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Abstract

The final repository for short-lived radioactive waste (SFR) is located in Forsmark in northern Uppland in the immediate vicinity of the Forsmark nuclear power plant. SFR is used for the final disposal of low- and intermediate-level operational waste from Swedish nuclear facilities. SKB plans to extend SFR. The objective of the safety assessment SR-PSU is to assess the long-term radiological safety of the present and extended SFR repository.

The regolith at the Forsmark site has been characterised using both a map of regolith distribution and a regolith depth model (RDM) that shows the stratigraphy and thickness of different deposits. Regolith refers to all the unconsolidated deposits overlying the bedrock, regardless of their origin. The surface geology and regolith depth are important parameters for hydrogeological and geochemical modelling and for the overall understanding of the area. However, the map of regolith and the RDM for the Forsmark area consider only the present conditions and do not take the temporal change of the regolith into account. Therefore, a regolith-lake development model (RLDM) was constructed that describes the surface geology, stratigraphy and thickness of different strata in the Forsmark area during a glacial cycle. This RLDM was used in the safety assessment for spent nuclear fuel, SR-Site. In the present study, a new RLDM was constructed by using new data and improved descriptions of some of the processes included in the previous modelling. The RLDM has been applied to three different climate cases, i.e. the global warming, the early periglacial, and the Weichselian glacial cycle climate cases.

The RLDM is divided into two modules: a marine module that describes the sediment dynamics (erosion and accumulation) caused by wind-generated waves, and a lake module that describes the lake infill processes during an interglacial. The RLDM marine module starts at the time when the area has recently been deglaciated and the local Quaternary geology consists of glacial sediments only (surface geology, stratigraphy, and thickness around 8500 BC). These conditions are generated using the regolith depth model (RDM).

Between 8500 BC and 7000 AD (with 500-year time steps), postglacial clay/silt or glacial clay are added or removed in each raster cell based on the sediment dynamic environment at that time. These sediment data is obtained as the output from the sediment dynamic model. In a cell where erosion is the predominant process, postglacial sediments or glacial clay are resuspended and transported out of the cell. Cells dominated by accumulation get a contribution of 0.06–0.39 m of postglacial clay/silt in each time step. The net sedimentation rate varies over time and is calibrated using the sediment dynamic model and measured postglacial clay thickness from the marine geological survey. For each time step, the RLDM marine module outputs are raster maps of surface geology, thickness of glacial clay and postglacial clay, and surface elevation (i.e. the DEM for that time).

When the water depth in the shallow sea bay within the extent of a future lake decreases to 1.3 m due to the land upheaval, the infilling with vegetation starts. This process continues until the lake is formed. The infilling of lakes is modelled with an equation for the net sedimentation rate and an equation for vegetation colonisation. Each lake is modelled separately. The DEM and the thickness of the marine postglacial clay from the time step before lake isolation are used as the only inputs 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 every 500-year time step. In a second post-processing routine, the wetlands not emanating from infilled lakes are added. These wetlands are small infilled local basins. Finally, so-called hanging wetlands are produced using the DEM for 40,000 AD and an equation for the topographical wetness index (TWI).

The transformation from sea to land in the Forsmark model area is a process that takes about 12,000 years. Until 1000 BC, the sea covers the whole area and after 10,000 AD the area consists of merely limnic and terrestrial ecosystems. This rapid transition also implies that the glacial isostatic adjustment (GIA) is the most important process in landscape development. The areas with limnic ecosystems show a large temporal variation because many lakes are rapidly transformed to terrestrial ecosystems.

The amount of marine postglacial clay during the first 5,500 years after the ice receded from the area varies due to shifts between accumulation and transport bottoms, and reached a minimum around 3000 BC. After that, the volume increases continuously. Lacustrine postglacial clay and peat increases continuously from around 500 BC due to the infilling of lakes.

There is a great variety in the distribution of surface regolith from 8500 BC to around 7000 AD. This is caused by the erosion and accumulation of postglacial clay during this time. From around 7000 AD, the changes in the distribution of surface regolith are limited. At 36,000 AD the last lakes are infilled assuming a global warming climate case. The landscape has come to a maturity stage.

Permafrost conditions will appear in the Forsmark area at around 17,000 AD in the early periglacial climate case. At that time, 44 of the 48 modelled lakes are already completely infilled and sedimentation processes will not be affected by the changed conditions. The four lakes that will be affected considerably by the cooler climate are both large and deep, and are situated far from the SFR repository. In the previous RLDM, a model version for permafrost conditions was constructed with a reduction of the sedimentation rate and the infilling of vegetation in lakes by 75% for all periods with permafrost. This was also applied in the current RLDM for the early periglacial climate case for the four remaining lakes at 17,000 AD. In the RLDM for the global warming and the Weichselian glacial cycle climate cases, no such adjustment was necessary, since permafrost appears first after all lakes are completely infilled.

The RLDM is used for hydrogeological modelling, in the radionuclide transport model for the biosphere and is also used to construct the landscape development model (LDM), which is a model at landscape level that describes the long-term development of the Forsmark landscape.

Sammanfattning

Slutförvaret för kortlivat radioaktivt avfall (SFR) är beläget i Forsmark i norra Uppland i omedelbar närhet till Forsmarks kärnkraftverk. SFR används för den slutgiltiga förvaringen av låg- och medelaktivt driftavfall från svenska kärntekniska anläggningar. SKB planerar att utöka SFR. Syftet med säkerhetsanalysen SR-PSU är att bedöma den långsiktiga radiologiska säkerheten för nuvarande SFR och det utökade SFR-förvaret.

Regoliten vid Forsmark har karakteriserats med en karta med regolitfördelning och en jorddjupsmodell (RDM) som visar stratigrafin och tjockleken för olika avlagringar. Med regolit avses alla icke konsoliderade avlagringar som överlagrar berggrunden, oavsett deras ursprung. Ytgeologi och regolitdjup är viktiga parametrar för hydrogeologisk och geokemisk modelleringen och för den allmäna förståelsen av området. Regolitkartan och jorddjupsmodellen för Forsmarksområdet beskriver dock enbart nutida förhållanden och tar inte hänsyn till förändringen i regolitfördelning och regolitdjup över tid. Därför konstruerades en regolit-sjöutvecklingsmodell (RLDM) som beskriver ytgeologin, stratigrafin och tjockleken av olika strata i Forsmarksområdet under en glacial cykel. Denna RLDM användes i säkerhetsanalysen för förbrukat kärnbränsle, SR-Site. I föreliggande studie konstruerades en ny RLDM genom att använda ny data och förbättrade beskrivningar av några av processerna som är inkluderade i den tidigare modelleringen. RLDM har applicerats på tre olika klimatfall, d.v.s. ett klimatfall med global uppvärmning, ett med tidiga periglaciala förhållanden och ett med en repetion av glaciationscykeln Weichsel.

RLDM består av två moduler: en marin modul som beskriver sedimentdynamiken (erosion och ackumulation) orsakad av vindgenererade vågor och en sjömodul som beskriver sjöigenväxningsprocessen under en interglacial. Den marina modulen startar när området nyligen har blivit isfritt och den lokala kvartägeologin enbart består av glaciala sediment (ytgeologi, stratigrafi och tjocklek omkring 8500 f kr). Dessa förhållanden är genererade från jorddjupsmodellen (RDM).

Mellan 8500 f Kr och 7000 e Kr (med 500 års tidssteg), läggs postglacial lera/silt eller glacial lera till eller tas bort i varje rastercell beroende på den sedimentdynamiska miljön för det specifika tidssteget. Dessa sedimentdata är erhållna från den sedimentdynamiska modellen. Postglaciala sediment eller glaciallera resuspenderas och transporteras ut ur en cell där erosion är den dominerande processen. I celler som domineras av ackumulation läggs mellan 0,06–0,39 m av postglacial lera/silt till för varje tidssteg. Nettosedimentationshastigheten varierar över tid och kalibreras med sedimentdynamiska modellen och uppmätta tjocklekar på postglacial lera från den maringeologiska undersökningen. För varje tidssteg i den marina modulen produceras rasterkartor för ytgeologi, tjocklek på glaciallera och postglacial lera och en höjdmodell.

