedimentation rate and an equation for vegetation colonization /Brydsten 2006a/. Each lake is modelled separately. The DEM and the thickness of the marine postglacial clay from the time step before lake isolation is used as the only input to the module. The lake module runs in 100-year time steps until the lake is completely infilled. Raster maps of surface geology, DEM, thickness of the marine and limnic postglacial clay (gyttja clay or clay gyttja), and thickness of the peat are outputs from the lake module for each time step.

In a post-processing routine, the outputs from the marine and lake modules are merged into single raster maps for surface geology, DEM, and RDM. In a second post-processing routine, the wetlands not emanating from infilled lakes are added. These wetlands are partly small infilled local basins and partly hanging wetlands. The extensions of the later are calculated using the DEM and an equation for topographical wetness index (TWI).

The major part of the study area was covered by postglacial clay shortly after the area was deglaciated. As the water got shallower following isostatic rebound, more postglacial clay resuspended and exposed the glacial sediments beneath. The minimum areal extension of the postglacial clay occurred about 2000 BC and was localized to a deep area west of the island Gräsö. Next, the area of postglacial clay increased again to reach a local maximum around 2500 AD, then successively decreased until the sea left the study area (about 11,500 AD), exposing the greater part of the postglacial clay found in the lakes.

In a small part of the study area (about 1.5%), along the *Gräsörännan*, postglacial clay accumulated during the whole period. The maximum-modelled thickness of the postglacial clay is found in this area, about 26.8 meters, of which about 5.6 meters settled in a marine environment.

Most of the lakes are shallow and will infill completely in 2,000 to 6,000 years. Exceptions are the deep lakes situated along today's *Gräsörännan* that will exist for about 25,000 years. The last lake will be totally infilled around 35,000 AD.

The RLDM assumes that the climate will not change during the modelled period. However, /Kjellström et al. 2009/ account for results from a climate model applied to a period of 120,000 years, which includes a full glacial cycle; their study shows permafrost climates for some of the period before all lakes at the Forsmark site will be completely infilled. This could be valid for future lakes with long infill times, e.g. lakes along the *Gräsörännan*.

Both colonization of vegetation and sedimentation decreases with lower water temperature /Löfgren 2010/, so both the modelled infill rate and the sedimentation rate could be overestimated. The infill rate can be measured as the average long-term apparent rate of carbon accumulation (LORCA) in peat. The LORCA is measured in one bog in Forsmark, which is entirely formed during a temperate climate, to 38 gC $m^{-2}y^{-1}$. Compared with LORCA, values from regions with cooler climate indicates a reduction in infill rate with 50–95% during permafrost conditions with successively higher reduction in a gradient from the Boreal zone to the High Arctic zone. During the next 50,000 years (during the period when there will be lakes in Forsmark), the climate conditions in Forsmark will probably contain periods that will be similar to the climates in Boreal, Subarctic, High Subarctic, Low arctic, and High Arctic zones /Kjellström et al. 2009/. Thus, a RLDM version for permafrost conditions was constructed with a reduction of infill rate by 75% for all periods with permafrost.

The periglacial periods are defined by a permafrost depth greater than zero using data from the permafrost simulations /Hartikainen et al. 2010/. Permafrost depths vary greatly in periglacial environments, even on a local scale. It is common to have open taliks (areas with no permafrost) beneath lakes. The occurrence of taliks will be important for modelling nuclide dynamics, especially for periods with few or no taliks in the study area. /Hartikainen et al. 2010/ describes the conditions of talik formation based on lake mean depth, lake area, and permafrost depth in the lake vicinity. The updated lake module gives the lake mean depths and areas for each time step, and the permafrost model /Hartikainen et al. 2010/ gives the mean permafrost depth for the Forsmark area, so by combining results from these two models it is possible to predict talik formations.

Permafrost conditions will appear in the Forsmark area at around 9400 AD. At that time, 30 of the 42 modelled lakes are already completely infilled and sedimentation processes will not be affected by the changed conditions. By 9400 AD, 10 of the remaining 12 lakes are infilled to more than 75% and will only to a minor degree be affected by climate change. The only two lakes that will be affected considerably by the cooler climate are both large and deep and are situated along the Gräsörännan.

The permafrost version of the RLDM was applied to these two lakes. The results show that adjusting the infill rate during permafrost periods will produce lakes with longer infill times and longer periods with taliks. In addition, this adjustment indicates that the model is very sensitive to the chosen reduction of the lake infill rate. Instead of choosing a mean reduction of 75% for all permafrost periods, it should be more accurate to use a variable reduction based on, for example, the mean permafrost depth. However, this requires more accurate climate data (air temperature, permafrost depth, etc.) from the reference sites accounted for in the articles or more precise climatic definitions of the arctic zones (Subarctic, High Subarctic, Low arctic, and High Arctic zones). If the result from the RLDM permafrost variant also is sensitive in the radionuclide modelling, future effort should focus on updating the RLDM with variable reduction of the infill rate during permafrost conditions.

The sensitivity analysis and the permafrost models showed that the infill rate is the most sensitive parameter in the RLDM. In the model, the infill rate occurs in two places: in model of vegetation colonization in shallow bays that later will become lakes and in the lake module. Both rates are reduced during permafrost conditions. The RLDM should be improved by updating the infill processes with a more process-based algorithm that includes both bottom substrate and nutrient status in the lake phase and beach processes in the marine phase.

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Co. (SKB) have been conducting site investigations at two sites, the Laxemar area and Forsmark, to locate a geological repository for spent nuclear fuel. The site investigations were initiated in 2002 and completed in 2007. The results of the investigations provide basic input of the site and its regional setting, including the current state of the geosphere and the biosphere, as well as ongoing natural processes of importance for long-term safety of a proposed repository. The site investigations provide parameters and models for further analyses within Safety Assessment, Repository Design and Environmental Impact Assessment.

In line with other SKB publications /e.g. Hedenström and Sohlenius 2008/, all unconsolidated deposits overlying the bedrock are collectively denominated regolith. This includes glacial- and postglacial minerogenic (e.g. till and clay) as well as organogenic deposits (e.g. peat and gyttja). Another term central for the following argument is the infill of lakes and marine bays. Infill describes the combined processes of sedimentation and organic deposition making lakes shallower and eventually evolves into dry land. The term infill replaces choke-up and terrestialisation, which might be found in earlier SKB publications.

Regolith in the Forsmark area described using both a map of regolith distribution /Hedenström and Sohlenius 2008/ and a regolith depth model (RDM) that shows stratigraphy and thickness of regolith units /Hedenström et al. 2008/. The regolith depth and surface distribution are important parameters for hydrogeological and geochemical modelling and for the overall understanding of the area. However, the safety assessment analysis should consider circumstances during a whole glacial cycle (about 120,000 years), but the regolith investigations within the site description model do not cover the temporal change of the regolith and therefore do not fulfil the safety assessment requirements. This study constructs a model that can predict the regolith depth and surface distribution of different strata at any time during a glacial cycle and apply the model to the Forsmark site. This study is a part of the SR-Site Biosphere project (Figure 1-1).

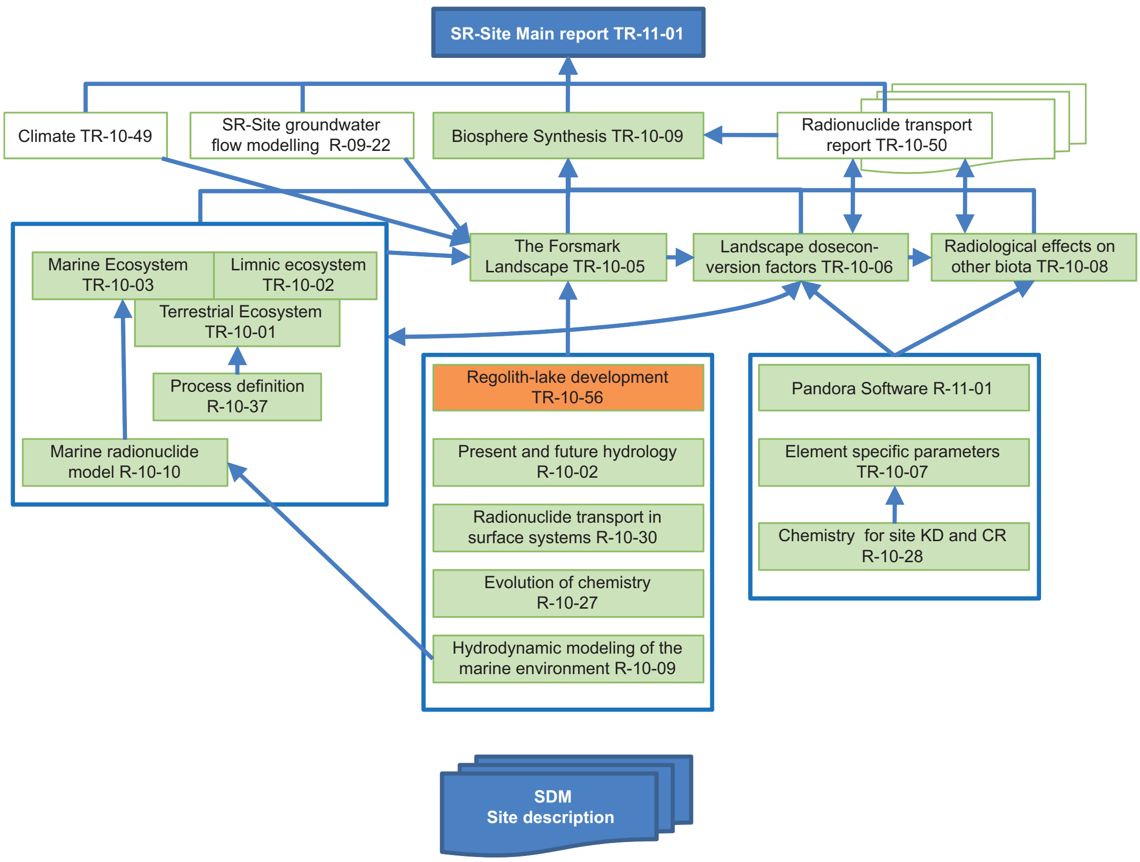

Figure 1-1. *The report structure of the SR-site Biosphere project. This report is marked with an orange background color.*

This report uses several maps to describe the Forsmark area, most of them with the same extension. To make these maps easy to grasp, most of the place names and roads are excluded. Instead, the reader is referred to Figure 1-2 where the main place names and roads are displayed. In most of the maps, the current shoreline is shown as a thin line that can be used for orientation.

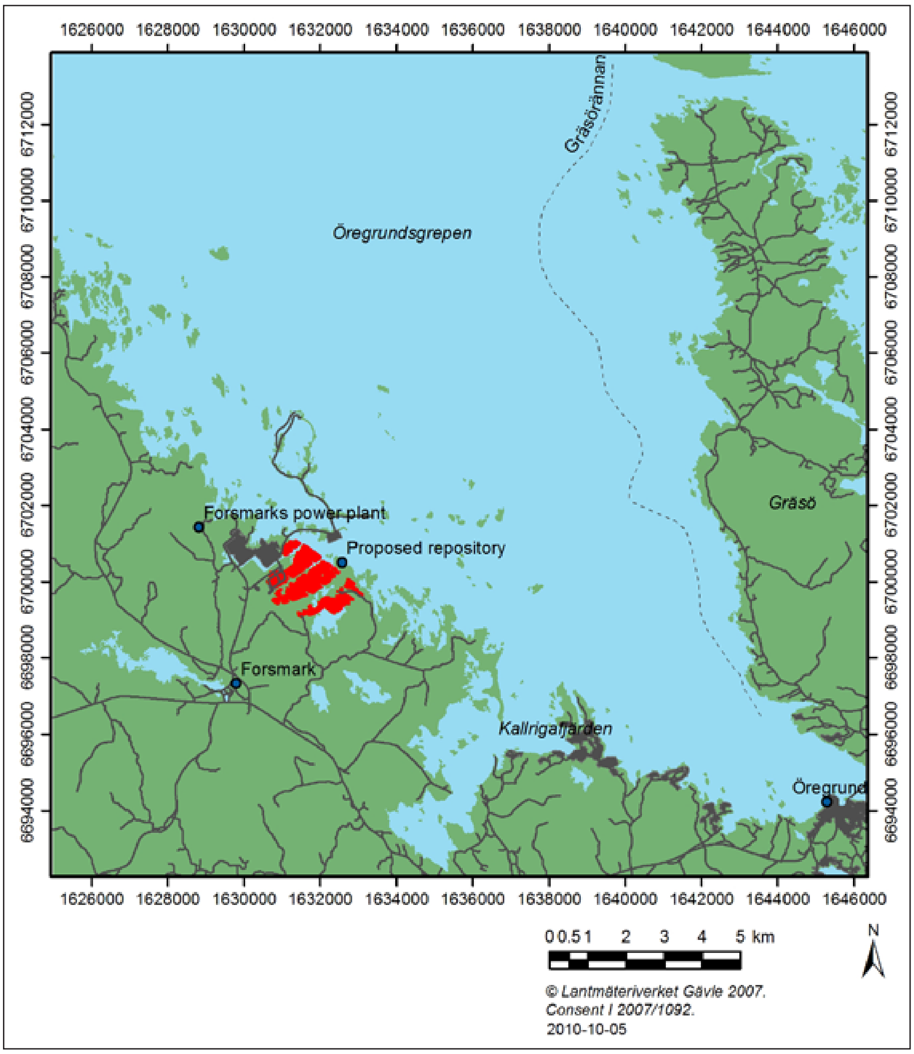

Figure 1-2. *Key map over the Forsmark area.*

2 Materials and methods

A coupled regolith-lake development model (RLDM) has been constructed and is applied to the Forsmark area. The model consists of two modules: a *marine module* that simulates sediment dynamics (erosion, transport and accumulation) in the sea (including the periods with fresh water in the Baltic) and a *lake module* that simulates lake ontogeny. In addition, two sub-models have been constructed: a sub-model that predicts generations of small wetlands that do not emanate from infilled lakes and a sub-model that calculates export of fine-grained particles out of the model area.

2.1 The marine module

The marine module is written in VisualBasic. The whole model area and all time steps are run in a single operation. Pre-processing and post-processing are done in GIS-programs. Figure 2-1 shows the outline of the RLDM marine module.

The module requires input from the Regolith depth model /Hedenström et al. 2008/, the Shore displacement model /Söderbäck 2008/ and the Sediment dynamic model /Brydsten 2009/. A marine geology map, marine regolith depths and a Digital Bathymetry Model (DEM for the sea) are outputs from the marine module for each 500-year time step. The outputs are produced in raster formats and cover the marine part of the model area. These outputs are later merged with outputs from the lake module and outputs from the sub-models to form continuous raster maps for the whole model area. The continuous raster results are finally discreticized into parameters for the Pandora model.

The calculation scheme for the marine module is illustrated in Figure 2-2.

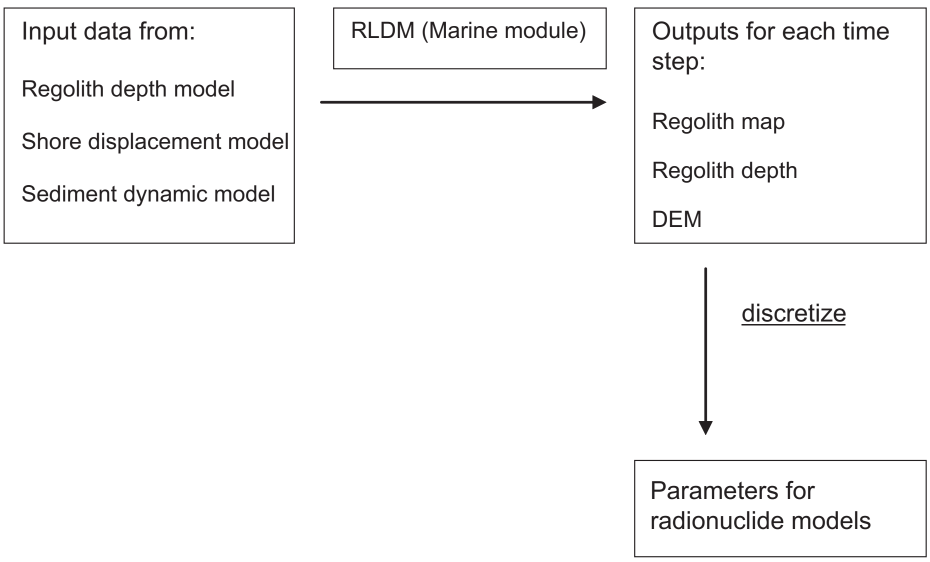

Figure 2-1. *Outline of the RLDM marine module. Inputs are from the Regolith Depth Model (RDM), the Shore Displacement Model and the Sediment Dynamic Model. Outputs are a surface geology, a Regolith Depth Model and a DEM for each time step (500 years time step during the period 9500 BC–7000 AD). The raster results are discreticized into parameters (e.g. mean values for basin areas).*

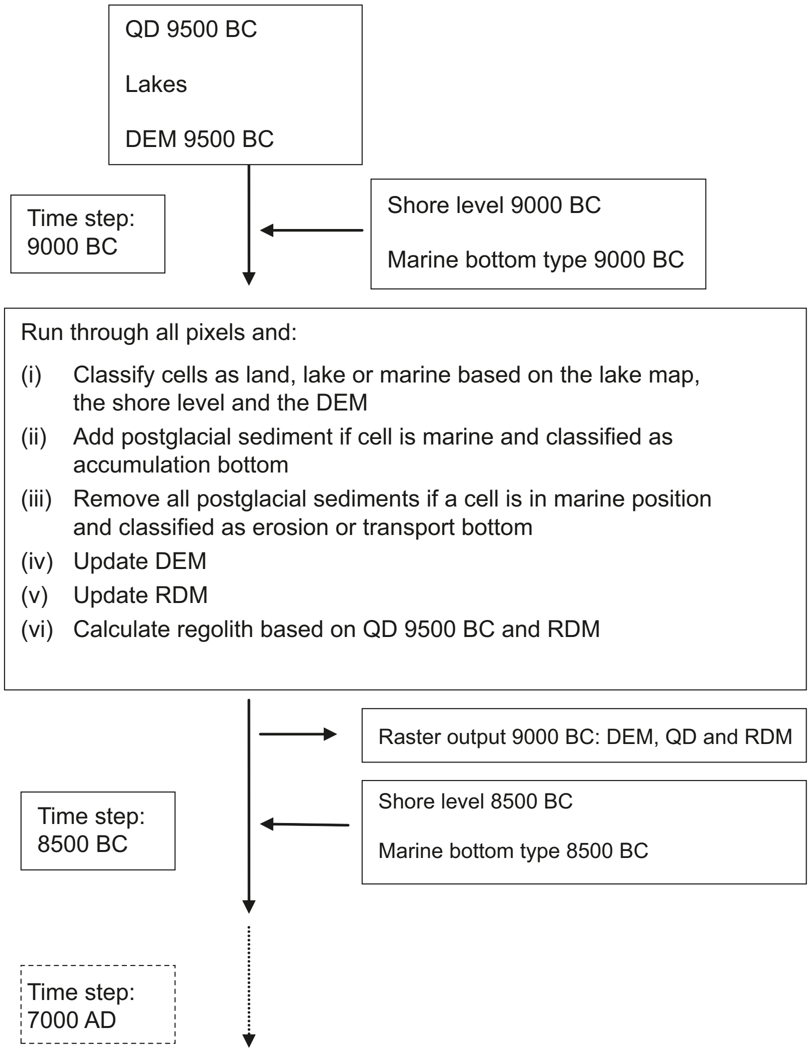

Figure 2-2. *Calculation scheme for the marine module. The module starts at 9500 BC just after the area is deglaciated and stops at 7000 AD.*

2.1.1 Data input to the marine module

2.1.1.1 Quaternary deposits at the time for deglaciation 9500 BC

After the Weichselian ice sheet receded from the Forsmark area (approximately 9500 BC), the whole area was covered by the sea. The ground surface consisted either of exposed bedrock, till or glacial clay. Today some of these glacial deposits are overlaid by postglacial clay and silt, wave washed sediments, and different types of organic deposits. Some of the glacial deposits are eroded, some of the till are wave washed and some of the glacial clays are resuspended and redeposited at new sites as postglacial clays.