När vattendjupet i de grunda havsvikarna inom utsträckningen för en framtida sjö minskar till 1.3 m på grund av landhöjningen börjar igenväxningen med vegetation. Denna process fortsätter till dess att sjön har bildats. Igenväxningen av sjöar modelleras med en ekvation för nettosedimentationshastighet och en ekvation för vegetationens kolonisering. Varje sjö modelleras separat. Den digitala höjdmodellen (DEM) och tjockleken av marin postglacial lera från tidssteget före det att sjön isoleras används som enda indata till modulen. Sjömodulen körs med 100 års tidssteg till dess att sjön är helt igenvuxen. Rasterkartor som visar ytgeologi, DEM, tjocklek på marin och limnisk postglacial lera (gyttjelera och lergyttja) och tjocklek på torv är utdata från sjömodulen för varje tidssteg.

I en efterbearbetning slås utdata från den marina modulen och sjömodulen ihop till rasterkartor för varje tidssteg (500 år). I en andra efterbearbetning läggs våtmarker som inte härrör från igenvuxna sjöar till. Dessa våtmarker är små igenfyllda lokala fördjupningar. Slutligen produceras så kallade hängande våtmarker från den digitala höjdmodellen för 40 000 e Kr och en ekvation för topografiskt fuktighetsindex (TWI).

Övergången från hav till land i Forsmarks modellområde är en process som tar ungefär 12 000 år. Till omkring 1000 f Kr täcker havet hela modellområdet och efter 10 000 e Kr består området av enbart limniska och terrestra ekosystem. Denna snabba övergång antyder att den glaciala isostatiska korrigeringen (GIA) är den mest betydelsefulla processen i landskapsutvecklingen. Områden med limniska ekosystem visar en stor tidsmässig variation eftersom många sjöar snabbt omvandlas till terrestra ekosystem.

Mängden marin postglacial lera varierade under de första 5 500 åren efter att isen retirerat från området på grund av skiftningar mellan ackumulation och transport och nådde ett minimum omkring 3000 f Kr. Efter det ökar volymen kontinuerligt. Lakustrin postglacial lera och torv ökar kontinuerligt från omkring 500 f Kr på grund av igenväxning av sjöar.

Det är stora variationer i fördelningen av ytligt belägen regolit från 8500 f Kr till omkring 7000 e Kr. Detta orsakas av erosion och ackumulation av postglacial lera under den här tiden. Från ungefär 7000 e Kr är förändringarna i fördelningen av ytligt belägen regolit begränsade. Vid 36 000 e Kr är den sista sjön igenvuxen förutsatt ett klimatfall med global uppvärmning. Landskapet har kommit till ett mognadsstadium.

Permafrostförhållanden kommer att förekomma i Forsmarksområdet omkring 17 000 e Kr för ett klimatfall med tidiga periglaciala förhållanden. Vid den tiden är redan 44 av 48 sjöar helt igenvuxna och sedimentationsprocesserna kommer inte att påverkas av de förändrade förhållandena. De enda fyra sjöarna som kommer att påverkas avsevärt av det kallare klimatet är både stora och djupa och belägna långt från SFR-förvaret. I föregående RLDM konstruerades en modelversion för permafrostförhållanden med en reduktion av sedimentationshastighet och igenväxning med vegetation i sjöar med 75 % för alla perioder med permafrost. Detta användes också i nuvarande RLDM för ett klimatfall med tidiga periglaciala förhållanden för de fyra återstående sjöarna vid 17 000 e Kr. I RLDM under antagande av ett klimatfall med global uppvärmning eller ett klimatfall där senaste glaciationscykeln, Weichsel, rekonstrueras var det inte nödvändigt att göra någon sådan korrigering eftersom permafrost förekommer först efter det att alla sjöar är helt igenvuxna.

RLDM används för hydrogeologisk modellering, i radionuklidtransportmodellen för biosfären och används också för att konstruera landskapsutvecklingsmodellen (LDM) som är en modell på landskapsnivå som beskriver den långsiktiga utvecklingen av landskapet i Forsmark.

Contents

1 Introduction

1.1 Background

The final repository for short-lived low- and intermediate-level radioactive waste, SFR 1, is located in Forsmark in the Östhammar municipality (Figure 1-1), in the immediate vicinity of the Forsmark nuclear power plant (Figure 1-2). The SFR 1 repository consists of a set of disposal chambers situated in rock at ca 60 m depth beneath the sea floor (Figure 1-3), and is built to receive and after closure serve as a passive repository for low- and intermediate-level short-lived radioactive waste. The radioactive waste stored in SFR includes operational waste from Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, as well as radioactive waste from other industries, research institutions and medical care.

In order to be able to also store decommissioning waste from the Swedish nuclear power plants in SFR, an extension of the repository, referred to as SFR 3, is planned (Figure 1-3). An SFR repository extension called SFR 2 was included in earlier plans for disposal of reactor core components and internal parts. However, according to present plans a separate repository (SFL) will be built for disposal of these types of waste.

As a part of the license application for the extension of SFR, the Swedish Nuclear Fuel and Waste Management Company (SKB) has performed the SR-PSU project. The objective of SR-PSU is to assess the long-term radiological safety of the entire future SFR repository, i.e. both the existing SFR 1 and the planned SFR 3. SR-PSU is reported in a series of SKB reports, which includes the SR-PSU main report (SKB 2014a), and a set of main references. These include, among others, the SR-PSU climate report (SKB 2014b) and main biosphere report (SKB 2014c). In addition to these main references, the safety assessment is based on a large number of background reports, of which the present report is one.

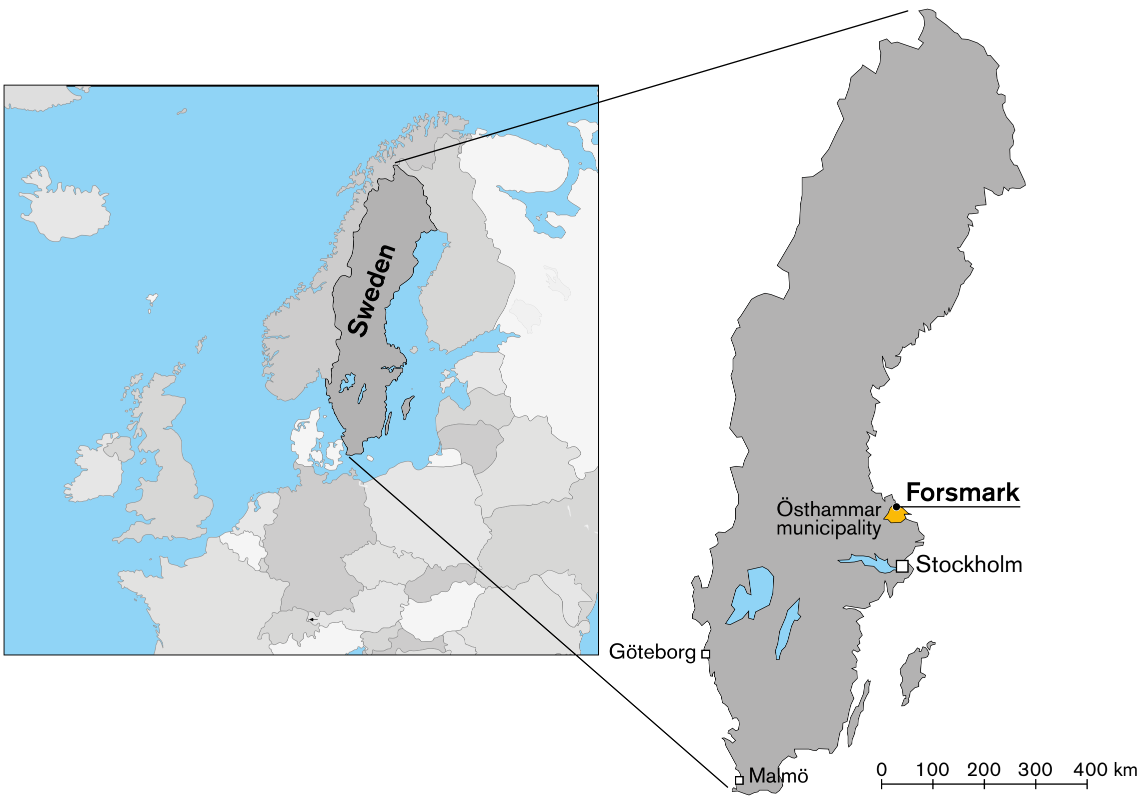

Figure 1-1. *Location of the Forsmark site in Sweden (right) and in context with the countries in Europe (left). The site is situated in the Östhammar municipality, which belongs to the County of Uppsala.*