To construct a map of the surface geology for the Forsmark area at 9500 BC, the regolith depth model (RDM) /Hedenström et al. 2008/ was used. The RDM is a model in raster format (20 m cell size) with seven layers where each layer is presented as the digital elevation model (DEM) for the upper surface of that layer (Figure 2-3). The uppermost layer – Z1 – represents the layer that may have been influenced by the impact from surface processes, e.g. bioturbation, frost action and chemical weathering. The next layer – Z2 – represents peat, followed by the next layer – Z3 – representing sand/gravel, glaciofluvial sediment or artificial fill and Z4a, corresponding to postglacial clay and clay gyttja/gyttja clay. Z4b consists of glacial clay and Z5 represents till. The bottom layer – Z6 – represents the uppermost bedrock, which has a high frequency of fissures and fractures. The lower level of Z5 constitutes the bedrock surface. All layers except Z6 may have a thickness of zero.

By subtracting a layer with its next lower layer, it is possible to detect areas with zero thickness. By multiple subtractions, it is possible to detect (i) exposed bedrock areas, (ii) areas with till on top of bedrock but no overlaying postglacial clay, (iii) areas with bedrock overlaid by till that is overlaid by glacial clay, and (iv) areas with glaciofluvial deposits. By assuming that erosion of glacial clay is uncommon and that till can be wave washed but not totally removed, the 9500 BC QD map is similar to the 2000 AD RDM with all postglacial layers removed except for the artificial fillings.

Unfortunately, the extension of the RDM does not cover the whole landscape model area /Lindborg 2010/. Two areas have been treated by different methods than described above. For the part of the landscape model area that today is the land area of Gräsö (dark brown area in Figure 2-4), the map of Quaternary deposits has been used /Persson 1986/. In this area, it is assumed that there is till beneath all postglacial deposits. For the marine area outside the RDM (yellow area in Figure 2-4), unpublished data from the Swedish Geological Survey is used.

2.1.1.2 A digital elevation model (DEM) for 9500 BC

The DEM for 9500 BC is constructed as the DEM for 2000 AD when all postglacial deposits except artificial fillings has been removed and then adjusted for the shoreline displacement at 9500 BC.

The DEM for 2000 AD with all postglacial deposits removed is similar to the Z4a-layer in the regolith depth model (RDM). In addition, for the DEM it is necessary to fill in the two areas missing in the RDM using a special method. For both areas (yellow and brown in Figure 2-4), the original DEM values are used /Strömgren and Brydsten 2008/: these areas are treated, for example, as areas with no postglacial deposits, so some values are overestimated. Finally, the values are adjusted for the sea level at 9500 BC (Appendix 1).

2.1.1.3 The extensions of accumulation, transport and erosion bottoms for each time step

The extensions of accumulation, transport and erosion bottoms for each time step are taken from the sediment dynamic model /Brydsten 2009/. These data are in raster format with a resolution of 100 meters. All other raster data inputs are with a resolution of 20 meters so the bottom type data are resampled to 20 meters resolution.

2.1.1.4 A list with relative shore levels (RSL) at each time step

The shore level at each time step is calculated using the equation published in /Söderbäck 2008/. Even though there are more recent shore level curves available, many other models within the main SKB project were developed before the new shore displacement curve was published. Since the results from the RLDM will be compared with results from these other models, the old shore displacement curve was used instead. The shore displacement values used in the RLDM are listed in Appendix 1.

The landscape model area is totally dry when the lowest level on future land (not on a future lake bottom) is above sea level (–35.9 m in the RH70 height system). This corresponds to about 11,800 AD using the curve from /Söderbäck 2008/.

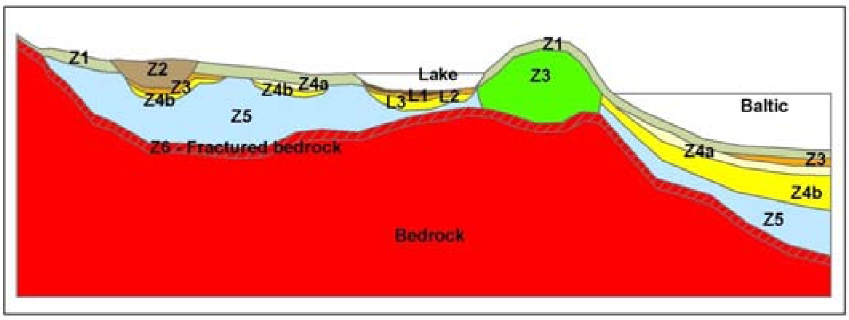

Figure 2-3. Conceptual model for the distribution of the generalized layers in the RDM (From /Hedenström et al. 2008/).

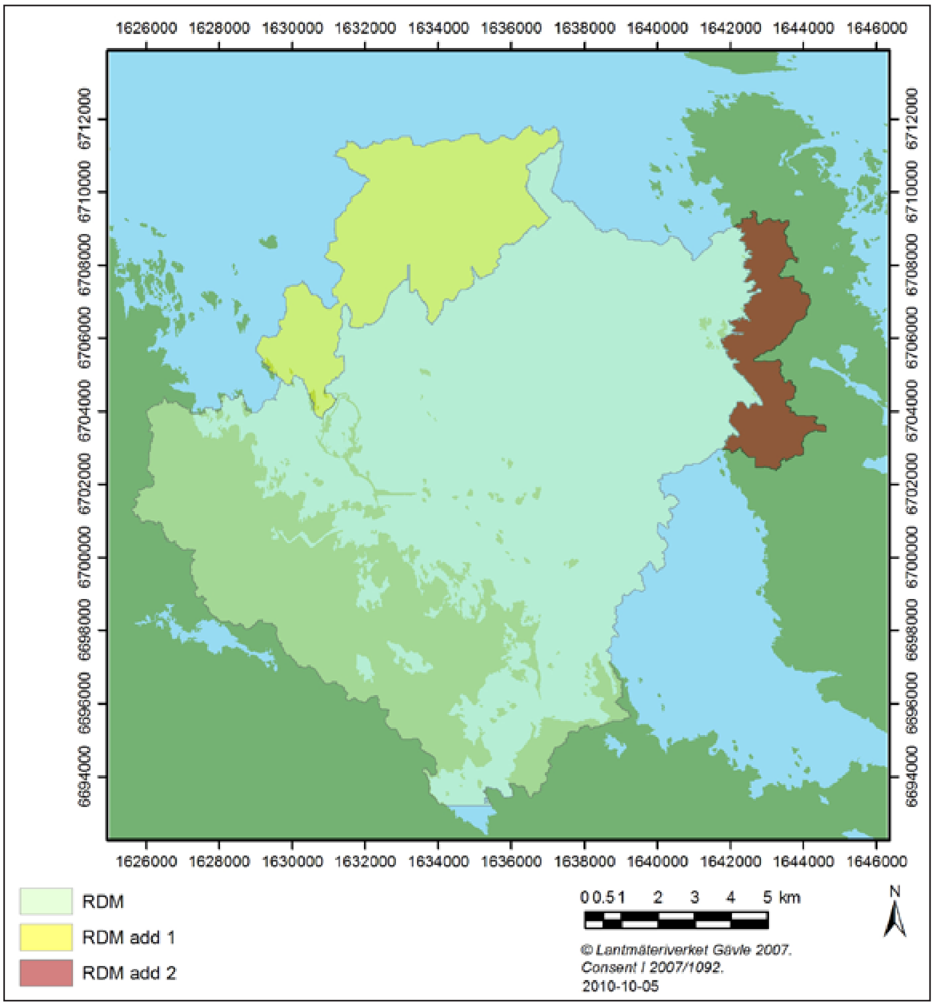

Figure 2-4. *Extensions of the landscape model area (all three models) and the Regolith depth model (RDM) area. The RLDM have been supplemented by two areas (RDM add 1 and 2) to make the extension of the RLDM similar to the Landscape model (see text).*

2.1.1.5 A list with sedimentation rates at each time step

The amount of resuspended particles varies greatly over time and therefore also the sedimentation rate. In a coastal area, the main sources of resuspended particles are fluvial transport to the sea, wave washed shores, and sea bottom material. The fluvial transported particles often settle close to the river mouth and require wave-generated resuspension processes for further sea-ward transport. During this transport, the material is sorted so the sand particles stay close to the river mouth and finer particles (silt and clay) settle in further distal position to the river mouth. The only major fluvial input today to the model area comes from the creeks Forsmarksån and Olandsån, of which both discharge into the narrow Kallriga bay (Figure 1-1). Based on typical turbidity in small Swedish brooks (1–8 g m^{-3}) and based on runoff (80–200×10^3 m^3 a^{-1}), the yearly input of particles is 80–1,600 kg a^{-1}. Assuming water content of 40%, the 1,600 kg value corresponds to about 1 m^3 of solid sediment or 8,000 m^3 during the period the brooks have existed (6000 BC–2000 AD). This should be compared to the store of fine-grained particles in the model area that is 10×10^6 m^3, so the fluvial input of particles is negligible compared to resuspension due to wave washing.

Particles resuspended due to wave washing resettle on deeper bottoms with low wave power (below the wave base). As a result of the shore displacement, these sediments will eventually be positioned above the wave base and can be resuspended again. Therefore, the wave processes act both on postglacial fine-grained sediments and on unwashed till. One measure of sedimentation rates could be the sum areas of postglacial sediment and unwashed till that are positioned above the wave base for each time step. This measure is used in the marine module calibration (further described in Section 2.1.2).

2.1.1.6 A map with current and future lakes

All existing lakes within the model area are mapped with GPS in the field /Brunberg et al. 2004/. For these lakes, the original extension has been used, i.e. the free water surface when the lakes were isolated.

The properties of future lakes are modelled with ArcGis Hydrological model extension using the 1,970 AD DEM. The DEM is filled (local depressions are lifted to levels of the thresholds of the depressions) and with the difference between the original DEM and the filled DEM the properties of the lakes can be calculated (extension, area, mean depth, maximum depth, and more). The two datasets are merged and this final map consists of 41 lakes (Figure 2-12 on page 22).

2.1.2 Calibration of the marine module

As mentioned earlier, the amount of suspended particles in the seawater varies greatly over time and therefore also the sedimentation rate. For example, immediately after the Forsmark area was deglaciated (c. 9500 BC), the whole area was submerged under deep enough water to eliminate wave washing. At this time, only accumulation bottoms existed and no resuspension occurred (Figure 2-5). Resuspension within the area starts about 8000 BC, when the first transport bottoms appear.

The area of erosion bottoms increase to its maximum at 500 AD and then decreases continuously until today. Figure 2-6 shows a calculation of non wave-washed bottoms areas that will become erosion bottoms for each time step, here termed "New erosion bottoms".

The area of "new" erosion bottoms is probably an indicator for sedimentation rate. This should mean that bottoms with accumulation environment during periods with large areas of "new" erosion bottoms will have almost the same thickness of postglacial sediment compared to areas that has been accumulation bottoms during the entire Holocene. But even during periods with no "new" erosion bottoms (9500 BC–2500 BC), there must have been some degree of sedimentation, so to the temporal variation of sediment rate a background constant value must be added.

The sediment rates are calculated using data from the marine geological survey /Elhammer and Sandkvist 2005/. The survey is performed with sonar equipment and provided sediment strata for about 1.6 millions points.

The minimum extension of accumulation bottoms occurs at about 2500 BC (Figure 2-5) and is found along the Gräsörännan (Figure 2-7). At these bottoms, the sediment dynamic model predicts only an accumulation environment during the Holocene (11,500 years).

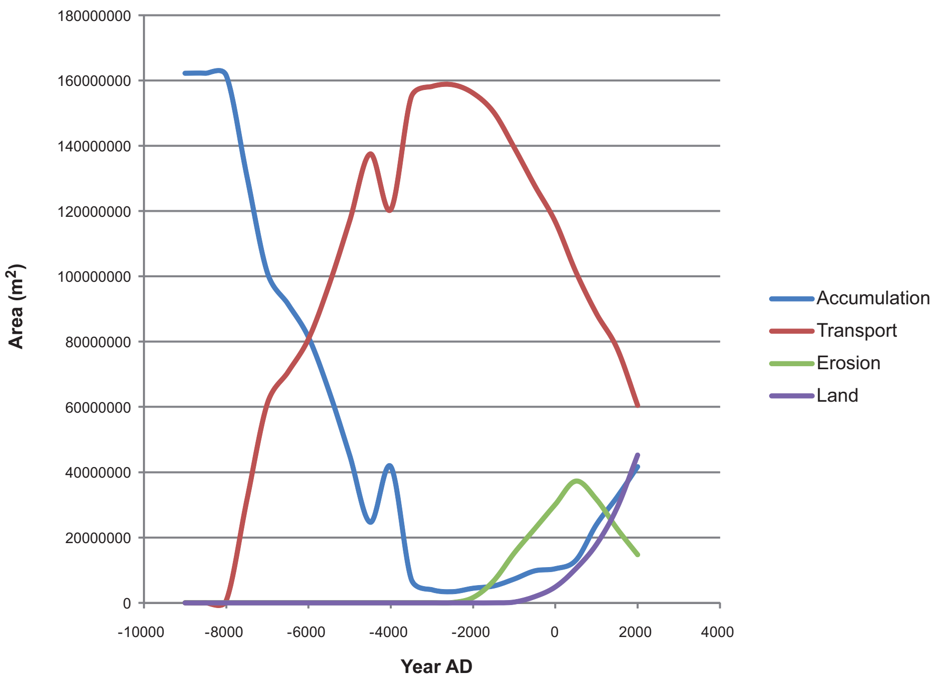

Figure 2-5. *Area of different bottom types within the landscape model area during Holocene /Brydsten 2009/.*

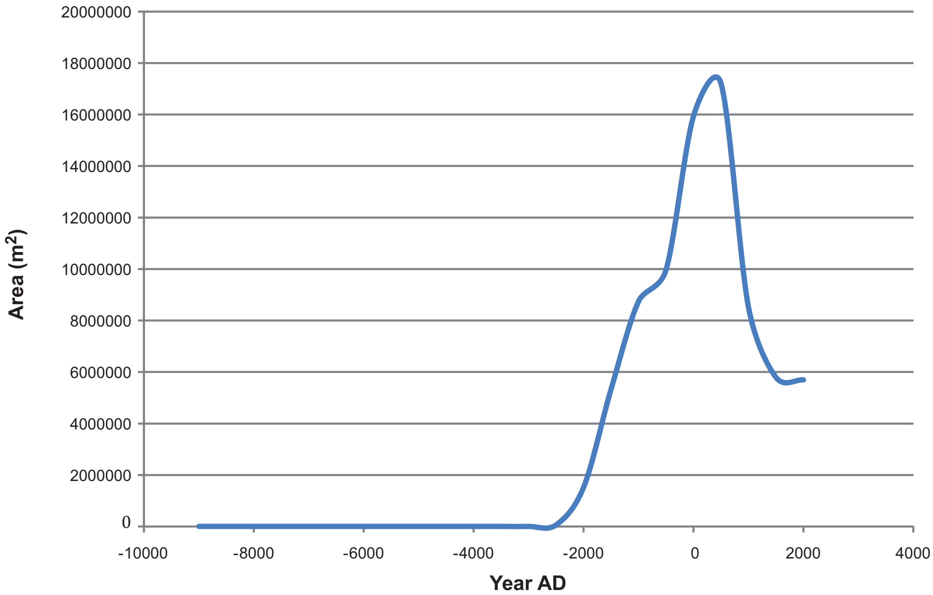

***Figure 2-6.** Area of bottoms beneath the wave base that will be erosion bottom in next time step.*

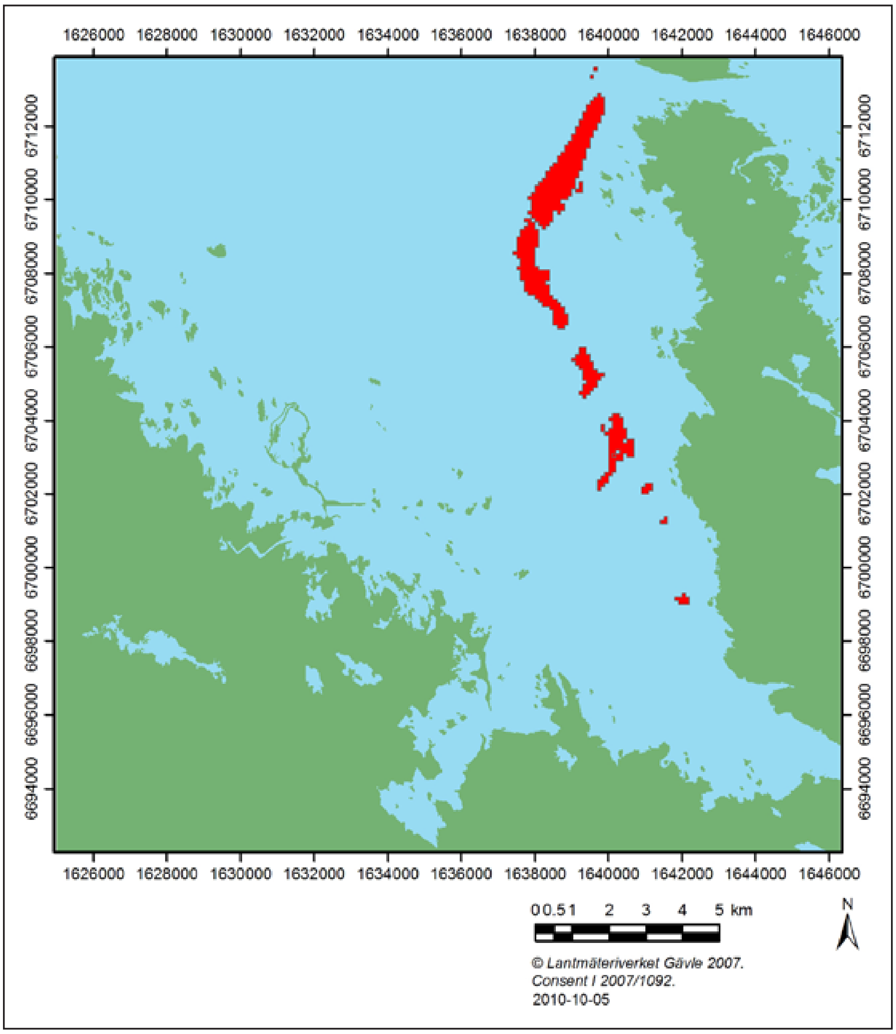

***Figure 2-7.** Extensions of bottoms with continuously accumulation throughout the Holocene (red).*

For all other bottoms, the period of continuous accumulation environments are less than 4,500 years (2500 BC–2000 AD) (Figure 2-8). To calibrate the RLD-model, four raster cells are chosen. These cells are chosen so the variation in continuous accumulation time is large and so that the water depths in the sediment dynamic model (with a raster resolution of 100 m) agree with the water depths in the DEM (with a raster resolution of 20 m).