***Figure 1-2.** The surface part of the SFR facility in the Forsmark harbour with the nuclear power plant in the background.*

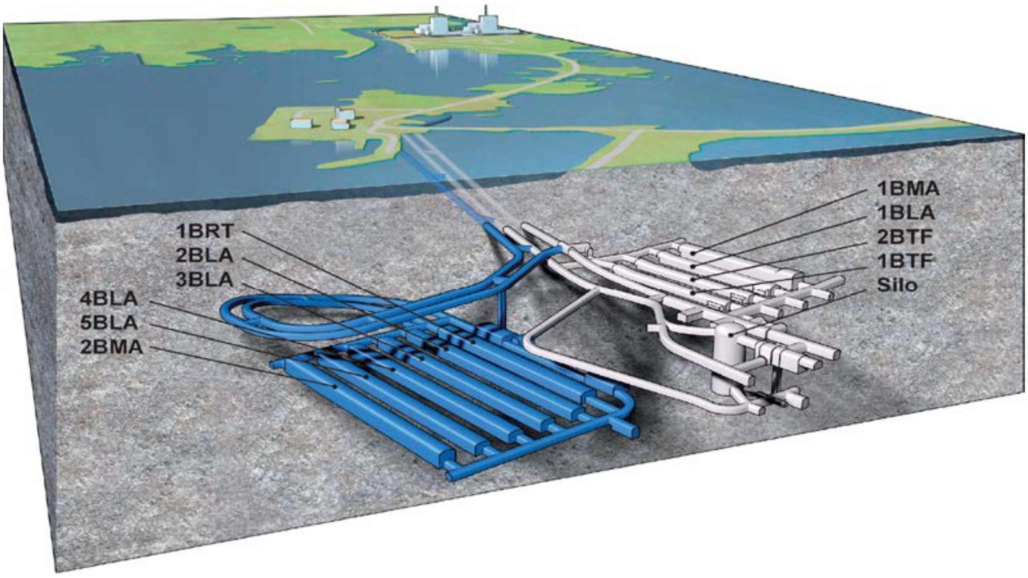

***Figure 1-3.** Schematic illustration of the SFR repository. The white part is the existing repository (SFR 1) and the blue part is the planned extension (SFR 3). The vaults in the figure are used/planned for different types of waste, e.g. the Silo and the BMA vaults for intermediate-level waste and the BLA vaults for low-level waste (SKB 2014a).*

The biosphere is a key part of the system considered in a safety assessment of a nuclear waste repository. This is where the consequences of potential future radionuclide releases from the repository arise, and hence near-surface radionuclide transport and dose calculations are performed within the framework of the biosphere assessment. This report belongs to the sub-project of SR-PSU called SR-PSU Biosphere. SR-PSU Biosphere mainly describes the information needed to calculate effects on humans and the environment in the case of a radionuclide release from SFR. The calculated effects are then used to show compliance with regulations related to future repository performance for time spans up to 100,000 years after closure. Because of the uncertainties associated with the prediction of future development of the site in this time frame, a number of calculation cases are analysed to describe a range of possible site developments.

The SR-PSU Biosphere project is divided into the following tasks:

1. Identification of features and processes of importance for modelling radionuclide dynamics in present and future ecosystems in Forsmark.
2. Description of the site and its future development with respect to the identified features and processes.
3. Identification and description of areas in the landscape that may be affected by releases of radionuclides from the existing repository and its planned extension.
4. Calculation of the radiological exposure to a representative individual of the most exposed group of humans in the future Forsmark landscape, and the radiological exposure to the environment.

The SR-PSU biosphere assessment builds on previous safety assessments for the existing and planned nuclear waste repositories in Sweden. This implies that SR-PSU is based on knowledge gathered from site data, site modelling and the previous safety assessments, together with modelling performed and data collected during the SR-PSU project. In particular, between 2002 and 2008 SKB performed site investigations for a repository for spent nuclear fuel in Forsmark. Data from these site investigations were used to produce a comprehensive, multi-disciplinary site description (SKB 2008). This description has been used as a basis for understanding and modelling the site and its development within the SR-PSU Biosphere project.

The relationships between the background biosphere reports and the main references are illustrated in Figure 1-4, where all reports are referred to by short descriptive names (rather than full titles) and their SKB report numbers. The present report, which is denoted by "RLDM report R-13-27" in the figure, provides input to the work presented in the Biosphere synthesis report (SKB 2014c), most notably the landscape development modelling, and to the hydrological modelling and the compilation of parameters used in the biosphere radionuclide transport and dose modelling. As explained further below, the main inputs to the work presented in this report are coming from the other reports in the same box in Figure 1-4, which describe the present topography and bathymetry (the DEM report) and regolith depth and stratigraphy (the RDM report). Note that the list of SR-Site reports is incomplete and does not include all background reports of particular importance to this work, such as the corresponding SR-Site report (Brydsten and Strömgren 2010).

1.2 Site overview

This section gives a brief summary of the site conditions. More detailed descriptions are available in, for instance, the above-mentioned site descriptive modelling report presenting the investigations for the spent fuel repository (SKB 2008) and reports focusing on surface and near-surface systems at Forsmark (Lindborg 2010, SKB 2014c).

Forsmark is located on the coast of the Baltic Sea (Bothnian Sea) in the County of Uppsala within the Municipality of Östhammar, about 120 km north of Stockholm, Sweden (Figure 1-1). The existing SFR and its planned extension are situated in the vicinity of the nuclear power plant in Forsmark (Figure 1-2). The surroundings show small-scale topographic variations of less than 20 metres. Post-glacial uplift, in combination with the flat topography, implies fast shoreline displacement. This has resulted in a young terrestrial system that contains a number of recently isolated lakes and wetlands, and new lakes are continuously formed as a consequence of the regressing shoreline (Figure 1-5).

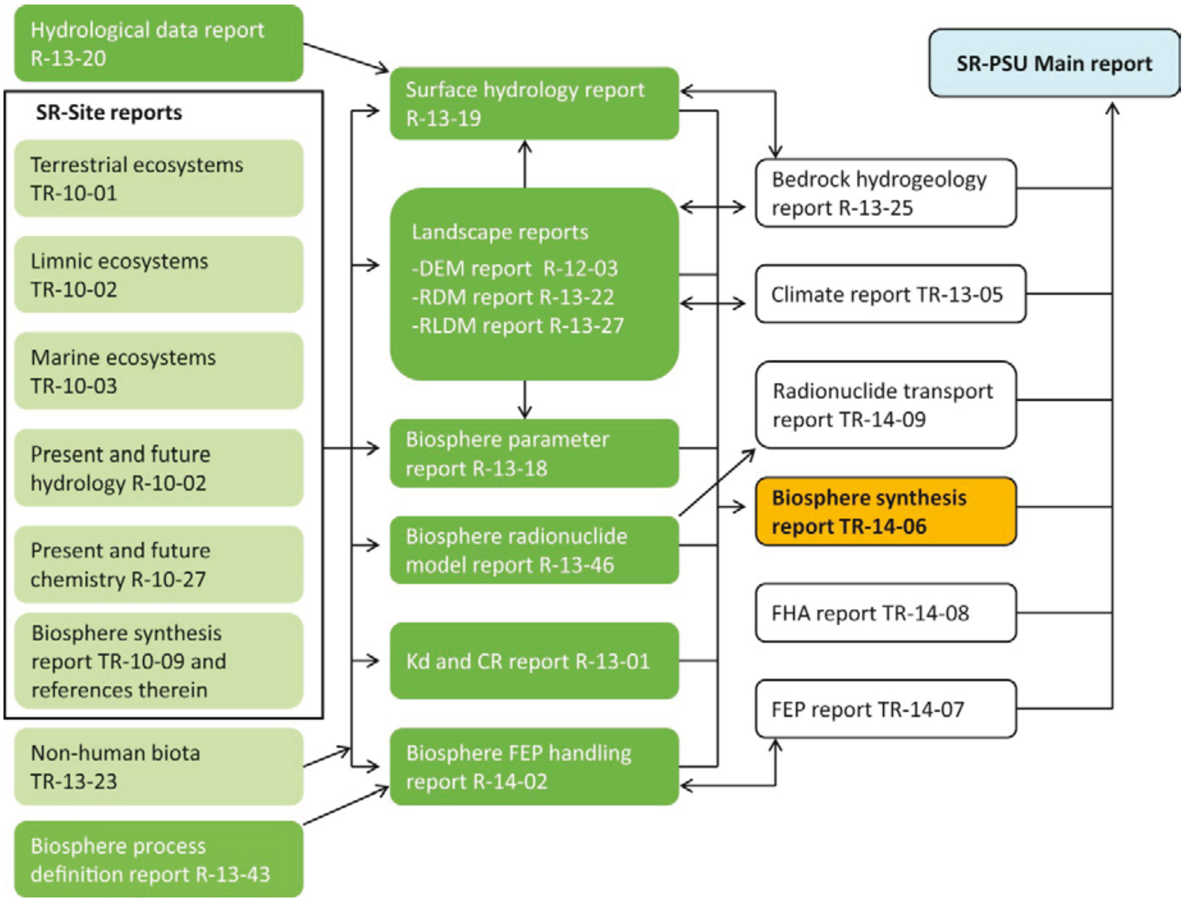

Figure 1-4. *Relationship between reports produced in the SR-PSU Biosphere project (dark green boxes, including the present report). The main biosphere report is marked in orange and bold. Supporting documents produced within other biosphere projects at SKB are shown as light green boxes, whereas other reports in the SR-PSU project are shown in white except the SR-PSU Main report, which is shown in blue.*

The coastline consists of sheltered shallow bays and small islands. The coast is exposed to 600 km of open sea towards the northeast, which creates fast water turnover and a long fetch for wave action (Brydsten 2009). Thus, the seabed in the coastal areas is dominated by erosion and transport bottoms with heterogeneous sediments, consisting mainly of sand and gravel with varying fractions of glacial clay. Most parts of the landscape are covered by a thin regolith layer, dominated by till (Hedenström and Sohlenius 2008). The mean regolith thickness in the Forsmark area is c 4 m in terrestrial areas and 8 m in marine areas (Sohlenius et al. 2013). The regolith thickness on the sea floor above the SFR repository is 1–4 m.

The underlying bedrock consists of crystalline rock that formed between 1,850 and 1,890 million years ago during the Svecokarelian orogeny, and it has been affected by both ductile and brittle deformation (Söderbäck 2008). The ductile deformation has resulted in large-scale ductile high-strain zones and the brittle deformation has given rise to large-scale fracture zones. Tectonic lenses, in which the bedrock is much less affected by ductile deformation, are enclosed between the ductile high strain zones.

1.3 Objectives and contents of the report

The objectives of this report are to describe the development of the SR-PSU regolith-lake development model (often abbreviated RLDM) and to present the resulting model. To this end, the development of the two main modules in the model, the lake and marine modules, and how they are merged into an integrated model are described in Chapter 2, which also describes the post-processing of GIS data and gives a brief comparison with the previous (SR-Site) RLDM. Chapter 3 presents the resulting model and Chapter 4 provides a discussion of the model, focusing on sensitivities and uncertainties.

Figure 1-5. *The coastal area in Forsmark, characterised by small altitudinal differences, shallow coastal bays and recently isolated small lakes and wetlands.*

2 Description of the modelling procedure

2.1 Overview of model and methodology

A coupled regolith-lake development model (RLDM) has been constructed for and is applied to the Forsmark area. The model area is the same as for the regolith depth model (RDM, Sohlenius et al. 2013), which describes the present regolith at Forsmark and hence is a basic input to the present work. The RLDM consists of two modules: *a marine module* that simulates sediment dynamics in the sea (erosion, transport and accumulation), including the periods with fresh water in the Baltic, and a *lake module* that simulates lake ontogeny, i.e. succession of the lakes (illustrated in Figure 2-1). In addition, a sub-model that predicts the generation of small wetlands that do not emanate from infilled lakes has been constructed.

Figure 2-2 describes the work process and the linkage between the underlying models used in the RLDM. The Baltic DEM, the Baltic wave model (Baltic wave) and the Forsmark wave model (Fm wave) are thoroughly described in Brydsten (2009). All other underlying models used in the RLDM are described further below in this report. The RLDM is also used to construct the SR-PSU landscape development model (LDM), which is a model at landscape level that describes the long-term development of the landscape. The work process and the results from the LDM are described in Chapter 5 of the Biosphere synthesis report (SKB 2014c).

The RLDM has been applied to three different climate cases, i.e. the global warming, the early periglacial, and the Weichselian glacial cycle climate cases. These three climate cases are defined and described in Chapter 4 of the SR-PSU Climate report (SKB 2014b). The global warming climate case represents temperate conditions until 50,000 AD followed by natural variability and cooling of the climate until 100,000 AD. The early periglacial climate case represents the same as the global warming case except for 3,000 years of periglacial conditions centred at 17,000 AD, and the Weichselian glacial cycle climate case represents a repetition of conditions reconstructed for the last glacial cycle.

Figure 2-1. *Illustration of ongoing lake succession in Forsmark. Lakes are transformed to terrestrial areas through ingrowth of vegetation in the advancing reed belts and sedimentation, which processes are modelled in the RLDM lake module.*

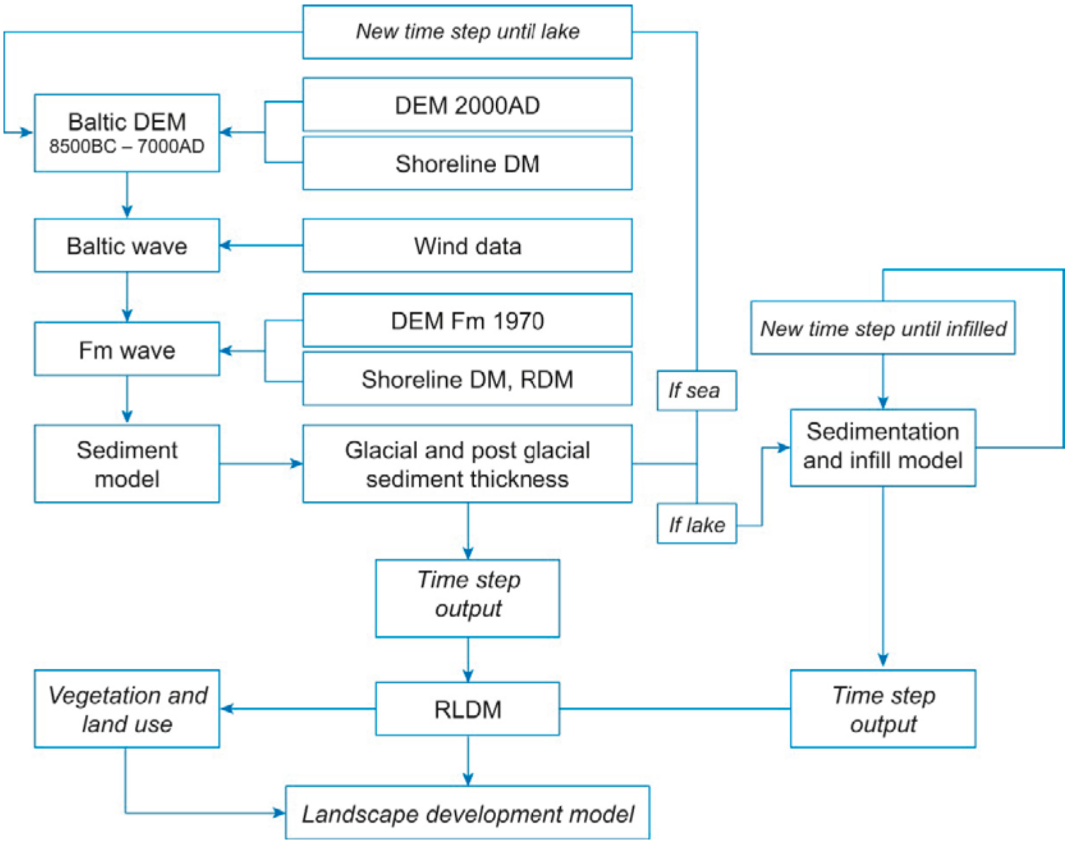

Figure 2-2. *A conceptual flow chart of the process of developing the coupled regolith-lake development model (RLDM). The flow chart describes the work process and the linkage between the underlying models used for each time step to build the landscape development model (LDM) for Forsmark ("Fm" in the figure). DEM stands for digital elevation model, RDM for regolith depth model and Shoreline DM for shoreline displacement model. The marine module runs independently from the lake module and the lakes are modelled separately depending on their appearance in time. The figure is modified from Lindborg et al. (2013).*

2.2 Definitions, inputs and comparison with previous model

In line with other SKB publications (e.g. Hedenström and Sohlenius 2008), all unconsolidated deposits overlying the bedrock are collectively denominated regolith, regardless of their origin. This includes glacial and postglacial minerogenic (e.g. till and clay), organogenic deposits (e.g. peat and gyttja) as well as artificial filling material.