The measured sediment thickness is the sum of postglacial clay and postglacial silt from the SGU data set /Elhammer and Sandkvist 2005/. The calibration is made using the following equation:

$$\textit{Sedimentation rate} = \sum \frac{J}{1} (\textit{Const}_1 + \textit{Eros.area}_J) \cdot \textit{Const}_2 \qquad \text{(Equation 2-1)}$$

Where sedimentation rate is in m 500 a^{-1}, J is the time step, and $Eros.area_J$ is given by Figure 2-5. With $Const_1$ = 8,000 and $Const_2 = 7.7\times10^{-6}$ the mean estimation error for the four calibration cells are 0.097 m (Table 2-1). This gives a temporal variation of the sedimentation rate (mm a^{-1}) for the Forsmark area during the Holocene shown in Figure 2-10. The mean sedimentation rate for the Holocene is calculated to 0.26 mm a^{-1}.

The RLDM marine module simulates the accumulation or erosion of postglacial clay or silt particles (PGC) and generates a raster map with thickness of the PGC. The QD map and the DEM are updated based on the thickness of the PGC. This is ongoing for each time step until a cell is a lake, then those lake cells are frozen. These are not handled in the marine module.

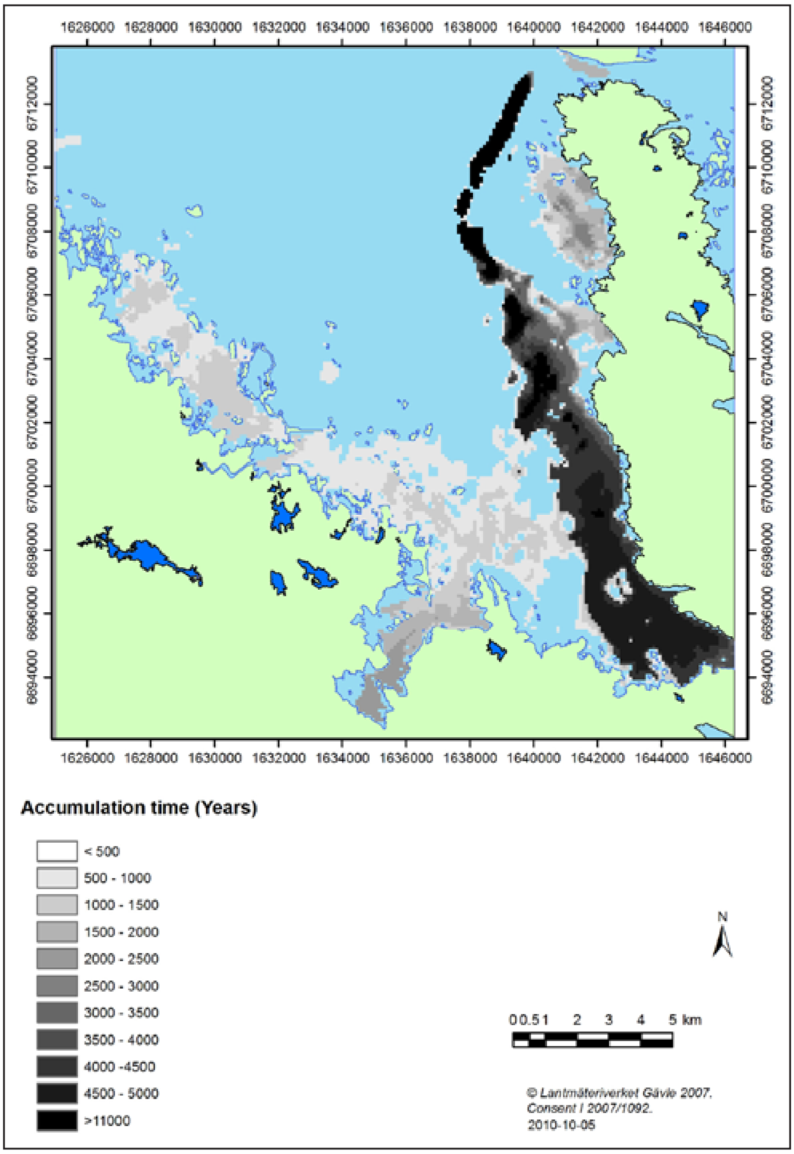

Figure 2-8. *The length of the period (years) with continuously accumulation until 2000 AD.*

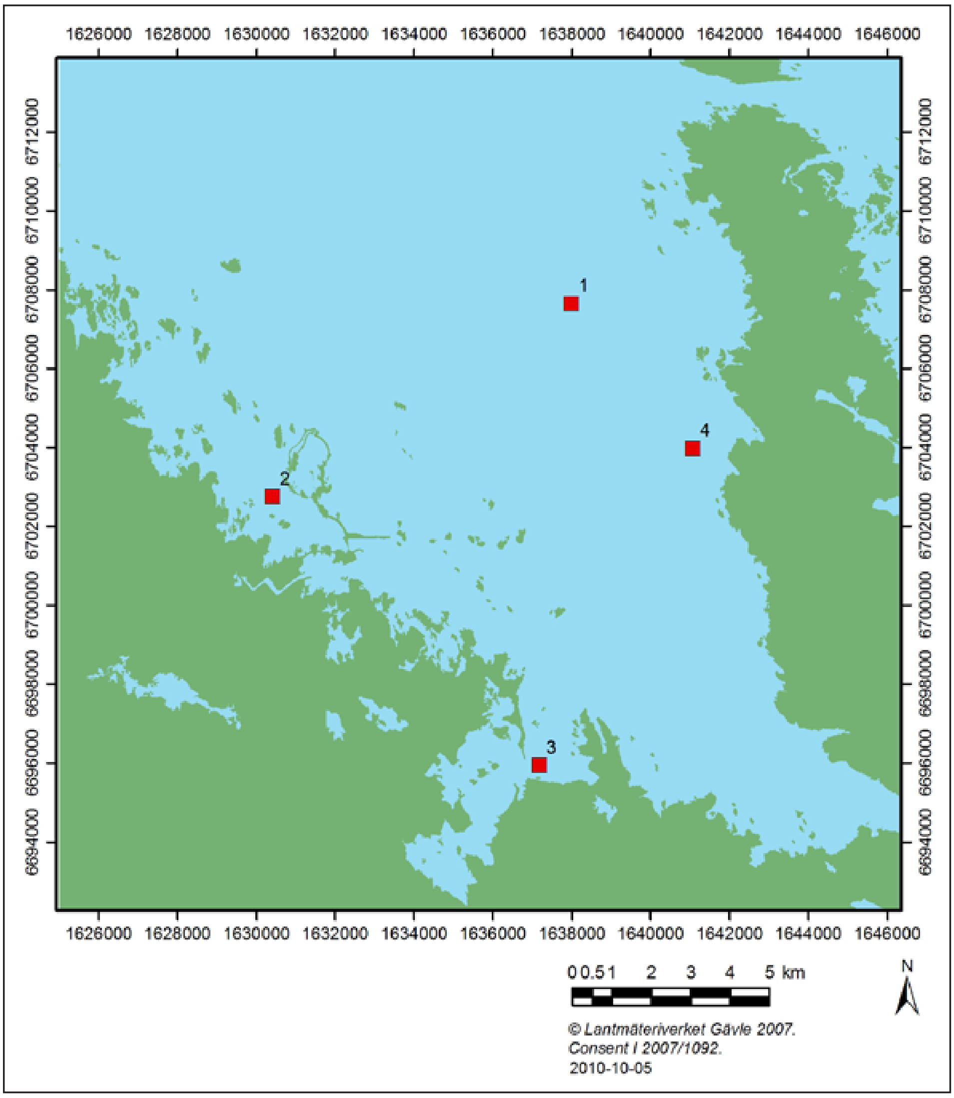

Figure 2-9. *Raster cells used for calibration of the RLD-model. Attributes for the cells are shown in Table 2-1.*

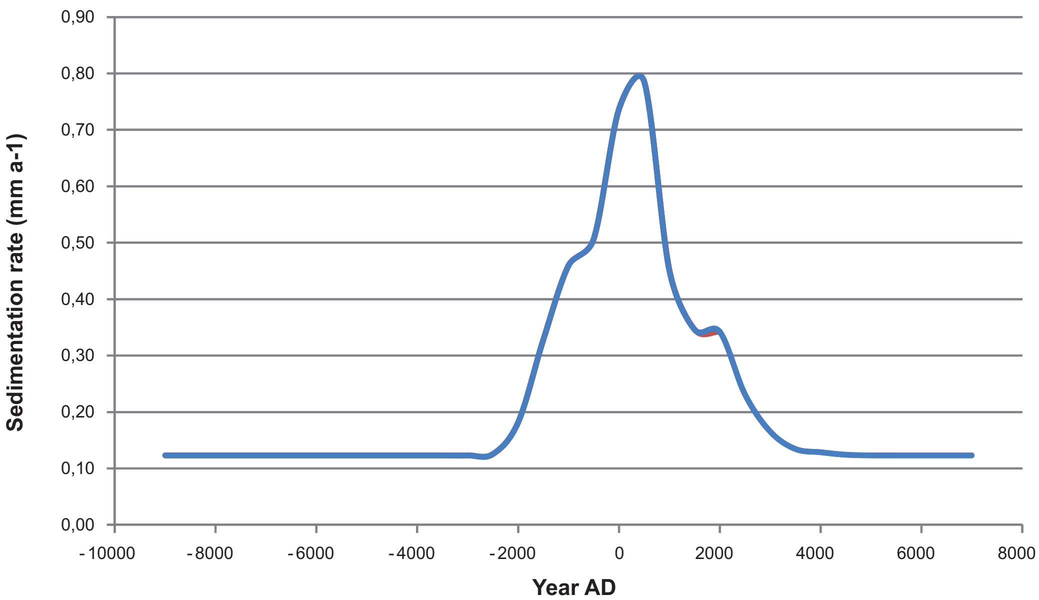

Figure 2-10. *Temporal variation in sedimentation rate for the Forsmark area during Holocene.*

Table 2-1. Attributes for the raster cells used in the calibration of the RLD-model. Locations of individual raster cells are given in Figure 2-9.

Cell No.	1	2	3	4
Water Depth (m)	53.0	9.3	12.2	19.1
Accumulation time (y)	11,500	2,500	1,500	1,000
Measured sediment thickness (m)	2.69	0.41	0.57	1.30
Modelled sediment thickness (m)	2.93	0.35	0.57	1.33

2.2 The lake module

The lake basin infilling processes were categorized into two parallel processes: sedimentation of minerogenic material (clay and/or silt) and infilling by growth of vegetation. The lake module is based on, and improved from a previous module /Brydsten 2004/.

In the previous module, infilling of vegetation started when the lake was isolated from the sea. This was not a correct description since many shallow sea bays in the Forsmark area have reeds growing in them. In this new version of the module, infilling with vegetation starts already in the marine stage on bottoms that are shallower than 2 meters and in the future will be lake bottoms /Komulainen et al. 2008/. A brief summary will be presented here. For detailed information about calibration and validation of the module see /Brydsten 2004/.

A statistical analysis of sediment cores from six lakes in the Forsmark area shows that the sedimentation rate depends on water volume. This can be expressed as follows:

Sedimentation rate = 49.967 + 102.786 · Water volume (Equation 2-2)

(sig. < 0.001, $r^2 = 0.971$)

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

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

The infilling of the lake with vegetation starts by colonization of littoral plants, followed by propagation of bryophytes when the resulting wetland becomes a bog. The colonization of littoral plants requires shallow water (< 2 meters), 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 uncommon in small lakes, because the short fetch does not produces sufficient wave power. There are no visible signs of erosion of the littoral vegetation in any of the orthophotos covering the lakes in Forsmark; therefore, the non wave-breaking zone criteria are not considered in the lake module. The low slope criterion is also not considered in the lake module because steep shores are uncommon in the Forsmark area. Data from mapping of vegetation extends in 25 lakes in the Forsmark area /Brunberg et al. 2004/, showing that the "rate of infill" in lakes depends on lake area. This can be expressed as follows:

"rate of infill" = 36.372 + 1.169E–4 · "Basin area" (Equation 2-3)

(sig < 0.000, $r^2 = 0.805$)

in which rate of infill is expressed as m^2 $year^{-1}$ and basin area as m^2. The rate of infill is a maximum value that can be lower since the area of the bottom shallower than two meters is not large enough, a depth that limits colonization.

2.2.1 Data input to the lake module

The only data input source to the lake module is the DEM output from the marine module at the time step just before lake isolation (Figure 2-11). The DEM output from the marine module are produced in raster format using 20 m cell size and this also sets the lake module resolution to 20 meters.

The initial lake DEM is calculated as the DEM minus the lake threshold value /Brydsten and Strömgren 2005/.

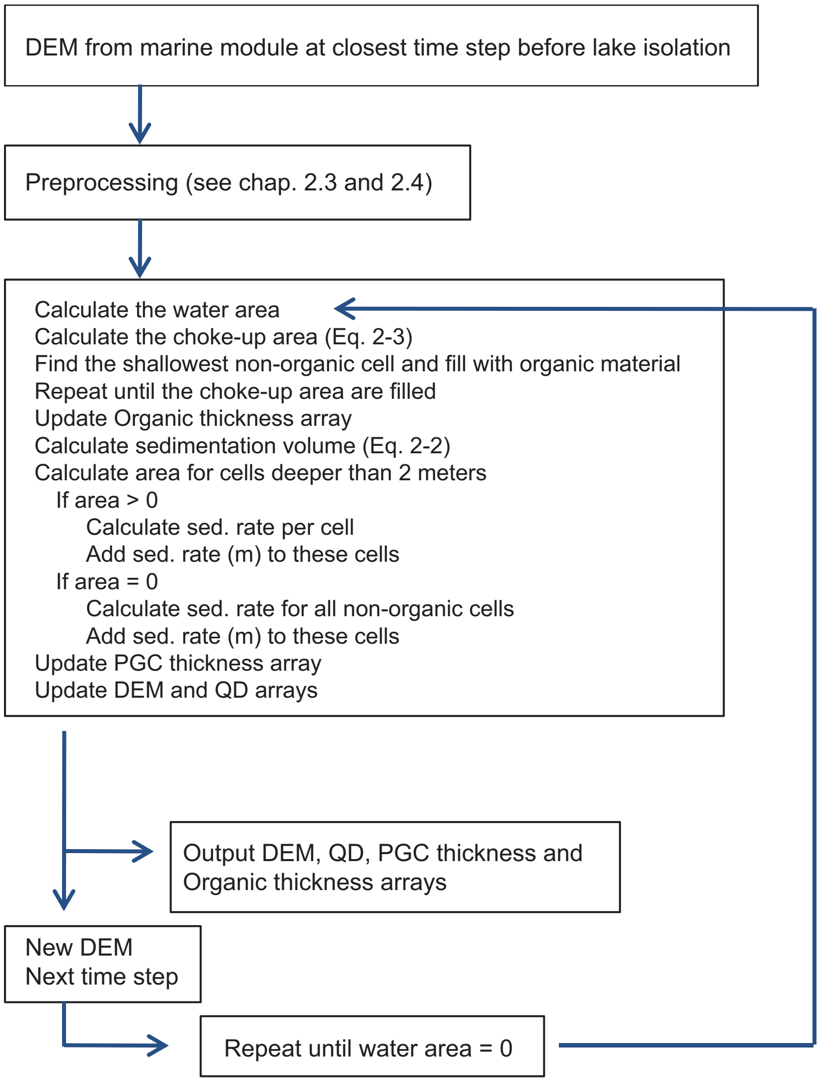

Figure 2-11. *Calculation scheme for the lake module.*

2.3 Linking the marine module to the lake module

For most lakes, there is a period between the time step in the marine module and the lake isolation time. This period can be up to 500 years. During this period, both the marine accumulation and the "infill" processes are ongoing. These pre-lake processes are managed manually for each lake.

For the accumulation of marine sediments, all cells of the future lake that have accumulation environment at the time step before the lake isolation are filled with sediments. The sediment thickness is calculated as the sediment rate for that time step multiplied with the number of years between the time step and the isolation year.

The colonization of reeds into the marine bay is calculated with the same algorithm as for the lakes. The same depths limit, two meters, /Komulainen et al. 2008/ is also used.

2.4 Prolongation of the marine module

The sediment dynamic model (SDM) simulates bottom status (erosion, transport, and accumulation) for the period 9500 BC–7000 AD. It was not possible to extend the period beyond 7000 AD since only a narrow bay was left of the sea in the model area. The coarse resolution of the SDM (100 m raster cells) caused the narrow bay mouth to close and prevented waves from entering the bay /Brydsten 2009/. As the SDM data is input to the RLDM, this model also must end at 7000 AD.

At the last time step in the SDM (7000 AD), the whole marine area becomes an accumulation bottom. Thus it is presumed for the time ahead, to be characterized by accumulation bottom as the bay mouth will successively be shallower. So, the marine module is prolonged from 7000 AD to the time when the whole model area is land (10,500 AD) assuming the sea bottom dynamic statues is always accumulation.

2.5 Modeled lakes

Shoreline of existing lakes are mapped with GPS and the bathymetry measured with echo soundings /Brunberg et al. 2004/. The extensions and bathymetry of future lakes are modelled with GIS fill tool using the 1970 DEM as input /Brydsten 2006a/. The GIS-based method gives a large number of future lakes, most of them very small and shallow. Based on the smallest existing lake (Lake Puttan), a set of requirements was defined to limit the number of future lakes in the model:

(i) the surface of the water should be larger than 60,000 m^2, and

(ii) the maximum water depth should be deeper than 0.8 meter.

By using the 1970 DEM to calculate the properties of the future lake, thresholds will not be lowered by erosion. Erosion of the thresholds will definitely take place if the threshold consists of postglacial deposits (postglacial clay or silt or wave-washed sand) and will probably take place if the thresholds consist of glacial clay and to some degree if the threshold material is till. The only material that completely resists erosion is bedrock. For this reason, it would be better to use one of the layers from the regolith depth model instead of the 1970 AD DEM, e.g. the Z4a layer (the upper surface of the glacial clay) or the Z5 layer (the upper surface of the till). Using the Z4a layer for modelling the properties of future lakes sometimes results in completely different results compared to using the 1970 AD DEM. The most common difference is that the Z4a-lakes are smaller and shallower.

The results from the RLDM will be used with results from other models (e.g. different hydrological models) and these models were developed before the RLDM was generated. Therefore, it is more important to use the same future lake extensions in the RLDM as in the other models rather than using the most reliable data. Data for the current lakes are not altered.

The number of lakes that will be modelled is 41, 31 future lakes and 10 existing lakes (Figure 2-12). The physical characteristics of these lakes are shown in Appendix 2.

Lake Biotestsjön, situated east of Lake 117 (Figure 2-12) and used for monitoring emissions in the nuclear power plant cooling water, is not included in the lake data set. This is because fieldwork permission was not granted for Lake Biotestsjön.

2.6 Merging data from the marine and lake modules

As mentioned earlier, the marine module is processed in one single run and results in three raster data sets for each time step (DEM, QD and PGC-thickness). However, the lakes are processed one by one. The data sets are merged to receive single raster data sets for each time step for the modelled lakes. This is done manually in the ArcGis program. In this process, the thickness of the postglacial clay (PGC) is split into a marine and a lacustrine stratum. A fourth raster data set referring to the thickness of fen peat is also produced. The result from the marine module at 10,500 AD is used for all later time steps.

2.7 Post processing the GIS data sets

Since only the largest lakes are processed in the lake module, the DEMs hold small local depressions that are the non-processed lakes. These small lakes are assumed to be infilled during one time step (500 year) and will therefore be filled with peat. This post processing is performed for each time step using the GIS function “fill” on the DEM from the merged data set. The fill function gives the thickness of peat at all cells in the model area, but only cells that have become land since last time step are used. To select these cells, a land/sea raster layer was used. The land/sea layers are produced using the DEMs and this can be done with different methods with different outcomes so the method we used needs to be described.

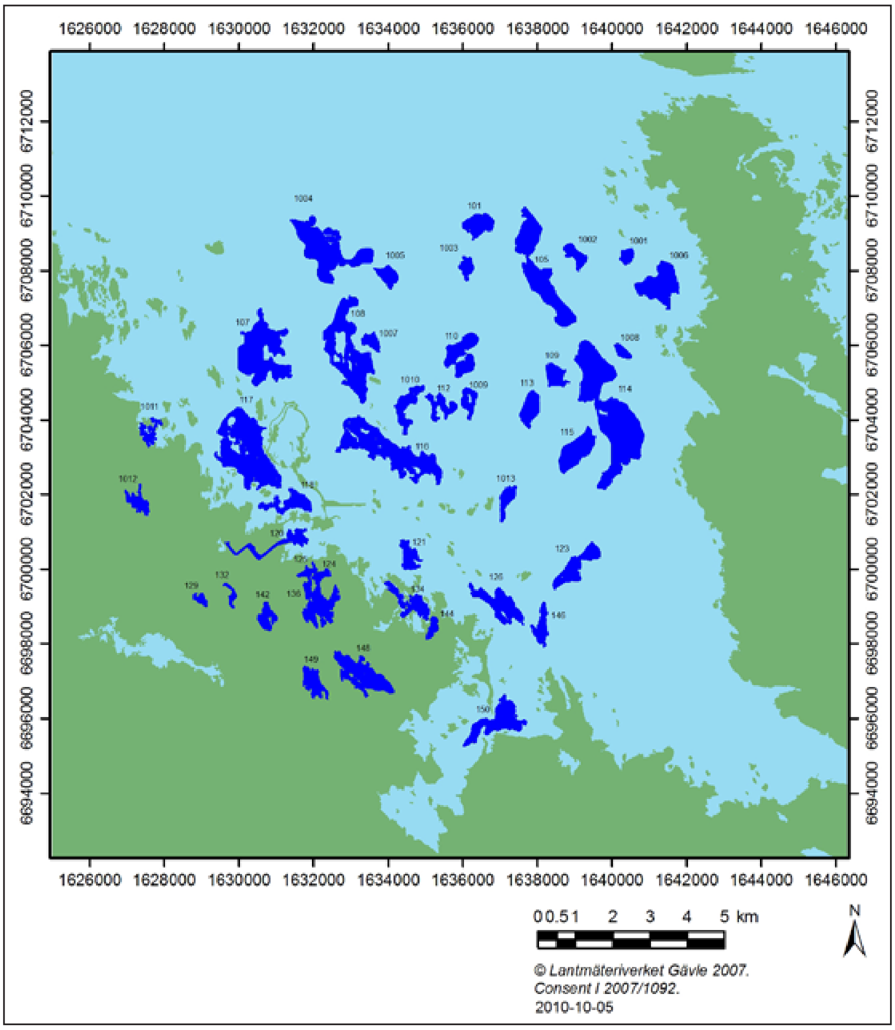

***Figure 2-12.** Existing and future lakes as output from the RLDM.*

The DEM is reclassified into two classes – positive and negative values. This new layer is converted into shape-format keeping the raster structure intact. A single large sea polygon is selected and all other polygons are set to land. With this method, the lake bottoms lower than the sea level are classified as land, but also small polygons adjacent to the large sea polygon where the contact between the two are cell-corner against cell-corner. Some of these small polygons are probably sea bays and some are small lakes, but it is impossible with the information from the DEM to make a correct classification. Using this method, the sea is set to its minimum extension; since the same method is used in the SDM, there is less risk of getting confusing results in near-shore cells.

The layer with thickness of "additional peat" is used to update the DEM, QD, and peat thickness layers.

A final post processing deals with wetlands not emanated from infilled lakes. These hanging wetlands are modelled with Topographical Wetness Index (TWI) calculated in GIS from the DEM:

$$TWI = ln\left(\frac{a}{\tan\beta}\right) \qquad \text{(Equation 2-4)}$$

where a is the local upslope area (m^2) and $\tan\beta$ is the local slope (degrees) /Beven and Kirkby 1979/.

High TWI values mean wet conditions and are associated with a large upslope area (a) and a low gradient (β). The continuous TWI raster layer is reclassified as dry/wet with a limiting TWI value of 13.2 /Brydsten 2006b/. Wet areas that have become land during last time step and are not lakes are classified as hanging wetlands.

Peats in hanging wetlands are generally thin. The thickness is therefore approximated to zero. As a consequence, the DEM is not updated for peat thickness. Only GIS QD layers are processed.

3 Sediment development model results

Results from the sediment development model are delivered to SKB in a set of GIS-projects (in ArcGis mxd-format). Individual projects for each time step consist of the following layers:

(i) Digital elevation model

(ii) Land/Sea

(iii) Thickness of marine postglacial fine-graded sediments

(iv) Thickness of lacustrine postglacial fine-graded sediments

(v) Thickness of organic sediments (peat)

(vi) Thickness of regolith (sum of all non consolidated layers)

(vii) Surface geology in nine classes

(viii) Streams

The time steps in the GIS projects are in 500 year intervals for the period 9500 BC–12,000 AD, and 5,000 year interval for the period between 15,000 AD and 35,000 AD when all lakes are totally infilled. As mentioned earlier, time steps of the lake module is in 100 year intervals, thus some results regarding the lakes from the RLDM are not presented in the GIS projects. Hence all results from the lake module are merged into a single Excel document with 43 sheets. The first sheet contains a map with lake identification numbers. All parameters are defined in the second sheet and each lake is presented with the time step in rows and parameters in columns in the remaining data sheets.

3.1 Overview of the RLDM results

The Weichelian ice sheet receded from the model area around 9500 BC and the last sea bay will be isolated and form a lake around 11,500 AD. This makes the marine stage calculated by the RLDM about 20,500 years. The first land appears along the south-western border of the model area around 1500 BC and the last lake is totally infilled around 35,000 AD, thus the terrestrial stage will be about 36,500 years. The first lake in the model area is isolated about 600 AD, so the limnic stage in the RLDM is about 34,400 years (Figure 3-1).

Figure 3-1 also shows the fast transformation of sea to land, a process that takes about 12,000 years. This also implies that the glacial isostatic adjustment (GIA) is the most important process in landscape development. The model area with limnic ecosystems shows a large temporal variation because many lakes are rapidly transformed to terrestrial ecosystems. The maximum areal content of limnic ecosystems will be about 5500 AD (1.9%).

To illustrate the importance of the relative sea level (RSL) change to sea/land distribution, two maps are shown in Figure 3-2, one at 500 AD with about 90% sea and one at 6500 AD with about 90% land.

The RLDM predicts the change in postglacial clay and peat thickness. The change in the DEM and the QD map are then calculated using the thickness of postglacial clay and peat as input.

The increase in postglacial clay volume between 9500 BC–7000 BC is caused by large areas of accumulation bottoms during that period (Figure 3-3). The decrease in volume during the period 7000 BC–3000 BC is caused by successively more sea bottoms being situated above the wave base and thus a shift from accumulation bottoms to transport bottoms. The figure also shows that at least 40 million m^3 postglacial clay is exported out of the model area during this period.

From 2000 BC, the volume increases constantly except during a short period around 7000 AD. This is caused partly by more lakes accumulating postglacial clay and partly by increasing areas of near-shore accumulation bottoms in the sea (light blue line in Figure 3-4).

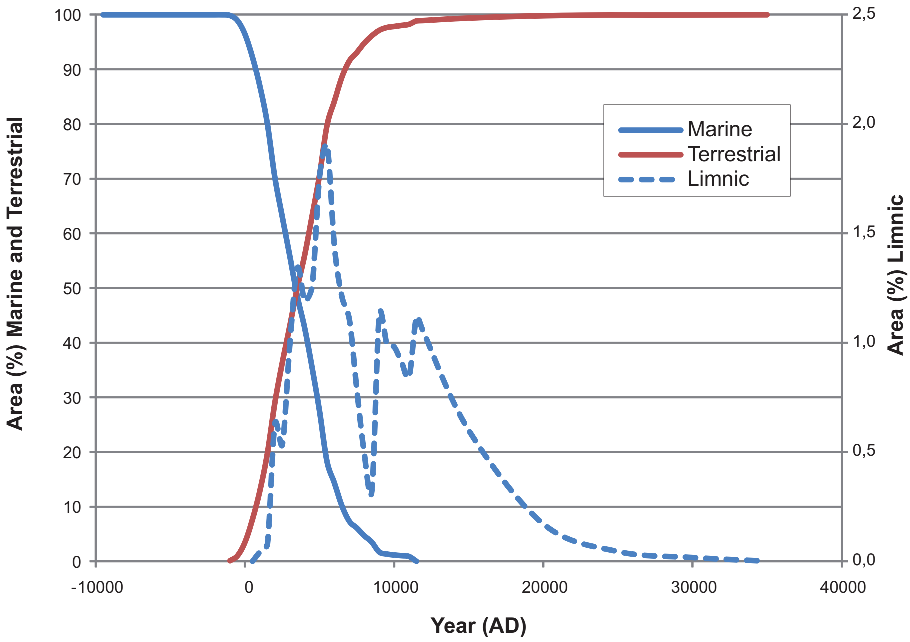

Figure 3-1. The temporal area development of the three main ecosystems: marine, terrestrial and limnic.

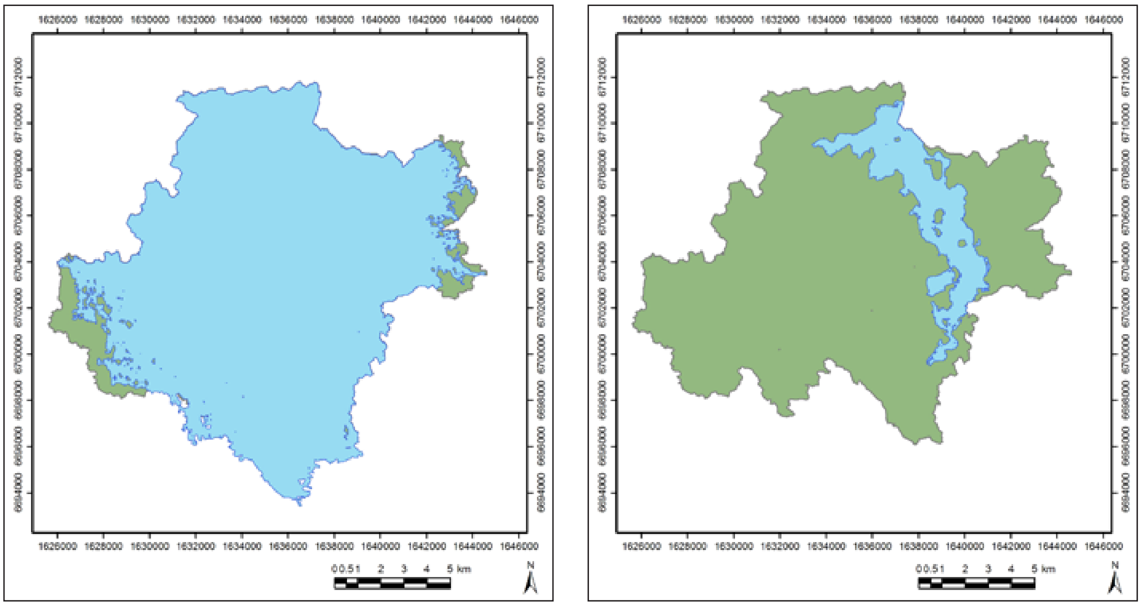

Figure 3-2. The distribution of sea and land at two chosen time steps: 500 AD with about 90% sea and 6500 AD with about 90% land.

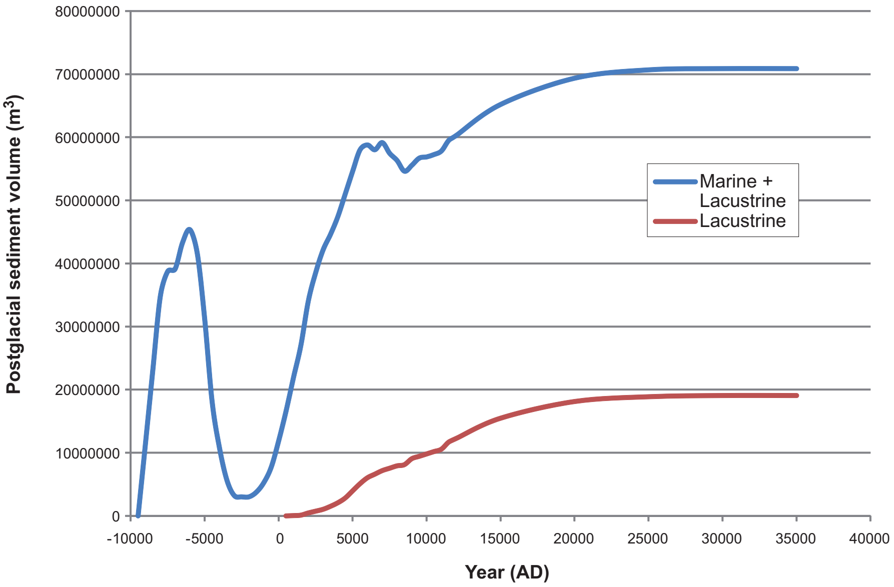

Figure 3-3. *The temporal variation in total postglacial clay volume (blue) and the share deposited in lacustrine environment (red).*

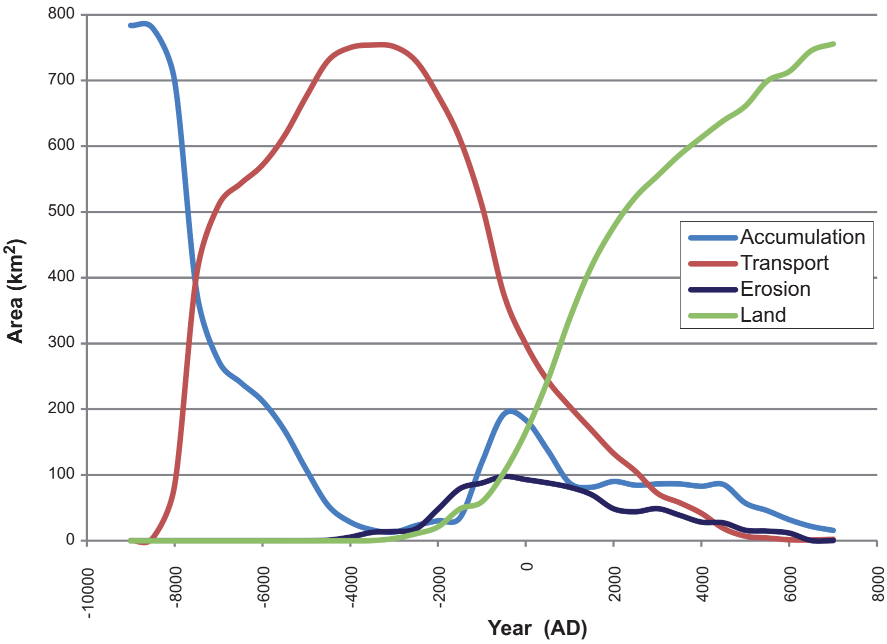

Figure 3-4. *Change in area extensions over time in three marine bottom types at the Forsmark site /Brydsten 2009/.*

At the end of the modelled period (35,000 AD), when all lakes are totally infilled and the development of the landscape is stabilized, the volume of the marine part of the postglacial clay is about 73% of the total volume. This agrees well with measured values of postglacial clay volumes in existing totally infilled lakes in the Forsmark area.

The organic sediment (end up as peat) is associated with infilled lakes or hanging wetlands and in the RLDM is treated as permanent accumulations, always increasing over time (Figure 3-5).

The total peat volume is dominated by organic material generated by the lake infill processes; therefore, the peat volume increase rate (Figure 3-5) is closely associated with the number of lakes with ongoing infill processes (Figure 3-6). At the end of the RLDM period (35,000 AD), the total fen peat volume is about 34 million m^3, i.e. about half of the volume of postglacial clay at the same time.

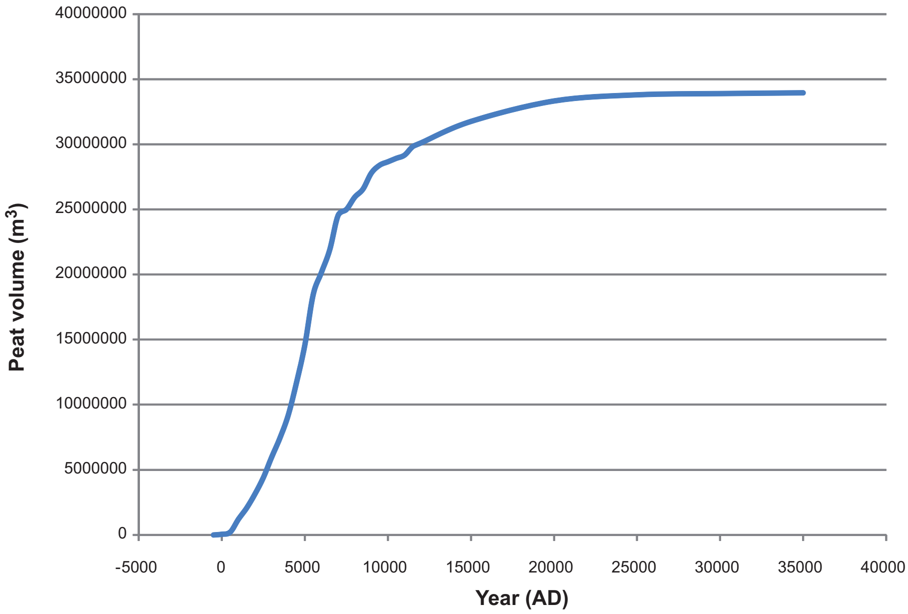

Figure 3-5. *The temporal increase in fen peat volume.*

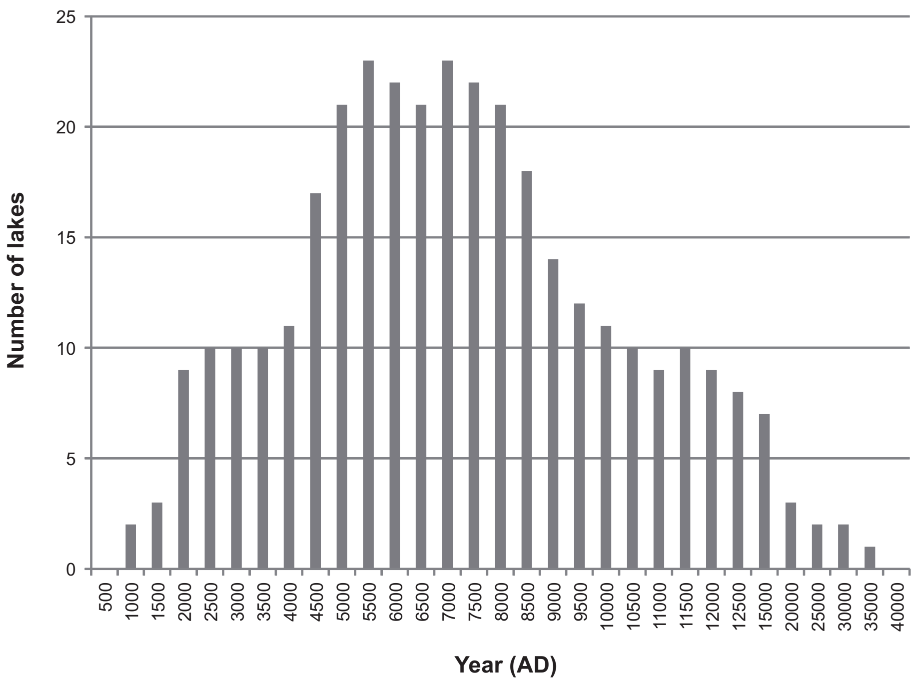

Figure 3-6. *Number of lakes with ongoing infill processes. The total number of modelled lakes are 41.*

3.2 The development of sediments

As mentioned earlier, the RLDM generates maps for surface geology for each time step. The maps are in raster format with a resolution of 20 meters. The maps have nine classes:

1. Bedrock
2. Till
3. Glacial clay
4. Postglacial clay or silt
5. Thin postglacial clay or silt
6. Glaciofluvial sediment
7. Artificial fillings
8. Lake
9. Peat and gyttja

The "Postglacial clay or silt" class is divided into two classes based on the thickness of the strata. If the postglacial fine-grade sediments are thicker than 0.5 m, it is classified as "Postglacial clay or silt" (Class 4), otherwise as "Thin postglacial clay or silt" (Class 5). The RLDM starts 9500 BC with the 2000 AD soil map with all postglacial sediment removed (Figure 3-7).