The regolith at the Forsmark site has been characterised using both a map of regolith distribution (Hedenström and Sohlenius 2008) and a regolith depth model (RDM) that shows the stratigraphy and thickness of different deposits in a sequence of layers on the bedrock surface (Sohlenius et al. 2013). The surface geology and regolith depth are important parameters for hydrogeological and geochemical modelling and for the overall understanding of the area. However, the map of regolith and the RDM for the Forsmark area do not cover the temporal change of the regolith and since the safety assessment analyses should consider circumstances during a long period there is a need for such information.

Brydsten and Strömgren (2010) constructed a regolith-lake development model (RLDM) that described the surface geology, stratigraphy and thickness of different strata and the ontogeny of lakes, i.e. succession of lakes, during a glacial cycle in the Forsmark area. This RLDM was used in the safety assessment for spent nuclear waste, SR-Site. For the SR-PSU assessment, a new RLDM is constructed by using new data and improved descriptions of some of the processes included in the previous modelling. Some of the layers included in the RDM are used in the construction of the RLDM and for that reason the extent and resolution (20 m cell size) of the RDM are also used in the RLDM. The model area (Figure 2-3) extends over almost 300 km^2 and at present includes marine areas, terrestrial areas and lakes.

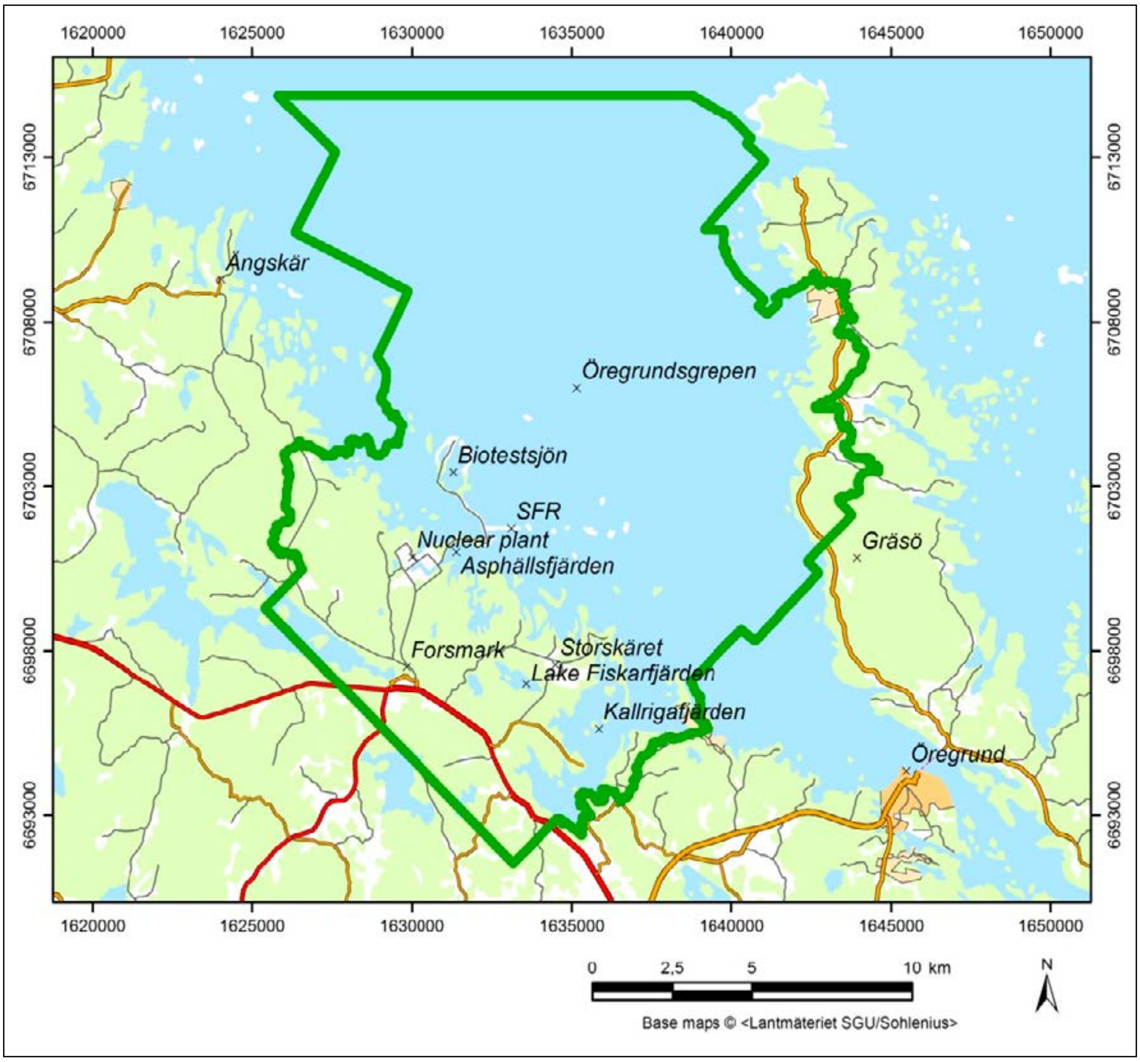

Figure 2-3. *The RLDM model area extends over almost 300 km² and at present includes marine areas, terrestrial areas and lakes. This model area was used also in the regolith depth model (RDM) (Sohlenius et al. 2013).*

The RLDM is divided into two modules: a marine module that describes the sediment dynamics (erosion and accumulation) caused by wind waves in 500-year time steps and a lake module that describes the lake infilling processes. Fine-grained unconsolidated materials such as clay and silt are important in safety assessments; their small grains can bind larger amounts of radionuclides than regolith consisting of coarser particles. Thick layers of clay can be found in deep marine basins that later become lakes when raised into a supra-marine position. The dynamics of especially clay and silt particles are described in the RLDM. The infilling of lakes is modelled with an equation for the net sedimentation rate and an equation for vegetation colonisation (Brydsten 2006a). Each lake is modelled separately. The lake module runs in 100-year time steps until the lake is completely infilled.

The RLDM is used for hydrogeological modelling (Werner et al. 2014), in the radionuclide transport model for the biosphere (Saetre et al. 2013) and is also used to construct the landscape development model (LDM, see the SKB 2014c), which is a model at landscape level that describes different variants of possible long-term landscape development at Forsmark. Also the modelling of bedrock hydrogeology (Odén et al. 2014) uses output from the RLDM to construct models representing times in the future.

This new version of the RLDM is improved in several respects compared to the previous RLDM (Brydsten and Strömgren 2010). The main developments are in some cases due to improved input data and in other cases to changes in the underlying assumptions or the modelling procedure itself, and can be summarised as follows.

- The new digital elevation model (DEM) presented in Strömgren and Brydsten (2013) is used as input.
- The new regolith depth and stratigraphy model (RDM) in Sohlenius et al. (2013) is used as input.
- The resolution of the wave model within the Forsmark area is enhanced and is now the same as for all other models.
- Erosion of glacial clay is now considered in the model.
- A new algorithm for infilling of vegetation in shallow sea bays is used.
- Consequences of erodible material at the lake thresholds were taken into account.