The development of QD according to the landscape model area is presented in Figure 3-8. Soon after deglaciation, the entire area is submerged by water and covered by a thin stratum of postglacial clay. Around 8000 BC the highest situated parts of the model area have been lifted above the wave base and the postglacial clay is eroded and the underlying deposits are exposed (bedrock, till, and glacial clay). This process is continued until about 2000 BC when the area of postglacial clay is at a local minimum (1.6%). The map of QD for this date is shown in Figure 3-9.

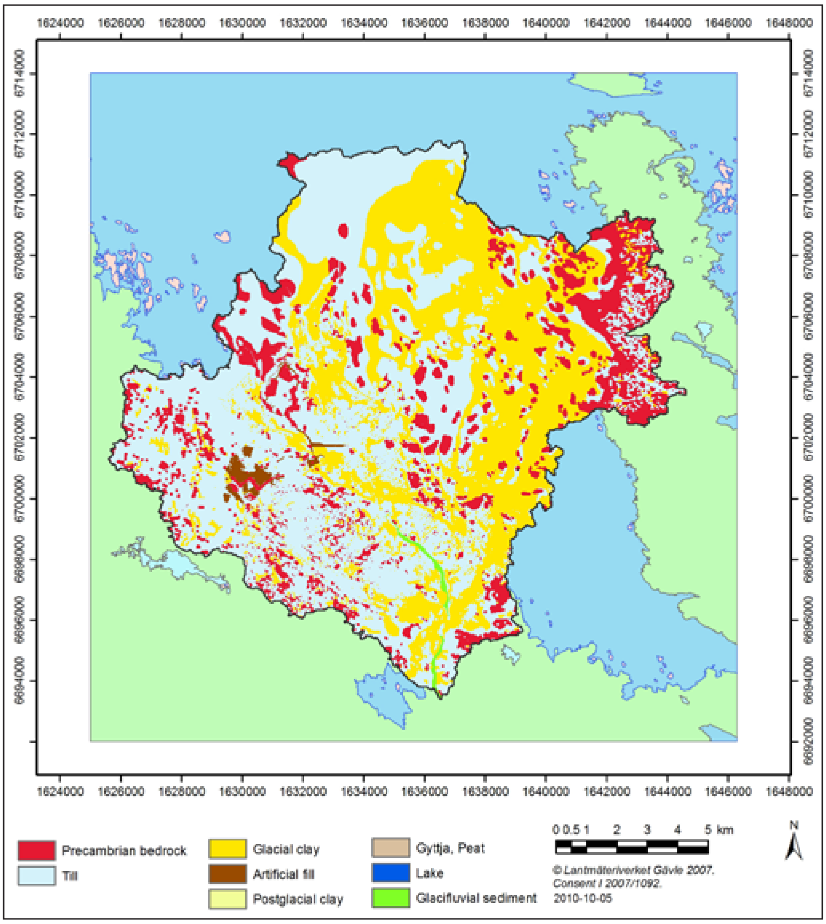

Figure 3-7. QD at 9500 BC. The classes "Postglacial clay or silt" and "Thin postglacial clay or silt" are merged into one class; "Postglacial clay". Extension of the class "Artificial fill" corresponds to present conditions.

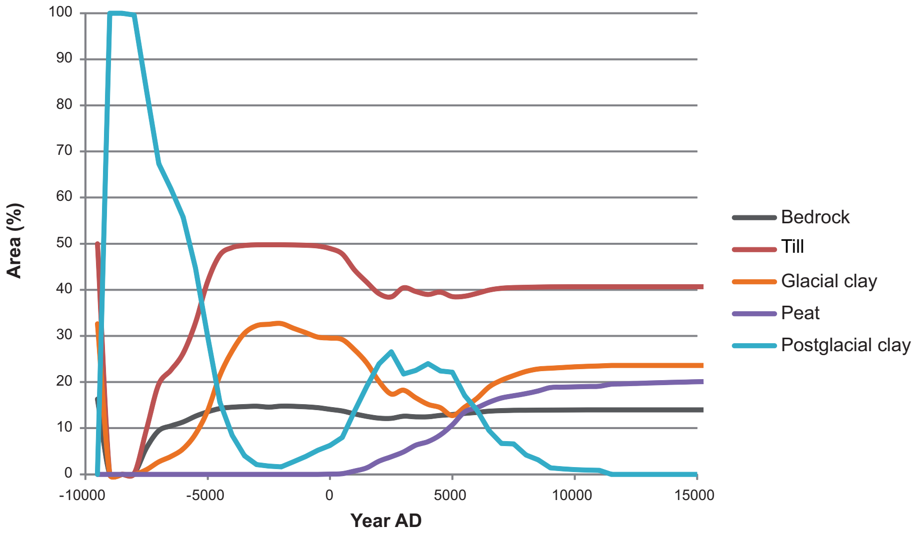

Figure 3-8. *The temporal area development of regolith deposits for the Forsmark model area.*

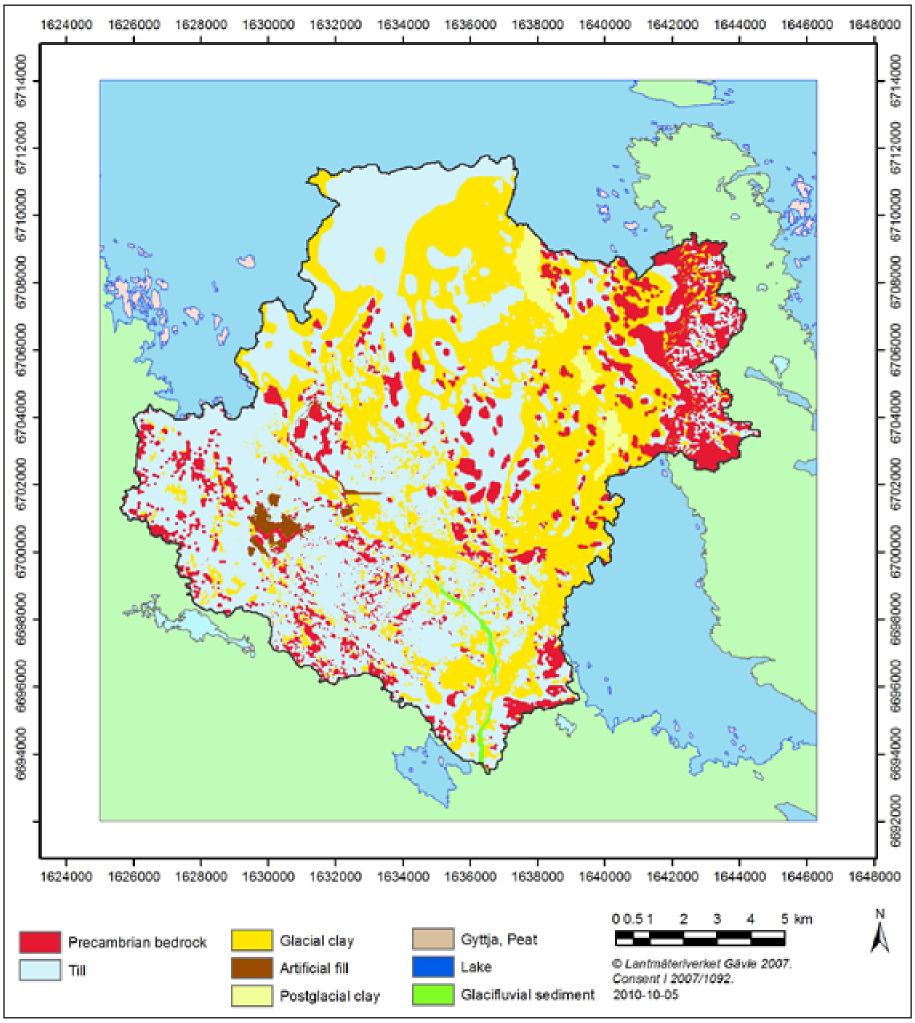

Figure 3-9. *QD at 2000 BC. This is the time when the model predicts minimum extension of postglacial clay. Extension of the class "Artificial fill" corresponds to present conditions.*

The postglacial deposits at 2000 BC are found along the deep north-south elongated basin groove (Gräsörännan). This is the only area with continuous accumulation from deglaciation to 2000 BC. Remaining areas will not contain any postglacial sediment older than 2000 BC.

The postglacial clay area increases from 2000 BC (1.6%) to a local maximum (24.0%) at 2000 AD. This development is due to a general decreasing wave power within the model area caused by an decreased fetch in the Bothnian Sea and shoaling in the north part of the Öregrundsgrepen /Brydsten 2009/. The QD when the postglacial clay has its local maximum (2000 AD) are shown in Figure 3-10.

After 2000 AD, the areas of postglacial clay are decreasing caused by larger erosion in the near-shore zone compared to areas recently formed in the deep sea (Figure 3-8). Geological units underlying the eroded postglacial clay in the near-shore zone (glacial clay, till and bedrock) are exposed, but are also covered by postglacial clay and peat in the successively more infilled lakes. The infill process also covers postglacial clay with peat so the sum of processes causes the postglacial gyttja (clay gyttja) areas to almost disappear. The Figure 3-11 shows the QD at 10,000 AD. The only larger area with postglacial clay is found in the northern part of the *Gräsörännan*, the part of the basin that will evolve into a future lake. At this time, only four lakes are not totally infilled and one lake is still to be isolated.

From about 10,000 AD, changes in the regolith surface distribution are limited. The former lakes are infilled so the peat area increases and the postglacial clay decrease. At 35,000 AD, the last lake within the model area is totally infilled (Figure 3-12) and the development of the QD is limited to change within the "Peat" class. The landscape has come to a maturity stage and will be relatively stable until the next glacial stage (ca. 57,000 AD).

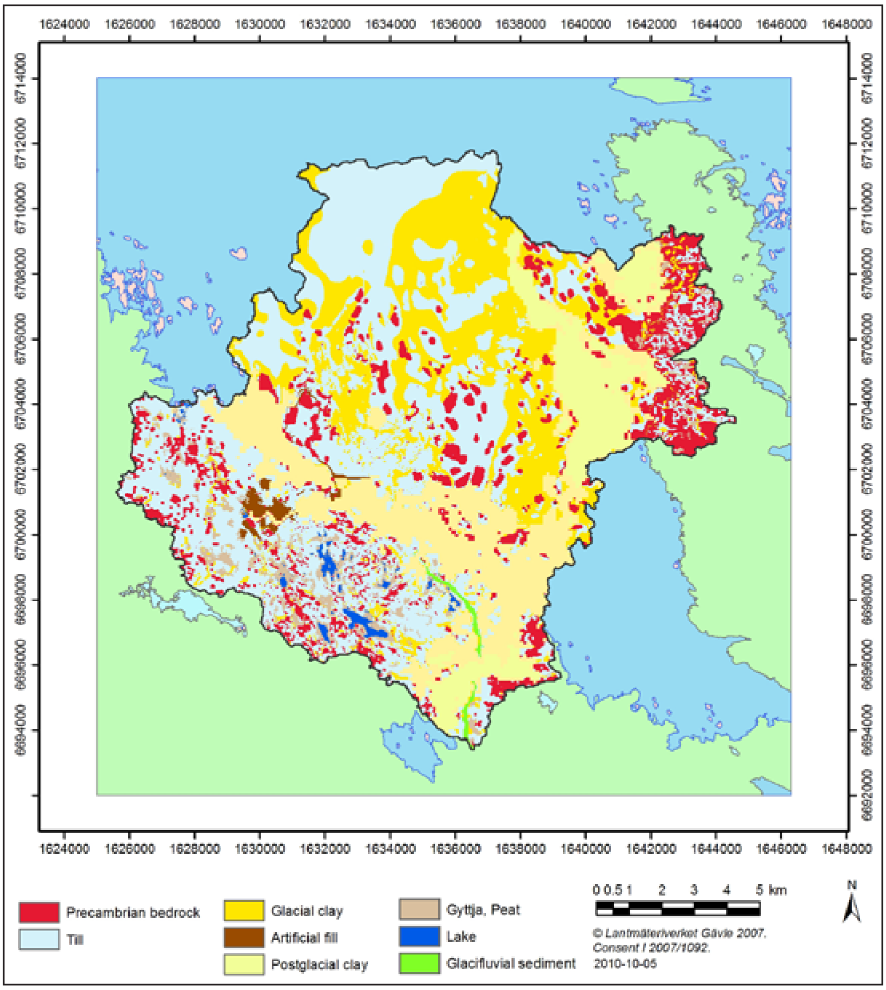

Figure 3-10. *QD at 2000 AD. This is the time when the model predicts maximum extension for postglacial clay. Note that the extremely thin strata of postglacial clay are shown as postglacial clay compared to conventional Quaternary maps where a thickness of at least 0.5 m is required.*

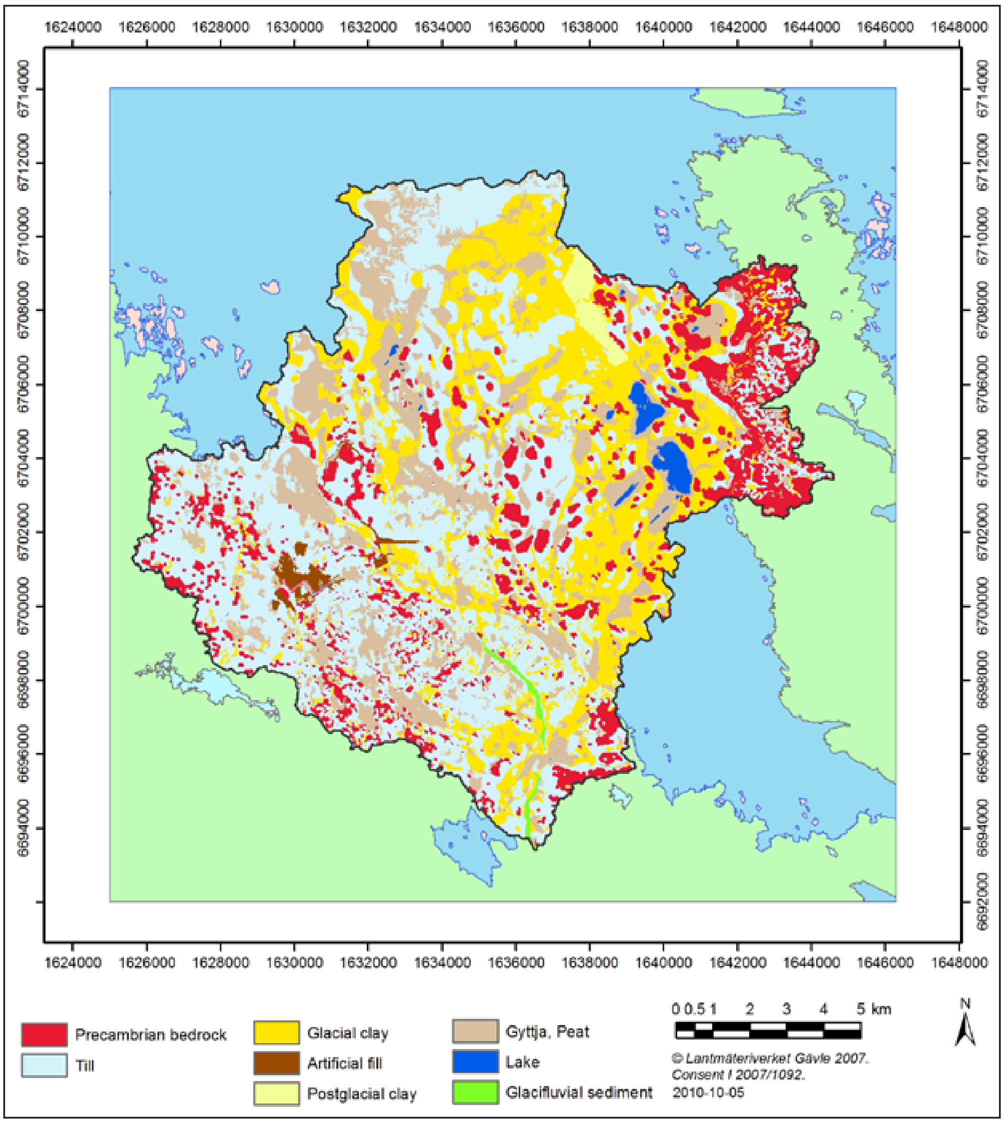

Figure 3-11. *QD at 10,000 AD.*

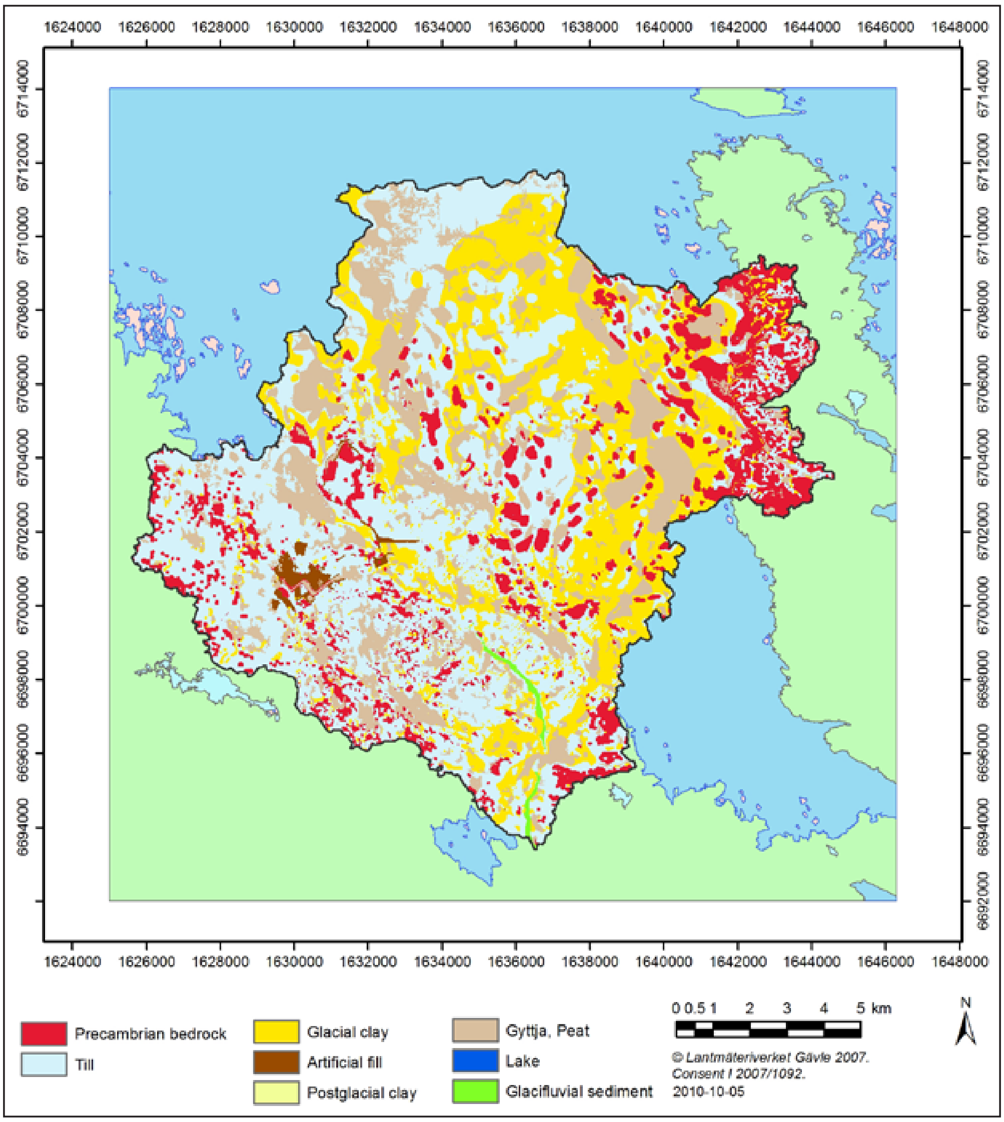

Figure 3-12. QD at 35,000 AD. All basins within the model area have been totally infilled.

3.3 Temporal variations in lake parameters

This brief summary of the results with tables and figures gives an overview of lake development in the Forsmark area during the Holocene and 20,000 years into the future. The future lake 116 (Lake Charlie) will be used as a representative lake for future lakes and will be examined in more detail.

Figure 3-13 shows the reconstructed bathymetry of the Lake Charlie basin just after deglaciation. The topmost strata consist of glacial clay. No postglacial sediments have yet accumulated and altered the bathymetry. The maximum water depth is 5.5 m in the central part of the basin. A deep part is also found in the eastern part of the basin (4.8 m).

The upper left map in Figure 3-14 shows the extension of reed vegetation in Lake Charlie at 5000 AD, i.e. 200 years after isolation. The vegetation already covers about 52% of the lake area. In lakes with large shallow areas, the migration of reeds already occurs when the area is a shallow bay. In many lakes in Forsmark, major parts are already vegetated at isolation. Exceptions are the deep lakes along the elongated basin *Gräsörännan*.

The further migrations of reeds generally occur in a high rate. Deeper parts of the basins do however take longer time to get colonized by reed, since it takes time for the water depth to get shallow enough. In these basins, often one or more small ponds remain for a long time situated over the originally deepest parts of the basin. In the Forsmark area, the maximum depth for colonization is two meters /Brydsten 2004/. These small ponds in an almost totally infilled lake can be observed in many existing basins, e.g. Lake Stocksjön southeast of the power plant.

Figure 3-15 shows the temporal increase in thickness of different sediment strata in Lake 116. The lake basin starts to fill up with marine post-glacial sediments around 1000 AD. The first colonization of reeds occurs about 4000 AD when part of the future lake basin is shallower than two meters. When the lake is isolated (about 4800 AD), almost 50% of the surface is covered by fen peat with a mean thickness of 0.74 m. After isolation, the marine sedimentation is followed by lacustrine sedimentation. The difference between the two strata is small, so the most common methods of finding the isolation level in the sediment sequence is with diatomic analysis. The final mean thickness of the marine strata is 0.38 m with a maximum value of 0.56 meters.

The rapid colonization rate during the shallow bay stage (4000–4800 AD) is controlled by the shore displacement process while the gentler rate during the lacustrine phase is controlled by the sedimentation processes.

The lake infill continues with successive colonization of vegetation and sedimentation until the basin is totally filled around 8500 AD. At this stage, the former lake basin consists of 20% marine sediments, 18% lacustrine sediments, and 62% peat.

The volumes of peat in the totally infilled lake 116 are larger than the combined volumes of marine and lacustrine sediment volumes. The volumes and times of when different sediment types are totally infilled lakes are presented in Appendix 3. There are large differences in these values between lakes (Table 3-1). In general, high amount of peat is associated with a shallow lake with a short accumulation period during the marine phase (e.g. lakes 107 and 117) and high amount of marine and lacustrine sediments are associated with deep lakes in low altitudes with long marine and lacustrine phases (e.g. lakes 105 and 114).

The thickness of different sediment types is listed in Table 3-2.

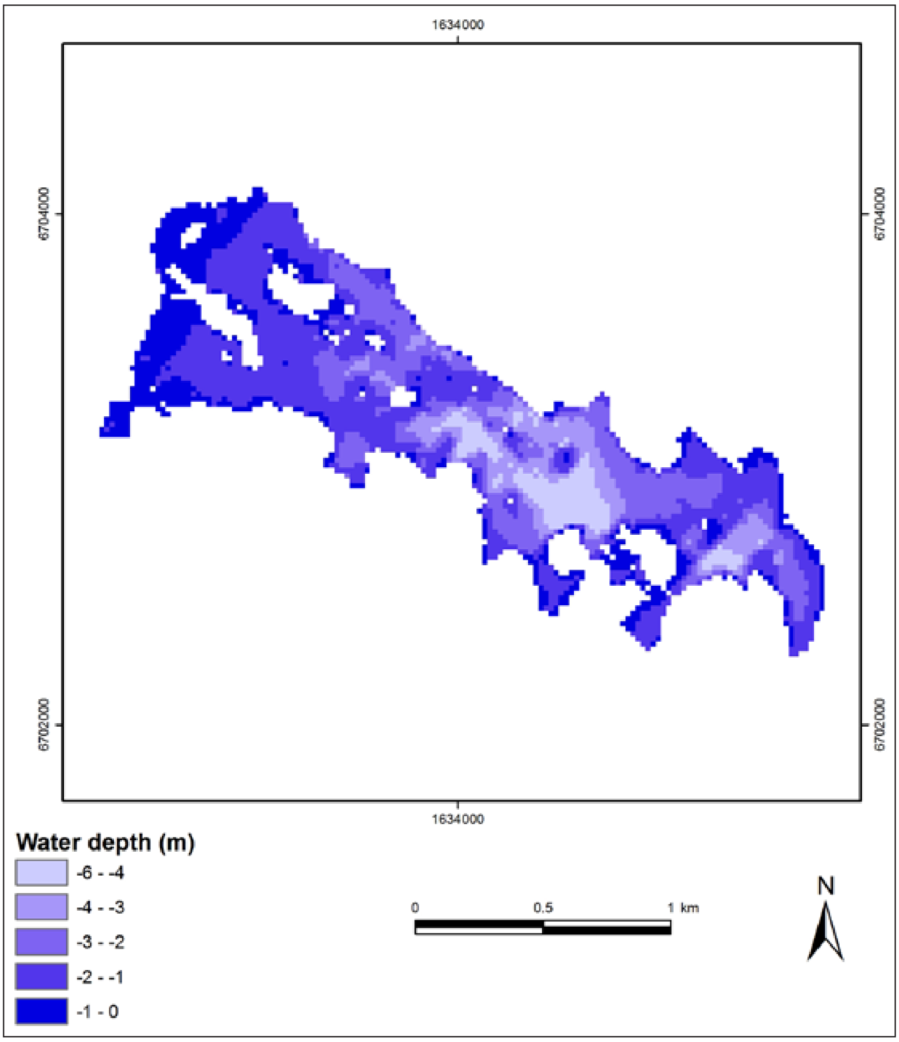

Figure 3-13. *The reconstructed deglacial bathymetry of the Lake Charlie basin (Lake 116) before any postglacial sediment accumulation.*

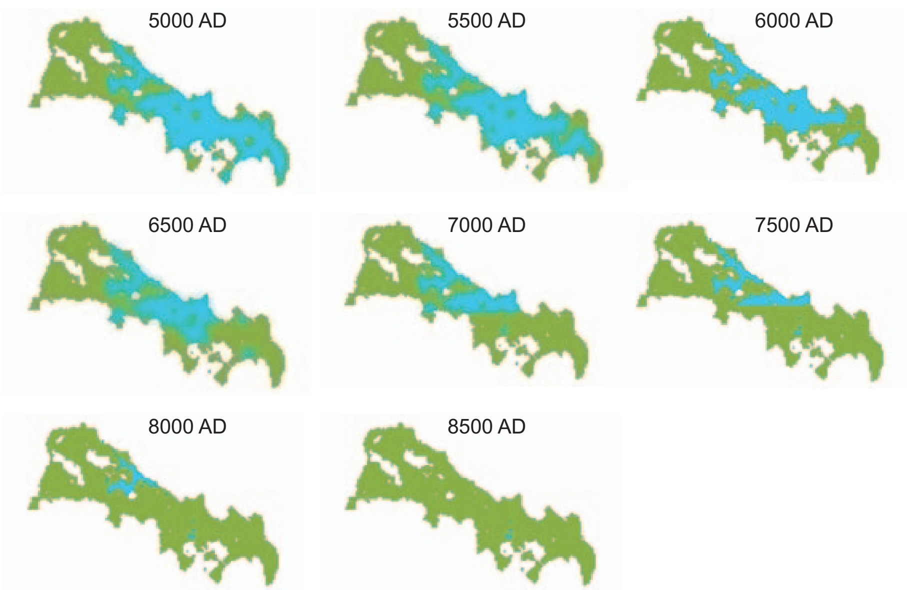

Figure 3-14. *The infill process of Lake Charlie (Lake 116). The basin will be isolated about 4800 AD and totally infilled about 8500 AD.*

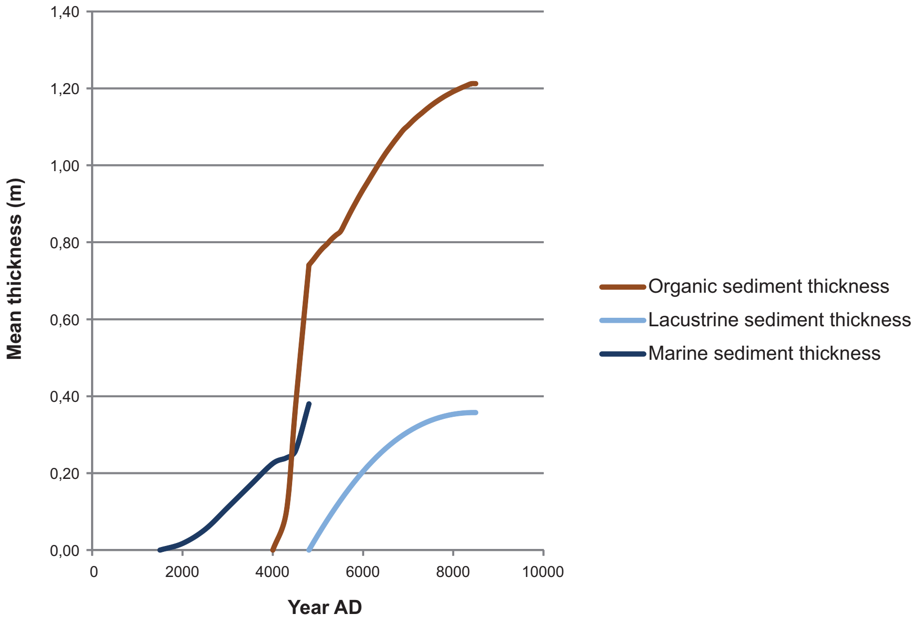

Figure 3-15. *The temporal increase in mean thickness of different sediment strata in Lake Charlie (Lake 116).*

Table 3-1. Volumes (%) of different sediment types when lakes are totally infilled. Values for individual lakes are listed in Appendix 3.

	Marine	Lacustrine	Peat
Mean	23	16	61
Min	3	0	20
Max	59	44	91
SD	13	11	16

Table 3-2. Thickness (m) of different sediment types at time for totally infilled lakes. Values for individual lakes listed in Appendix 4.

	Marine	Lacustrine	Peat
Mean	0.51	0.55	1.08
Max	3.63	21.49	2.00
SD	0.67	0.61	0.32

4 The RLDM applied to permafrost conditions

The lake module in the RLDM is calibrated using data from existing lakes at the Forsmark site /Brydsten 2004/. These lakes are isolated at 1200 BC to 1900 AD, a period with temperate climate and low climate variability. Therefore, the module should only be applied to future lakes with approximately the same climate. However, /SKB 2006/ account for results from a climate model applied to a complete glacial cycle (about 120,000 years) that shows permafrost climates for some of the period before all lakes at the Forsmark site will be completely infilled. This could be valid for future lakes with long infill times, e.g. lakes along the elongated basin *Gräsörännan*.

Both colonization of reed and sedimentation decreases with lower water temperature /Löfgren 2010/, so both the modelled infill rate and the sedimentation rate could be overestimated. /Löfgren 2010/ summarizes carbon storage in peat from different climates. One peat object in Forsmark (Rönningarna) has been studied by /Sternbeck et al. 2006/. In this study, the average long-term apparent rate of carbon accumulation (LORCA) was estimated to be 38 gC $m^{-2}y^{-1}$ for the last 1,600 years. This value is in the expected range of 20–50 g C m^{-2} yr^{-1} for a temperate climate /Turunen et al. 2002, Malmer and Wallén 2004/. The value from Rönningarna could be compared with accumulation rates from regions with colder climates. For the Boreal to the Subarctic region of Finland, /Turunen et al. 2002/, calculated the mean LORCA to be 18.5 g C $m^{-2}y^{-1}$, and /Vardy et al. 2000/ calculated the LORCA for mires in the Low arctic/High subarctic of Canada to be 14.2 g C $m^{-2}y^{-1}$, and /Tarnocai 1988/ estimated the LORCA to be 9 g C $m^{-2}y^{-1}$ in a mire on the Subarctic of Canada. For the High Arctic (Baffin Island), /Schlesinger 1990/ estimated LORCA to be 0.4–2.4 g C $m^{-2}y^{-1}$. These values indicate a 50–95% decrease in infill rate during periglacial conditions compared to the rate in temperate climate.

The climate conditions in Forsmark for the next 50,000 years (during the period there will be lakes in Forsmark) will probably include periods that can be analogous to all present climates in Subarctic, High Subarctic, Low arctic, and High Arctic zones /Kjellström et al. 2009/.

The decreases in LORCA during each future periglacial periods are difficult to predict; however, by assuming lake infill rates to be zero during these permafrost periods, the maximum length of the limnic phases for these lakes can be calculated. By setting the rate to 50% and comparing the results with the results from the original non-periglacial model runs, the minimum effect of the periglacial processes in the lake infill process can be estimated. Moreover, by reducing the lake infill rate with 75% of the non-periglacial rate during all the future permafrost periods, a plausible future scenario of lake ontogeny can be determined.

The sedimentation rate will also decrease when the region change from temperate to periglacial climate /Appleby 2004, Birks et al. 2004/. Such a climatic change often results in a decreased precipitation and run-off, important parameters for fluvial transport of clastic particles to the lake. In a model of future climate in Forsmark /Kjellström et al. 2009/, give a reduction of precipitation up to 35% during permafrost conditions compared with recent past climate. Therefore, it is very likely that also the sedimentation rate should be decreased when the model is applied to permafrost conditions.

The lake module is adjusted so both the infill rate and the non-organic sedimentation rate can be decreased during selectable time steps. The periglacial periods are defined by a permafrost depth greater than zero using data from the permafrost simulations /Hartikainen et al. 2010/ (Figure 4-1).

During periglacial climates, the permafrost depths vary greatly, even on a local scale. Because through taliks (areas with no permafrost and open connection between surface water and deep ground water) are often located beneath lakes, through taliks will be important for modelling nuclide dynamics especially for periods with few or no taliks in the study area. /Hartikainen et al. 2010/ gives the conditions to talik formation based on lake mean depth, lake area, and permafrost depth in the lake vicinity. The updated lake module gives the lake mean depths and areas for each time step, and the permafrost model /Hartikainen et al. 2010/ gives the mean permafrost depth for the Forsmark area; by combining the results from these two models, it is plausible to predict locations for future talik formations.

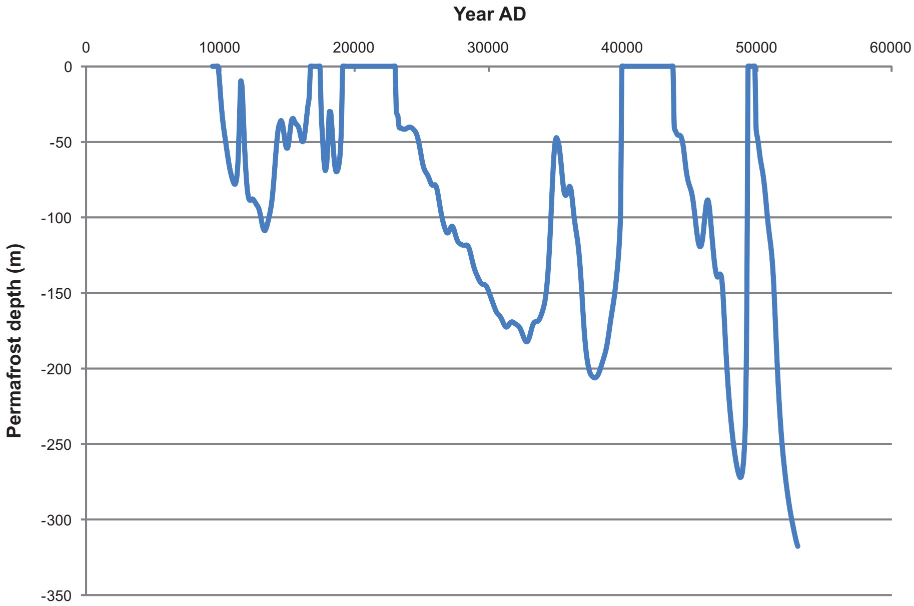

Figure 4-1. *The mean permafrost depth along a transect through the Forsmark area (From /Hartikainen et al. 2010/).*

A talik procedure is added to the lake module that predicts existence of taliks. The conditions for talik formation given in /Hartikainen et al. 2010/ are as follows:

(i) For a lake with a mean depth greater than four meters, the radius of a circular lake should be larger than 0.6 × for the permafrost depth for a talik to be present.