However, there is also one simplification in this version of the RLDM compared to the previous one. In the previous RLDM several wind speeds were used in the wave model, whereas in the current RLDM only one wind speed, 20 m s^{-1}, is used. A sensitivity analysis described in Brydsten and Strömgren (2010) shows a small difference in the results generated by the wave model using one wind speed of 20 m s^{-1} compared to that using several different wind speeds. Running the wave models is highly time-consuming and by using only one wind speed the simulation time was reduced significantly.

2.3 The marine module

The marine module is written in Visual Basic. The whole model area and all time steps are run in a single sequence. Pre-processing and post-processing are done in GIS-programs. Figure 2-4 shows the outline of the RLDM marine module.

The module requires input from the RDM (Sohlenius et al. 2013), the shoreline displacement model (Lindborg 2010) and the sediment dynamic model (Brydsten 2009). A marine regolith map, marine regolith depths and a 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 raster layers produced from post-processing of the results from the marine and lake modules to form continuous raster layers for the whole model area. Finally, parameters for the radionuclide transport model (Saetre et al. 2013) for the biosphere are calculated from the merged raster layers. These parameters are described in Grolander (2013).

2.3.1 Recalibration of the sediment dynamic module

The sediment dynamic module is thoroughly described in Brydsten (2009). However, in the present version of the RLDM erosion of glacial clay is modelled, which was not the case in the previous version of the RLDM. Consequently, a recalibration of the sediment dynamic module was necessary. A description of this procedure follows.

During the calibration the results for 2000 AD from the sediment dynamic module were compared with the map of regolith presented in Hedenström and Sohlenius (2008). The sediment dynamic module gives U_{max} (the highest orbital speed at the sediment surface in m s^{-1}). The aim of the calibration was to obtain the critical U_{max} for accumulation of postglacial fine-grained sediment (clay or silt), the critical U_{max} for erosion of the same material and the critical U_{max} for erosion of glacial clay. Since glacial clay is more consolidated than the postglacial fine-grained sediment, a higher critical U_{max} for erosion of glacial clay was expected.

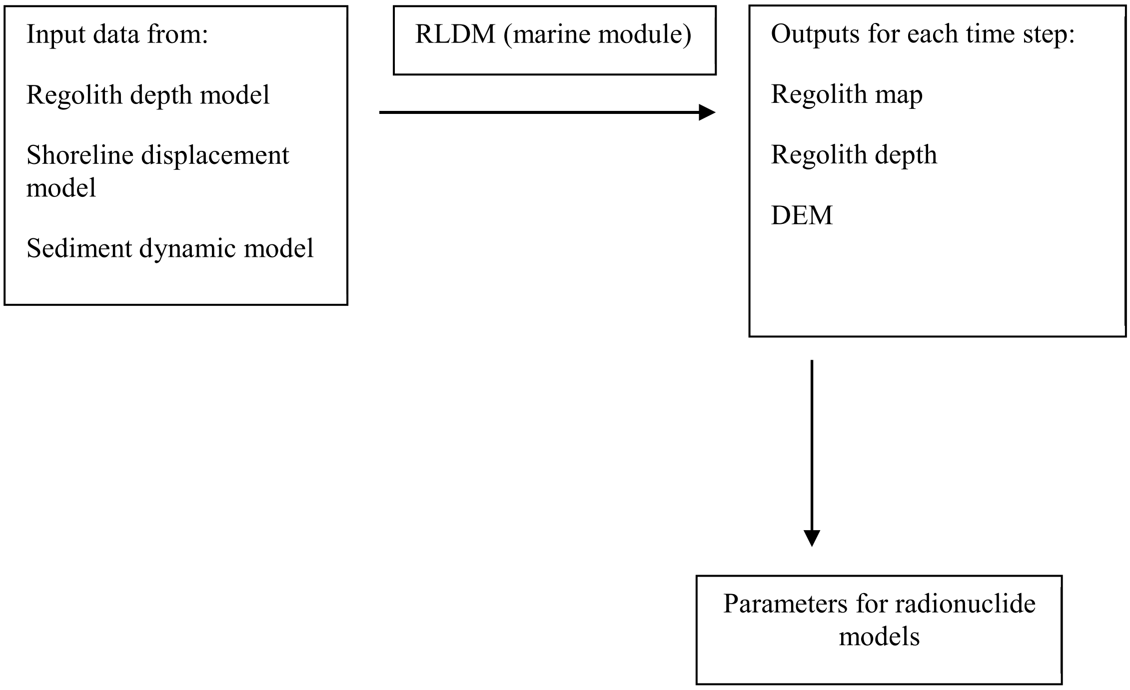

Figure 2-4. *Outline of the RLDM marine module. Inputs are from the regolith depth model (RDM), the shoreline displacement model and the sediment dynamics model. Outputs are a surface geology map, a regolith depth model and a digital elevation model for each time step (500-year time steps during the period 8500 BC–7000 AD). The raster results are discretised into parameters (e.g. mean values for basin areas).*

Postglacial clay and silt from the map of regolith (Hedenström and Sohlenius 2008) were used for calibration of the critical U_{max} for accumulation of postglacial fine-grained sediment. However, erosion may be ongoing on some of these surfaces. One indication of ongoing erosion is a thin layers of coarser sediment (sand) superimposing postglacial fine-grained sediment. Since the coarser sediments are much less important for the radionuclide model, these surfaces have been excluded from this part of the calibration.

The border between glacial clay and postglacial fine-grained sediment on the map of regolith (Hedenström and Sohlenius 2008) was used for calibration of critical U_{max} generating erosion of postglacial fine-grained sediment and the border between glacial clay and silt was used for erosion of glacial clay.

The results of the calibration are summarised as follows (U_{max} in m s^{-1}):

i) If $U_{max} \leq 0.53$ accumulation of postglacial fine-grained sediment occurs,

ii) If $U_{max} > 0.53$ erosion of postglacial fine-grained sediment occurs,

iii) If $U_{max} > 1.09$ erosion of glacial clay occurs.

2.3.2 Method for calculation of erosion of postglacial fine-grained sediment and glacial clay

The data on wave height and wave period for the considered time step are read by the sediment dynamic module and U_{max} is calculated for all cells classified as marine within the model area. The module runs through all marine cells and the following calculations are performed for every cell:

i) If $U_{max} \leq 0.53$ postglacial clay/silt with different thickness for different time steps is accumulated (see Chapter 2 in Brydsten and Strömgren 2010). The arrays for the thickness of the postglacial sediments and water depth are updated.

ii) If $U_{max} > 0.53$ and the thickness of the postglacial sediments > 0, then 1 cm of the sediment is eroded. The arrays for the thickness of the postglacial sediments and water depth are updated. U_{max} is calculated again with 1 cm deeper water. This procedure is repeated until $U_{max} < 0.53$ or the thickness of the postglacial sediment = 0. If all postglacial sediment is eroded, the thickness of the glacial clay > 0 and $U_{max} > 1.09$, the erosion continues as described above but with a critical value of 1.09 until the thickness of the glacial clay = 0 or $U_{max} < 1.09$. The arrays for the thickness of the postglacial and glacial sediments and water depth are updated.

iii) When all marine cells are processed, the thickness of the glacial and postglacial sediments and the water depth are written to raster files in ASCII-format for subsequent analysis in GIS. The whole procedure is repeated for the following times steps until the module has run through all time steps.

2.3.3 Data input to the marine module

The data input and the calculation scheme for the marine module are described in Figure 2-5. Regolith map, DEM, marine bottom type, relative shore level and sedimentation rate are the data inputs to the module. The marine module runs between 8500 BC and 7000 AD for each 500-year time step.

Regolith at the time for deglaciation 8500 BC

After the Weichselian ice sheet receded from the Forsmark area (approximately 8500 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 is wave washed, and some of the glacial clay is resuspended and redeposited at new sites as postglacial clay.

To construct a map of the surface geology in the Forsmark area at 8500 BC, the regolith depth model (RDM) (Sohlenius et al. 2013) was used. The RDM is a model in raster format (20 m cell size) with six regolith layers where each layer is presented as the thickness of that layer (Figure 2-6). The uppermost layer, Z2, represents peat, followed by the next layer, Z3 (a, b and c), representing sand/gravel, glacio-fluvial 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 fractures compared to the deeper rock. All layers except Z6 may have a thickness of zero.

From the thickness of the regolith layers described above, it is possible to derive (i) exposed bedrock areas, (ii) areas with till on top of bedrock but not overlaying postglacial clay, (iii) areas with bedrock overlaid by till that is overlaid by glacial clay, and (iv) areas with glaciofluvial deposits. In the previous RLDM (Brydsten and Strömgren 2010) erosion of glacial clay was not treated and it was assumed that till can be wave washed but not totally removed. According to this argument, the 8500 BC RDM should be similar to the 2000 AD RDM with all postglacial layers removed.

However, erosion of glacial clay is included in this version of the RLDM. Hence, an additional modification of the 2000 AD RDM (Sohlenius et al. 2013) was necessary to use it as the regolith map for 8500 BC. Data from Elhammer and Sandkvist (2003) indicate that there should be a glacial clay thickness of at least 2 m everywhere in the area 8500 BC. Based on this information, glacial clay was filled up to 2 m thickness on all surfaces in the 8500 BC RDM with a glacial clay thickness less than 2 m.

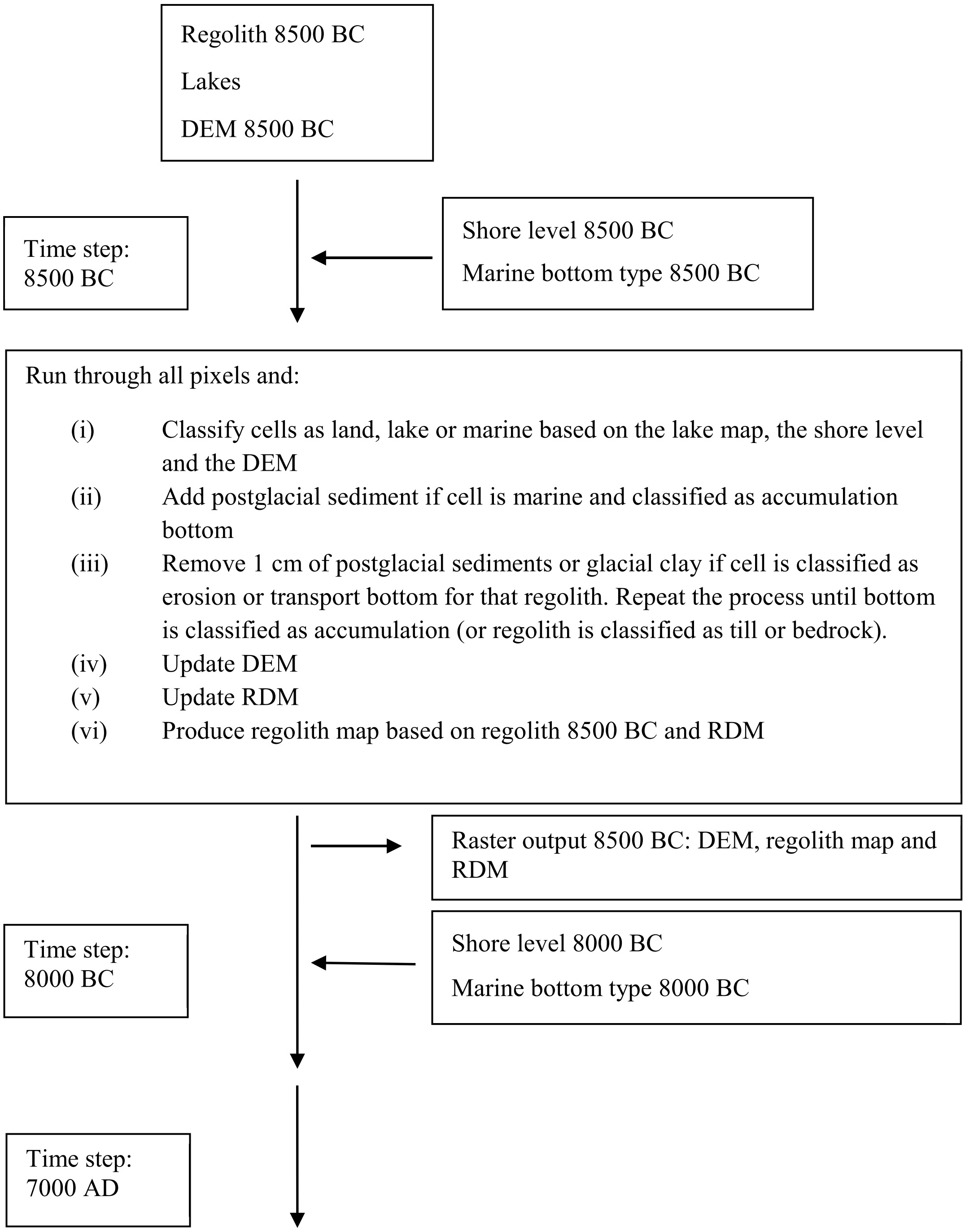

Figure 2-5. *Data input and calculation scheme for the marine module. The simulation starts at 8500 BC, just after the area is deglaciated, and stops at 7000 AD.*

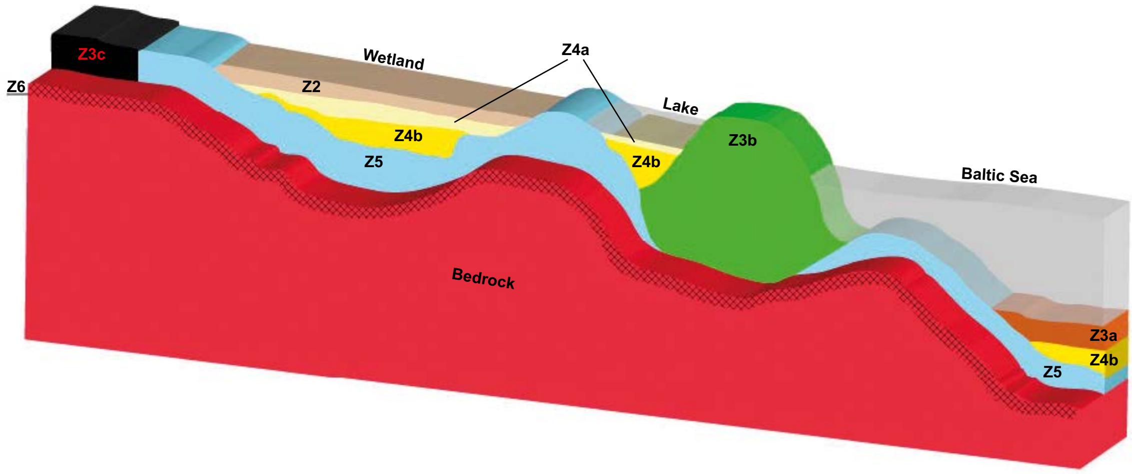

Figure 2-6. Conceptual model for the distribution of the generalised layers in the RDM (from Sohlenius et al. 2013).

A digital elevation model (DEM) for 8500 BC

The DEM for 8500 BC is constructed as the RDM for 2000 AD (Sohlenius et al. 2013) when all postglacial deposits have been removed, glacial clay has been added as described above and finally an adjustment for the shoreline displacement at 8500 BC has been performed. Artificial filling, which is material deposited by man, was not removed from the 2000 AD RDM. According to Sohlenius et al. (2013) there are uncertainties regarding the depth of this material, what this material rests upon and the properties of artificial fill which yet not have been studied. However, direct observations suggest that the material mostly consists of gravel, stones and boulders. Due to these uncertainties artificial fill was not removed from the 2000 AD RDM.

The extents of accumulation, transport and erosion bottoms at each time step

The extents of accumulation, transport and erosion bottoms at each time step are taken from the sediment dynamic model (Brydsten 2009).

Relative shore levels (RSL) at each time step

The global warming, early periglacial and Weichselian glacial cycle climate cases are defined and described in the SR-PSU Climate report (SKB 2014b). The same shoreline displacement curve is used for the global warming and early periglacial climate cases and there is a different shoreline displacement used for the Weichselian glacial cycle climate case from 12,000 AD compared to the other two climate cases. All shoreline displacement values used in the RLDM are listed in Appendix 1.