(ii) For a lake with a mean depth of 0.5 meters, the radius of a circular lake should be larger than the permafrost depth for a talik to be present.

(iii) In lakes with a mean depth less than 0.5 meters, no taliks are present.

Furthermore, we have assumed the following conditions:

(iv) For lakes with mean depths between 0.5 and 4 meters, there is a linear relationship in the permafrost coefficient between 1 and 0.6 (Coefficient = 1.057–0.114 × mean depth).

The lake radius is calculated as the radius of a circle with the same area as the lake. This means that for elongated lakes, the model overestimates the talik lifetime because the distance from the deepest part of the lake to the shore (or distance to the area with deep permafrost) is shorter than the calculated radius.

The first permafrost will appear in Forsmark at around 9400 AD. At this time, 29 of the 41 modelled lake basins (Figure 2-12) are already totally infilled and will therefore be unlikely locations for through taliks. By around 9400 AD, 10 of the remaining 12 lakes are infilled to more than 75% whereby through taliks will be unlikely at this point. The only two basins that remain as lakes are Lake 105 and Lake 114 (Figure 4-2). Both are large and deep and are situated along the basin Gräsörännan.

The modified lake module is applied on Lake 114 with infill rates reduced by 50, 75, and 100% during permafrost periods (Figure 4-3).

The figure shows that the lake ontogeny is very sensitive to decrease of infill rate during permafrost conditions. For example, at isolation (8600 AD) the lake is colonized by reed to 23% (not shown in figure). At 20,000 AD, the lake is infilled to 90% if the infilled rate is not adjusted for permafrost (red line), but only to 40% if the infill processes are stopped when permafrost is present (black line). If the infill rate is reduced by 75% (most plausible reduction), the lake is infilled to about 50% (green line). The figure also shows that Lake 114 will exist until the ice sheet covers the area (around 57,000 AD) if the infill rate reduction during permafrost is set to lower than 75%, but it will be totally infilled around 35,000 AD if no adjustments are made to the infill rate.

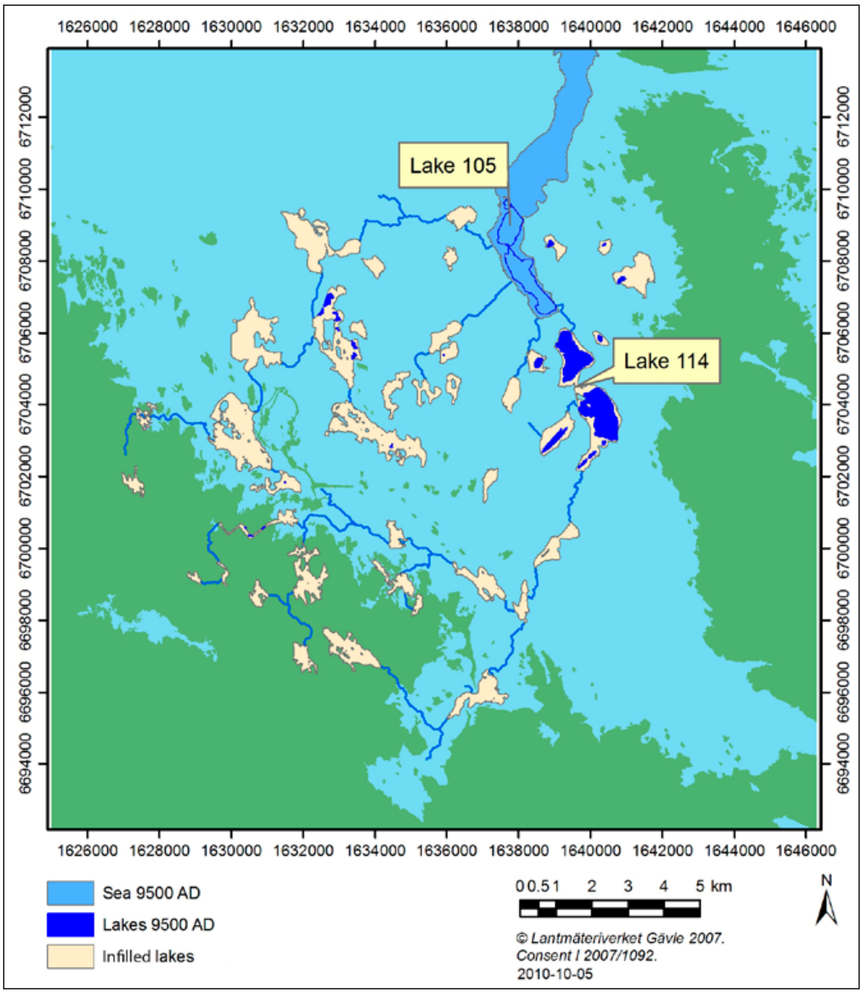

Figure 4-2. *Lakebasin infill status at 9500 AD, the first permafrost period in Forsmark. Lake 114 is split into two basins and Lake 105 has not yet been isolated and is displayed with a blue line as the future shoreline at 11,500 AD. All other lakes are infilled to at least 75%.*

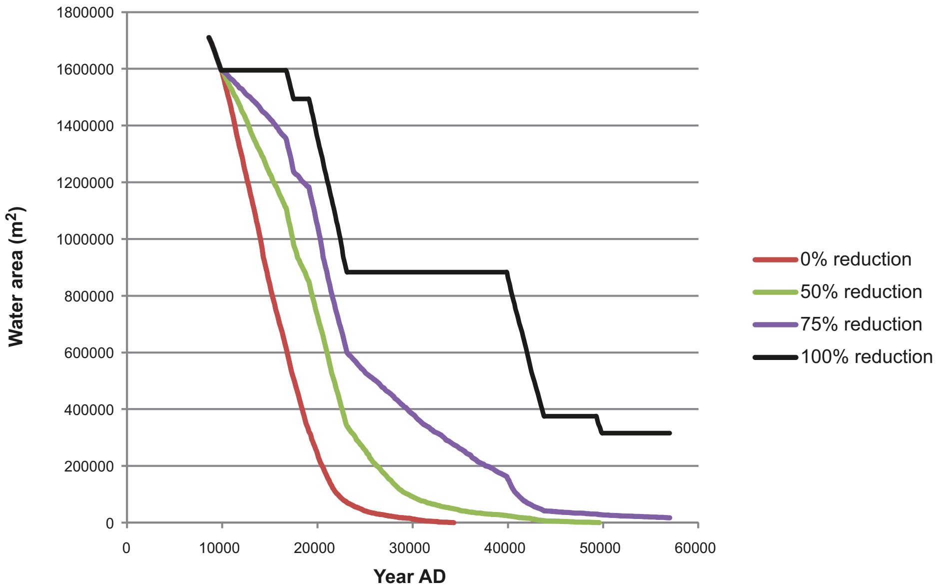

Figure 4-3. *The decrease in water area of Lake 114 dependent on the reduction in infill rate during permafrost periods (0% is no change in infill rate and 100%, is a total stop in the infill processes during permafrost periods).*

Figure 4-4 shows the talik status of Lake 114 depends on the decrease in infill rate during permafrost periods. The talik formation is also very sensitive to decrease of infill rate during permafrost conditions. The statuses for the talik are identical for the period up to around 28,000 AD. Afterwards, the time when the talik freezes depends on the decrease in infill rate. Since a deep and large lake is favourable to talik formation, a slow infill rate gives longer periods with "Permafrost and Talik" (Code 1 in Figure 4-4). With no adjustment of the infill rate (top diagram), the talik is closed by 28,000 AD, but it is always present until the ice sheet enters (57,000 AD) if the infill processes are stopped during permafrost periods (bottom diagram).

The permafrost lake module was also applied to Lake 105. The results were largely the same as for Lake 114. Figure 4-5 shows the talik status for both lakes with a reduction of the infill rate of 75%. Both lakes have taliks during permafrost periods up to around 37,000 AD; from around 23,000 AD these are the only two taliks in the study area. During two periods (47,700–49,200 AD and 51,300–57,000 AD), the whole model area is frozen (Code = 4). If no adjustments are made to the infill rate during permafrost, the whole model area will be frozen after 28,400 AD.

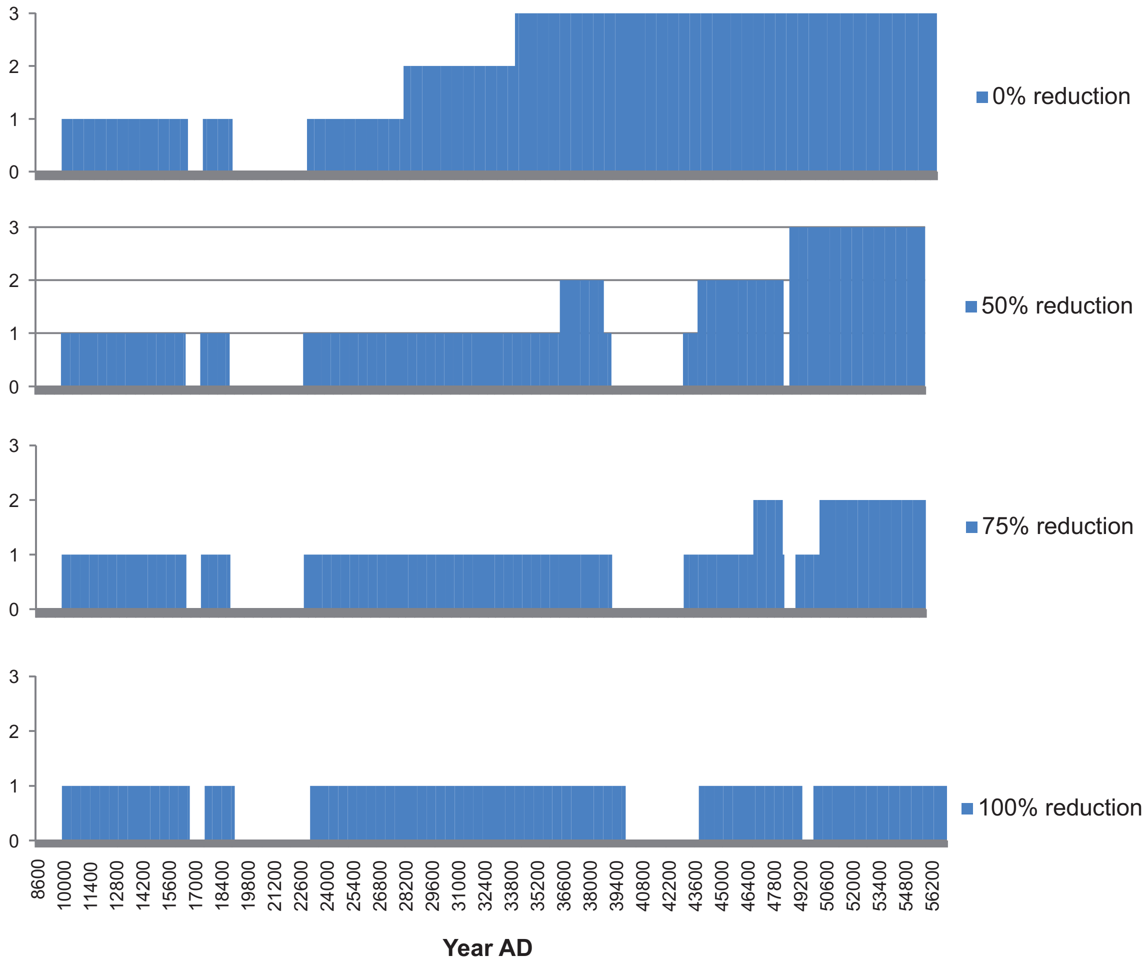

__Figure 4-4.__ Talik status of Lake 114 depends on the decrease in infill rate during permafrost periods. The top diagram shows no change in infill rate (0% reduction) and the diagram below shows a stepwise reduction down to 100% in the bottom diagram. The most probable decrease is 75%. Code 0 = "No Permafrost"; 1 = "Permafrost and Talik"; 2 = "Permafrost and No Talik"; and 3 = "Totally infilled lake".

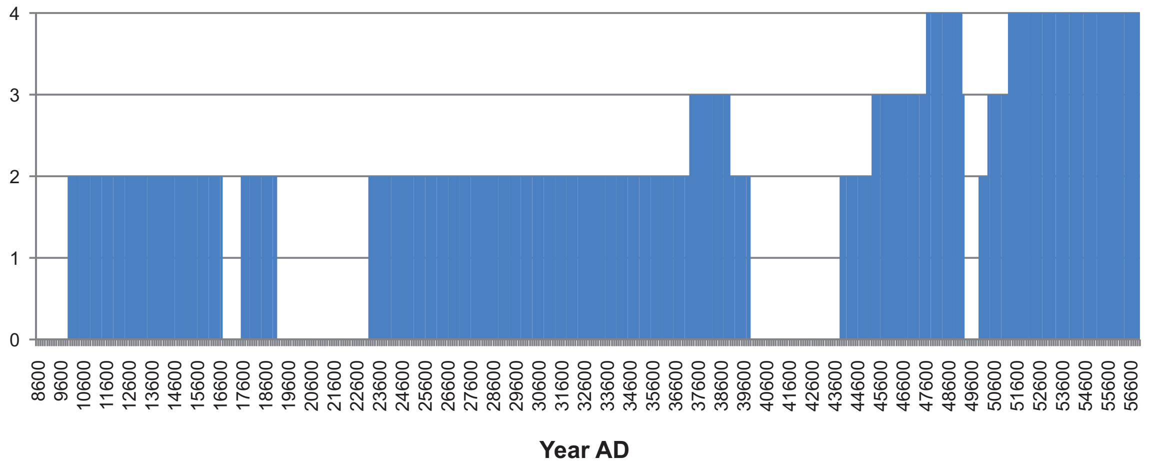

Figure 4-5. *Talik status of Lake 114 and Lake 105 at a reduction in infill rate during permafrost periods with 75%. Code 0 = "No Permafrost"; 2 = "Permafrost and Talik" in both lakes; 3 = "Permafrost and Talik" in one lake and "Permafrost and No Talik" in the other; and 4 = "Permafrost and No Talik" at both lakes.*

5 Sensitivity analysis

The marine module uses the RDM, SDM, and the shoreline displacement model as input and generates a RDM, QD map, and a DEM for each time step. If a cell in the model is classified by the SDM as marine and accumulation bottom, postglacial fine-graded sediment is added to the cell. This sedimentation rate is constant over the model area but varies over time and is the only internal parameter in the marine module that can be analyzed using sensitivity analysis.

The lake module has two site-specific parameters: the sediment rate and the infill rate.

The sensitivity test has been applied on Lake 116 (Table 5-1 and 5-2), a lake of medium size and situated close to the proposed repository.

The analysis shows that the Lake infill rate is the most sensitive parameter. The same infill rate algorithm is used for both the reed colonization during the marine shallow bay phase as for the lake phase. In order to find out if one of the two phases is more sensitive, four additional sensitivity models are tested (Table 5-3).

Table 5-4 shows the differences between the basic model run (Model 1) and the four models with different infill rates. The infill rate during the marine shallow bay phase is more sensitive than the rate during the lake phase.

The Lake 116 will be totally infilled at the latest (Model 6) around 9800 AD, so the permafrost variant of the RLDM will only affect the infill to a minor degree since the first permafrost enters the area about 9400 AD. The RLDM permafrost variant is applied to Lake 114 (Figure 4-3 and 4-4); however, this variant shows that the choice of reduction of infill rate during permafrost conditions is also very sensitive for the modelled lake ontogeny.

Table 5-1. The scheme for sensitivity analysis in the RLDM. Model 1 is the original setup.

Sensitivity model	1	2	3	4	5	6	7	8	9
Marine sed. rate	0%	+10%	–10%	+10%	0%	0%	–10%	0%	0%
Lacustrine sed. rate	0%	+10%	–10%	0%	+10%	0%	0%	–10%	0%
Lake infill rate	0%	+10%	–10%	0%	0%	+10%	0%	0%	–10%

Table 5-2. Differences for Lake 116 between the basic model run (Model 1) and sensitivity models for time at totally infilled lake (Time), and Peat volume, Mean sediment thickness and Sediment volume at time for totally infilled lake. The minimum and maximum values are displayed in bold. Model 1 is the original setup.

Model	Time	Peat volume	Mean sed. thickness	Sediment volume
1	0.0	0.00	0.0	0.00
2	–8.2	3.15	–0.5	–0.54
3	9.4	–3.38	0.9	0.88
4	0.0	–0.25	4.8	5.04
5	0.0	–2.39	3.8	3.92
6	12.9	4.84	–8.6	–7.93
7	0.0	0.18	–5.2	–4.95
8	0.0	2.51	–4.3	–4.11
9	9.4	–7.02	10.3	11.51

Table 5-3. The scheme in RLDM for sensitivity analysis of the Infill rate parameter.

Sensitivity model	10	11	12	13
Lake infill rate	+10%	0%	–10%	0%
Shallow bay infill rate	0%	+10%	0%	–10%

Table 5-4. The differences between the basic model run (Model 1) and the four models with different infill rates.

Model	Time	Peat volume	Mean sed. thickness	Sediment volume
1	0	0	0	0
10	–3.53	1.80	–3.04	–2.95
11	–4.71	3.61	–6.30	–5.92
12	4.71	–2.57	4.05	4.22
13	3.53	–3.44	5.33	5.64

6 Calculation of the export of fine-grained particles from the model area

It is not possible to predict the export of fine-grained particles out of the model area with RLDM. However, with assumptions that the fluvial input and the input from the outer sea are of minor importance (see Section 2.1.1.5 for an estimation of the fluvial input), it is possible to make a rough estimation of the export. Figure 6-1 shows a conceptual model for sediment dynamics in coastal zones.

The dotted lines are the wave bases at two time steps and the red line is erosion or transport bottoms, the yellow line is a accumulation bottom and the blue line is accumulation bottom at time step one and erosion or transport bottom at time step two. The wave power generates resuspension of the till (R1) and some of these particles are resettled on accumulation bottoms (S1) and some are exported out of the model area (E1). In reality this process are many repetitions or resuspension and resettling events. Some of the particles are settled on bottoms close beneath the wave base (blue line). At next time step the resuspension processes acts on both the non-washed till and the recently settled postglacial clay (R2). Again, some particles are resettled on accumulation bottoms (S2) and some are exported out of the model area (E2).

The RLDM is calibrated for the sum of S1 and S2 and do not distinguish the two sources. The export E2 can be calculated as the sum of S over time minus the storage of postglacial clay for that time. This calculation is shown in Figure 6-2. The cumulative export 7000 AD of clay from postglacial sediments is c. 80 Mm^3. This should be compared to the total accumulation of postglacial clay within the model area at the same time which is c. 46 Mm^3. As this export is only from one source this is a minimum value.

Figure 6-2 also shows that the major part of the total export (c. 80%) occurs during a 4000 year period (7500 BC–3500 BC).

A method for calculation of the total export of fine-grained particles (sum of E1 and E2) is to use values for mean sedimentation rates in the Baltic Sea. /Pustelnikov 1977/ gives the mean sedimentation rate for the entire Baltic Sea during Holocene to 0.079 mm y^{-1}. Using this value gives at 7000 AD a cumulative accumulation of postglacial clay volume (S1 + S2) of c. 190 Mm^3, and a cumulative export volume of c. 145 Mm^3. Thus, a rough estimation is that c. ¾ of the fine-grained particles is exported out of the model area and c. ¼ is permanently accumulated within the area.

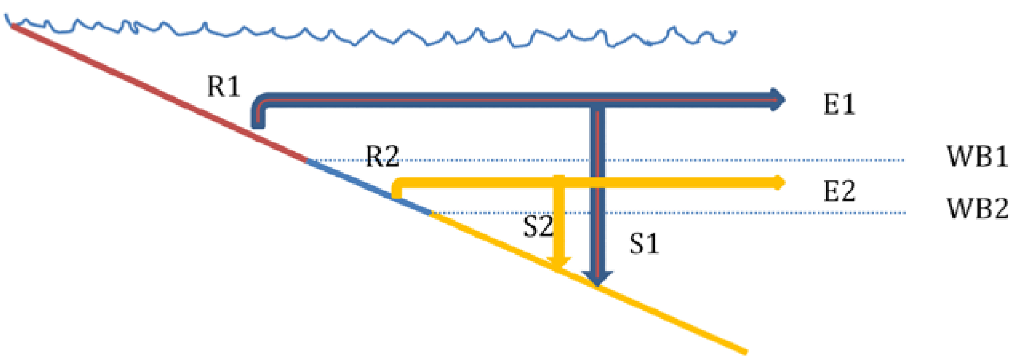

Figure 6-1. *Conceptual model for sediment dynamics in coastal zones. See text for a description of the processes.*

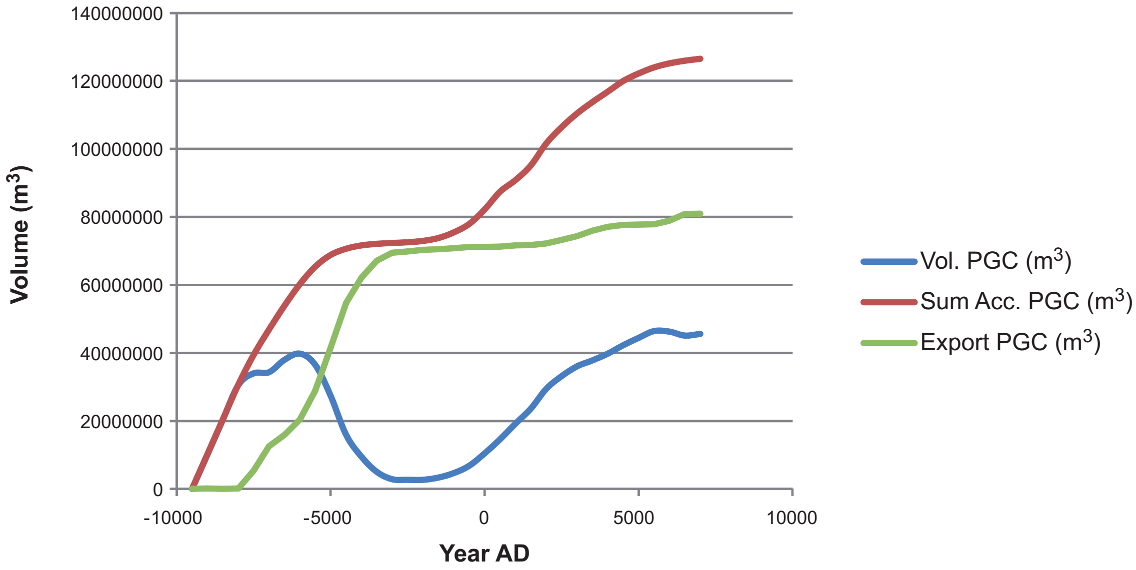

Figure 6-2. *The temporal variation in postglacial clay volume (blue), the cumulative volume of settled postglacial clay (red) and the cumulative export of postglacial clay (green).*

7 Discussion

The accuracy of the DEM influences the accuracy of the RLDM in many ways; these two are the most important:

(i) the modeling of the wave base depth in the SDM depends on an accurate DEM and errors in the SDM results give errors in the accumulation and erosion rates in the RLDM; and

(ii) the DEM is used for modeling extension of future lakes and small errors in the DEM at the lake thresholds gives errors in the lake altitudes, isolation dates and large errors in the calculations of the areas and water volumes.

The accuracy of the DEM is analyzed in /Strömgren and Brydsten 2009/ based on accuracy of raw altitude data. The use of the DEM is discussed in the sections below.

As shown above, the DEM is sensitive to relative sea level change, sediment dynamics, and lake infill processes. In the SDM, the 1970 AD DEM was used and only adjusted for the relative sea level change because no other variant of the DEM was available. In an update of the SDM, it should be more correct to use the Z4a-layer of the regolith depth model (upper surface of the glacial clay). This should lead to increased water depths, larger areas with accumulation bottoms, and thicker postglacial clay strata. The optimal method should run the SDM and RLDM in parallel:

(i) the SDM starts 9500 BC with the Z4a-layer as DEM;

(ii) the SDM results are used as input to the RLDM and a new 9000 BC DEM are the output; and

(iii) the 9000 BC DEM is used as input to SDM 9000 BC run, etc.

The accuracy of the calculations of future lake extensions, as shown above, depends on the accuracy of the DEM as well as on possible erosion of the thresholds. If the thresholds consist of postglacial clay or glacial clay, the fluvial erosion at the lake outlets will lower the threshold down to the altitude of the upper surface of the till or bedrock. Because the RLDM includes data on the stratigraphy at the lake thresholds, RLDM could be used to adjust the lake thresholds. Unfortunately, almost all lake thresholds are situated far from measured stratigraphy (marine geology survey with sonar), so the accuracy of the stratigraphy is fairly low.

In this study, the lake thresholds are not adjusted for the future lowering by erosion. This means that many future lakes have overestimated areas, depths, and volumes. This, in turn, results in an overestimation of the lake infill times. In a possible update of the RLDM, it will be important to measure both the bathymetry and the regolith stratigraphy in areas around future lake outlets.

The RLDM applied to permafrost conditions (chapter 4) showed that the model is very sensitive to the chosen reduction of the lake infill rate. A mean reduction of 75% was chosen for all permafrost periods. Instead, it should be more accurate to use a variable reduction based on, for example, the mean permafrost depth (Figure 4-1). However, this requires more accurate climate data (air temperature, permafrost depth, etc.) from the reference sites or more precise climatic definitions of the arctic zones (Subarctic, High Subarctic, Low arctic, and High Arctic zones). If the result from the RLDM permafrost variant also is sensitive in the radionuclide modeling, it will be possible to update the RLDM with variable reduction of the infill rate during permafrost conditions.

Some episodic periglacial processes such as niveo-aeolian processes /van Dijk and Law 1995/ or mire erosion due to permafrost degradation /Kokfelt et al. 2010/ are not possible to implement in the model but can be of major importance for lake ontogeny.

The sensitivity analysis and the permafrost models showed that the infill rate is the most sensitive parameter in the RLDM. The infill rate occurs in two places in the model: in modeling vegetation colonization in shallow bays that later will become lakes and in the lake module. Both rates are reduced during permafrost conditions. The infill rates during the lake phase are calibrated and validated using lakes in the Forsmark area with varying infill stages. These lakes have been entirely infilled during a temperate climate. As mentioned above, the algorithm used for infill of shallow bays is the same as for the lake and is based on the same maximum colonization depths in lakes /Brunberg et al. 2004/ and in the sea /Komulainen et al. 2008/. This assumption will overestimate the infill rate in the marine environment since some erosion processes (such as littoral erosion) that can be ignored in small lakes can be important in the sea. This, in turn, means that the sediment volume is underestimated and the peat volume is overestimated (Model 11 in Table 5-4). The sensitivity analysis clearly shows the need for an update of the infill procedure in the RLDM. This renewal should be based on all the major processes that influence the colonization including substrate and nutrient status (not only the physical properties of the water masses).

Another major source of error is the resolutions of the results from the SDM. The SDM was modelled in 500 year time steps. It was therefore necessary to use the same time resolution in the RLDM. If a cell is classified as accumulation bottom in a particular time step the model calculates the sedimentation as if this cell is accumulation bottom during 500 years. Using a higher time resolution in the SDM (say one year), might show a transition from transport to accumulation mode in this cell the last year of the 500 year period. If this is the case, the 500 year time step model overestimates the sedimentation in that particular cell with a value of 0.38–0.06 m based on the maximum and minimum sedimentation rate, respectively. However, this error will only occur at cells that change from transport to accumulation mode and this occur only for a particular cell at one time step during the modelled period. This error have probably limited significance on the modelling of radionuclide dynamics but can cause substantial errors on QD maps (Figure 3-7–3-10) for some time steps, especially at time steps with large changes from transport to accumulation modes (1500 BC–3000 AD, see Figure 3-4). A time resolution of 500 year also means that the time scales in figures should not be look on as absolute, rather as time periods +/– 250 years around the date.

The spatial resolution of the SDM is 100 meters. All other input data to the RLDM are in a resolution of 20 meter so the SDM results are converted into 20 meter resolution. This means that only the central 20×20 m cells in the 100×100 m area are correctly modelled.

The two resolutions problems in the SDM can be solved by rerunning the SDM using a more powerful computer. By setting the time step to 100 years the maximum error can be decreased to approximately 0.1 m and by setting the SDM resolution to 20 meters some model uncertainty can be eliminated.

The start of the deglaciation of the model area is set to 9500 BC based on /Fredén 2002/. Later studies /Hedenström and Sohlenius 2008/ have adjusted the date to 8800 BC. This 700 years difference overestimates the modelled thickness of the postglacial sediments at some cells with approximately 0.1 m.

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Appendix 1

Relative sea level for the Forsmark area

Altitude in RH70 height system.

Year AD	Altitude (m)
9500 BC	171.12
9000 BC	148.47
8500 BC	131.62
8000 BC	104.22
7500 BC	82.92
7000 BC	74.04
6500 BC	71.83
6000 BC	68.90
5500 BC	64.83
5000 BC	59.98
4500 BC	54.74
4000 BC	49.40
3500 BC	44.11
3000 BC	38.97
2500 BC	34.04
2000 BC	29.33
1500 BC	24.87
1000 BC	20.64
500 BC	16.65
0 AD	12.88
500 AD	9.32
1000 AD	5.97
1500 AD	2.81
2000 AD	–0.17
2500 AD	–2.99
3000 AD	–5.65
3500 AD	–8.17
4000 AD	–10.56
4500 AD	–12.81
5000 AD	–14.95
5500 AD	–16.99
6000 AD	–18.92
6500 AD	–20.75
7000 AD	–22.50
7500 AD	–24.16
8000 AD	–25.75
8500 AD	–27.27
9000 AD	–28.71
9500 AD	–30.10
10,000 AD	–31.42

Appendix 2

Physical properties of the 41 lakes that are treated in the RLDM

The Lake Id refers to the labels in Figure 2-12.

Lake Id	Area (m^2)	Volume (m^3)	Altitude (m)	Mean depth (m)	Max depth (m)	Isolation (Year AD)	Name
101	336,800	218,920	–25.80	0.65	1.39	8015	Nameless future lake
105	1,359,700	8,443,737	–34.27	6.21	24.50	11,156	Nameless future lake
107	1,431,600	2,619,828	–8.16	1.83	5.03	3497	Nameless future lake
108	1,422,074	2,417,526	–15.00	1.70	5.57	5011	Nameless future lake
109	227,800	419,152	–22.30	1.84	4.82	6941	Nameless future lake
110	547,600	350,464	–18.70	0.64	4.95	5492	Nameless future lake
112	242,800	148,108	–12.04	0.61	1.43	4325	Nameless future lake
113	314,000	408,200	–16.78	1.30	3.40	5447	Nameless future lake
114	2,655,500	16,198,550	–27.40	6.10	17.78	8545	Nameless future lake
115	568,400	1,040,172	–21.12	1.83	4.77	6602	Nameless future lake
116	1,601,900	2,194,603	–14.04	1.37	4.79	4783	Nameless future lake
117	1,866,600	3,434,544	–5.64	1.84	4.55	2997	Nameless future lake
118	359,800	402,976	–4.86	1.12	3.12	2848	Nameless future lake
120	301,100	605,211	–2.49	2.01	10.19	2409	Nameless future lake
121	238,300	157,278	–10.59	0.66	2.22	4007	Nameless future lake
123	465,500	321,195	–20.69	0.69	2.38	6482	Nameless future lake
124	82,741	30,614	0.48	0.37	1.29	1888	Puttan
125	76,070	23,582	0.40	0.31	0.88	1902	Norra Bassängen
126	560,200	845,902	–12.28	1.51	4.13	4379	Nameless future lake
129	67,453	34,401	5.82	0.51	1.29	1023	Gunnarsboträsket
132	60,042	16,211	3.66	0.27	1.07	1363	Labboträsket
134	340,900	497,714	–1.35	1.46	4.54	2205	Nameless future lake
136	611,311	372,900	0.42	0.61	1.81	1898	Bolundsfjärden
142	187,048	31,798	1.82	0.17	1.51	1663	Gällsboträsket
144	97,663	72,271	0.41	0.74	1.72	1900	Bredviken
146	241,400	200,362	–13.89	0.83	2.30	4748	Nameless future lake
148	754,302	279,092	0.56	0.37	1.86	1874	Fiskarfjärden
149	283,849	258,303	5.32	0.91	2.12	1101	Eckarfjärden
150	699,300	1,300,698	–7.93	1.86	6.56	3450	Nameless future lake
1001	112,800	234,624	–12.40	2.08	6.18	4406	Nameless future lake
1002	188,400	305,208	–21.01	1.62	9.04	6571	Nameless future lake
1003	144,000	86,400	–22.13	0.60	1.01	6891	Nameless future lake
1004	1,376,000	1,348,480	–15.01	0.98	4.18	5013	Nameless future lake
1005	198,800	192,836	–14.98	0.97	3.10	5006	Nameless future lake
1006	744,800	1,623,664	–12.22	2.18	7.01	4365	Nameless future lake
1007	138,000	175,260	–13.12	1.27	3.82	4570	Nameless future lake
1008	97,200	309,096	–19.54	3.18	10.03	6166	Nameless future lake
1009	186,000	158,100	–12.27	0.85	3.66	4377	Nameless future lake
1010	341,600	187,880	–13.22	0.55	1.35	4593	Nameless future lake
1011	154,000	23,100	–0.11	0.15	0.53	1989	Nameless future lake
1012	192,800	138,816	8.43	0.72	1.71	630	Degermossen
1013	191,200	221,792	–10.61	1.16	3.03	4011	Nameless future lake

Appendix 3

Volumes (%) of different sediment types at time for totally infilled lakes

Lake Id	Marine	Lacustrine	Peat
101	59	0	41
105	36	44	20
107	7	23	70
108	9	27	64
109	24	28	48
110	23	14	63
112	12	9	80
113	18	11	71
114	42	36	22
115	24	29	47
116	27	11	62
117	13	23	64
118	24	13	63
120	16	36	48
121	30	7	63
123	46	8	46
124	32	3	65
125	32	2	66
126	23	17	61
129	25	2	73
134	10	20	70
136	30	14	56
142	28	9	63
144	13	4	82
146	47	6	47
148	20	22	58
149	25	39	61
150	31	20	49
1001	29	20	50
1002	17	31	52
1003	30	5	66
1004	6	23	71
1005	3	6	91
1006	38	18	44
1007	7	20	73
1008	33	30	37
1009	13	9	78
1010	14	11	75
1011	3	6	91
1012	13	7	79
1013	12	10	78

Appendix 4

Thickness (m) of different sediment types at time of totally infilled lakes

	Marine sediments (m)			Lacustrine sediments (m)			Peat (m)		
Lake Id	Mean	Max	STD	Mean	Max	STD	Mean	Max	STD
101	0.42	0.43	0.03	0.07	0.16	0.07	0.21	0.84	0.26
105	3.09	3.63	1.10	2.58	21.49	3.83	1.22	2.00	0.86
107	0.12	0.20	0.07	0.43	2.91	0.67	1.29	2.00	0.73
108	0.21	0.45	0.07	0.65	3.95	0.91	1.54	2.00	0.56
109	0.67	2.16	0.35	0.87	5.65	1.26	1.41	2.00	0.69
110	0.25	0.26	0.01	0.25	7.28	0.50	0.87	1.50	0.31
112	0.09	0.13	0.04	0.15	0.47	0.14	0.95	1.50	0.26
113	0.28	0.34	0.04	0.27	3.94	0.44	1.32	2.00	0.64
114	3.12	3.63	0.50	2.55	16.60	2.92	1.47	2.00	0.78
115	0.87	2.56	0.64	0.97	5.67	1.31	1.56	2.00	0.65
116	0.34	0.56	0.09	0.38	5.33	0.69	1.18	2.00	0.59
117	0.34	0.46	0.03	0.55	2.65	0.68	1.52	2.00	0.64
118	0.31	0.34	0.07	0.30	3.58	0.42	1.03	2.00	0.62
120	0.23	0.40	0.08	1.03	7.73	1.55	1.16	2.00	0.67
121	0.38	0.54	0.03	0.08	1.16	0.16	0.74	1.67	0.39
123	0.83	2.59	0.28	0.20	3.29	0.34	0.81	1.56	0.50
124	0.27	0.40	0.11	0.18	1.19	0.12	0.85	1.90	0.42
125	0.16	0.17	0.05	0.16	0.24	0.03	0.61	1.00	0.18
126	0.59	0.67	0.08	0.26	7.27	0.45	1.22	2.00	0.72
129	0.42	0.62	0.07	0.03	0.17	0.05	1.22	1.63	0.33
132	0.47	0.62	0.16	0.00	0.00	0.00	0.54	1.15	0.34
134	0.11	0.34	0.08	0.54	3.17	0.67	1.56	2.00	0.54
136	0.29	0.40	0.13	0.33	2.53	0.34	0.79	1.50	0.32
142	0.23	0.40	0.06	0.16	4.04	0.31	0.67	1.96	0.51
144	0.06	0.17	0.08	0.20	3.65	0.37	1.22	2.00	0.49
146	0.68	0.74	0.12	0.11	6.11	0.28	0.66	1.70	0.45
148	0.22	0.40	0.02	0.56	6.58	0.98	1.09	2.00	0.65
149	0.27	0.62	0.19	0.75	3.24	0.94	1.58	2.00	0.52
150	0.75	1.16	0.13	0.59	3.73	0.84	1.22	2.00	0.74
1001	1.29	3.43	0.00	1.24	4.81	1.13	1.25	2.00	0.74
1002	0.38	0.50	0.13	0.98	7.34	1.42	1.14	2.00	0.64
1003	0.36	0.36	0.15	0.22	0.56	0.13	0.79	1.16	0.27
1004	0.06	0.13	0.00	0.28	3.51	0.52	0.70	1.86	0.60
1005	0.03	0.06	0.00	0.09	1.12	0.18	0.91	2.00	0.70
1006	1.14	1.65	0.00	1.40	5.61	1.09	1.11	2.00	0.79
1007	0.13	0.15	0.00	0.49	2.44	0.59	1.34	2.00	0.63
1008	1.35	2.36	0.90	1.93	9.57	1.83	1.38	2.00	0.72
1009	0.18	0.20	0.00	0.30	2.28	0.38	1.09	2.00	0.49
1010	0.16	0.34	0.00	0.28	0.71	0.18	0.86	1.45	0.19
1011	0.03	0.17	0.00	0.08	0.26	0.09	0.88	1.13	0.18
1012	0.20	0.53	0.00	0.30	1.03	0.20	1.15	1.60	0.33
1013	0.21	0.44	0.00	0.38	1.66	0.38	1.35	2.00	0.58