Sedimentation rates at each time step

The amount of suspended particles in the seawater varies greatly over time and therefore also the sedimentation rate. Consequently, a calculation of the sedimentation rate for every time step was necessary. 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 seaward transport. During this transport, the material is sorted so that the sand particles stay close to the river mouth and finer particles (silt and clay) settle in positions further distal to the river mouth. However, Brydsten and Strömgren (2010) shows that the fluvial input of particles in the Forsmark area 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 shoreline 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 total areas of postglacial sediment and unwashed till that are positioned above the wave base for each time step. This measure was used in the marine module calibration for the previous RLDM (Brydsten and Strömgren 2010). This calibration showed a very good agreement between modelled and measured sediment thickness and was also used in the present RLDM. The calculated net sedimentation for all time steps varies between 0.06–0.39 m.

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, their original extents have 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 present-day DEM (Strömgren and Brydsten 2013). The DEM is filled, which means that 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 (extent, area, mean depth, maximum depth, and more). The final map with existing and future lakes consists of 48 lakes (cf. Figure 2-9 in Section 2.5).

2.3.4 Extension of the modelled marine phase

Between 8500 BC and 7000 AD the marine module simulates erosion or accumulation depending on the sediment dynamic environment at that time. In a cell where erosion is the predominant process, postglacial sediments or glacial clay are resuspended and transported out of the cell. Cells dominated by accumulation get a contribution of 0.06–0.39 m of postglacial clay/silt in each time step. The regolith depth, the map of regolith and the DEM are updated based on the thickness of the postglacial clay/silt layer. This is ongoing for each time step until a cell is classified as a lake. Thereafter the cells are not handled in the marine module but in the lake module.

It is not possible to extend the simulated period beyond 7000 AD since no waves generated by the wave model can reach the narrow bay that is the only remaining part of the sea in the model area. In the previous RLDM (Brydsten and Strömgren 2010), the period modelled by the marine module was prolonged until the whole model area was land by assuming that only accumulation occurred during this time interval. However, in this version no such correction was done and the lake module was used after 7000 AD. Consequently, the marine part of postglacial clay is somewhat underestimated in areas with sea bottom after 7000 AD.

2.3.5 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 lake isolation are filled with sediments. The sediment thickness is calculated as the sediment rate for that time step multiplied by the number of years between the time step and the isolation year.

The colonisation of reed into the shallow sea bays is calculated with an algorithm described in Section 2.4.1, using 1.3 m depth as the limit for colonisation. However, the colonisation of the shallow sea bays by reed is only calculated within the extension of the prospective lakes.

2.4 The lake module

2.4.1 Infilling

The lake basin infilling processes are categorised into two parallel processes: sedimentation of minerogenic material (clay and/or silt) and infilling by growth of vegetation.

A statistical analysis of sediment cores from six lakes in the Forsmark area (Hedenström 2004) shows that the sedimentation rate depends on the water volume. This can be expressed as follows:

Sedimentation rate = 49.967 + 102.786 × Water volume (Equation 2-1)

(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 infilling processes.

In the previous study for SR-Site (Brydsten and Strömgren 2010), the same algorithm for infilling by growth of vegetation was used for lakes and shallow sea bays. However, a validation of the results from the model shows that the calculated infilling by vegetation in shallow sea bays is too fast. For that reason, a separate algorithm was developed for shallow sea bays in order to get the correct starting conditions for the lake module. The new infilling algorithm is based on data from the mapping of vegetation in lakes (Brunberg et al. 2004) and the mapping of reed distribution in shallow sea bays in the Forsmark area (Strömgren and Lindgren 2011).

The four youngest lakes, Fiskarfjärden, Bredviken, Norra Bassängen and Bolundsfjärden (see Brunberg et al. 2004) were chosen, since the infilling of vegetation in the lake phase is lower in these lakes compared to the older lakes in the area. Initially, the ages of these lakes were calculated from their known altitudes (Brunberg et al. 2004) and the sea shoreline displacement curve for the global warming climate case (SKB 2014b). Next, the infill area during the lake phase was calculated from the lake age using the algorithm for the lake phase (Brydsten and Strömgren 2010). The remaining vegetation area is assumed to have arisen during the time when the prospective lake was a shallow sea bay.

The study of existing lakes in the Forsmark area (Brunberg et al. 2004) shows that the vegetation usually reaches a water depth of 2 m but never deeper. However, Strömgren and Lindgren (2011) showed that reed rarely reaches this depth in shallow sea bays and that the median water depth value for colonisation of reed is only approximately 1.3 m. Consequently, the infilling of vegetation in the prospective lakes is assumed to be initiated when the water depth in the shallowest part of the lake is 1.3 m. The beginning of this process and the time interval for the shallow sea bay stage was calculated from the DEM (Strömgren and Brydsten 2013) and the sea shoreline displacement curve for the global warming climate case (SKB 2014b).

The method to calculate infilling in the sea bays is adapted based on the algorithm for infilling of lakes (Brydsten and Strömgren 2010), i.e. emanates from the original area of the lake:

Growth = constant + factor × the original area of the lake

The calibration was performed in Microsoft Excel's "Solver" by using an unlikely high value on the constant. Once the equation was solved, the error was noted. In the next step, the constant was halved and the equation was solved in Excel once again. If the error was reduced, the constant was halved and if the error increased the mean value of the previously calculated constants was used. This procedure was repeated in an iterative process until the error was minimised.

The result of the calibration was:

Growth = 100 + 8.3/10000 × the original area of the lake (Equation 2-2)

in which growth is expressed in m^2 $year^{-1}$ and the original area in m^2.

Infilling of lakes with vegetation starts by colonisation of littoral plants, followed by propagation of bryophytes when the resulting wetland becomes a bog. The colonisation 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 produce 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 extents in 25 lakes in the Forsmark area (Brunberg et al. 2004) show that the "rate of infill" in lakes depends on lake area. This can be expressed as follows:

"rate of infill" = 36.372 + 1.169 × 10^{-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 where the area of the bottom shallower than two meters is not large enough, which means that the depth limits colonisation.

The consistency in using different algorithms for infilling of vegetation in the shallow sea bay phase and the lake phase is shown for Lake Bolundsfjärden in Figure 2-7. In Figure 2-7A, the algorithm for infilling of vegetation in the lake phase is also used for the shallow sea bay phase and in Figure 2-7B the new algorithm for the shallow sea bay phase is used instead. As seen in the picture, the agreement between the modelled and mapped lake surface is significantly better using the new algorithm for the shallow sea bay phase. For further description of calibration and validation of the lake module, see Brydsten (2004).

2.4.2 Post-processing of lakes

In the early periglacial climate case, permafrost will occur around 17,000 AD (SKB 2014b). At that time, 44 of 48 modelled lakes are already completely infilled and consequently the sedimentation processes will not be affected by the changed conditions for most lakes. The only four lakes that will be affected considerably by the cooler climate are both large and deep and are situated far from the SFR repository.

Brydsten and Strömgren (2010) constructed an RLDM version for permafrost conditions with a reduction of the sedimentation rate and the infilling of vegetation in lakes by 75% for all periods with permafrost. This was also applied in the current RLDM for the early periglacial climate case for the four remaining lakes at 17,000 AD. In the RLDM for the Weichselian glacial cycle and global warming climate cases no such adjustment was necessary since permafrost will appear after all lakes are completely infilled (SKB 2014b).

2.4.3 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 2-8). The DEM output from the marine module is produced in raster format using 20 m cell size, and consequently this resolution was also used for the lake module. The initial lake DEM was calculated as the previous DEM (Strömgren and Brydsten 2013) minus the lake threshold value.

2.5 Modelled lakes

Shorelines of existing lakes were mapped with GPS and the bathymetry was measured with echo soundings (Brunberg et al. 2004). The extensions and bathymetry of future lakes are modelled with the GIS fill tool (Brydsten 2006a) using the present-day DEM (Strömgren and Brydsten 2013) as input. The GIS-based method gives a large number of future lakes, most of them very small and shallow. In order to limit the number of future lakes in the model, only future lakes with volumes larger than the smallest included existing lake (Labboträsket) were chosen.

By using the present-day DEM to calculate the properties of the future lakes, 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. In this version of the RLDM, consequences of erodible material at the lake thresholds are taken into account by lowering the thresholds to the level of the till, which will only to a minor degree be subjected to erosion. In the previous RLDM, no such adjustment was done.

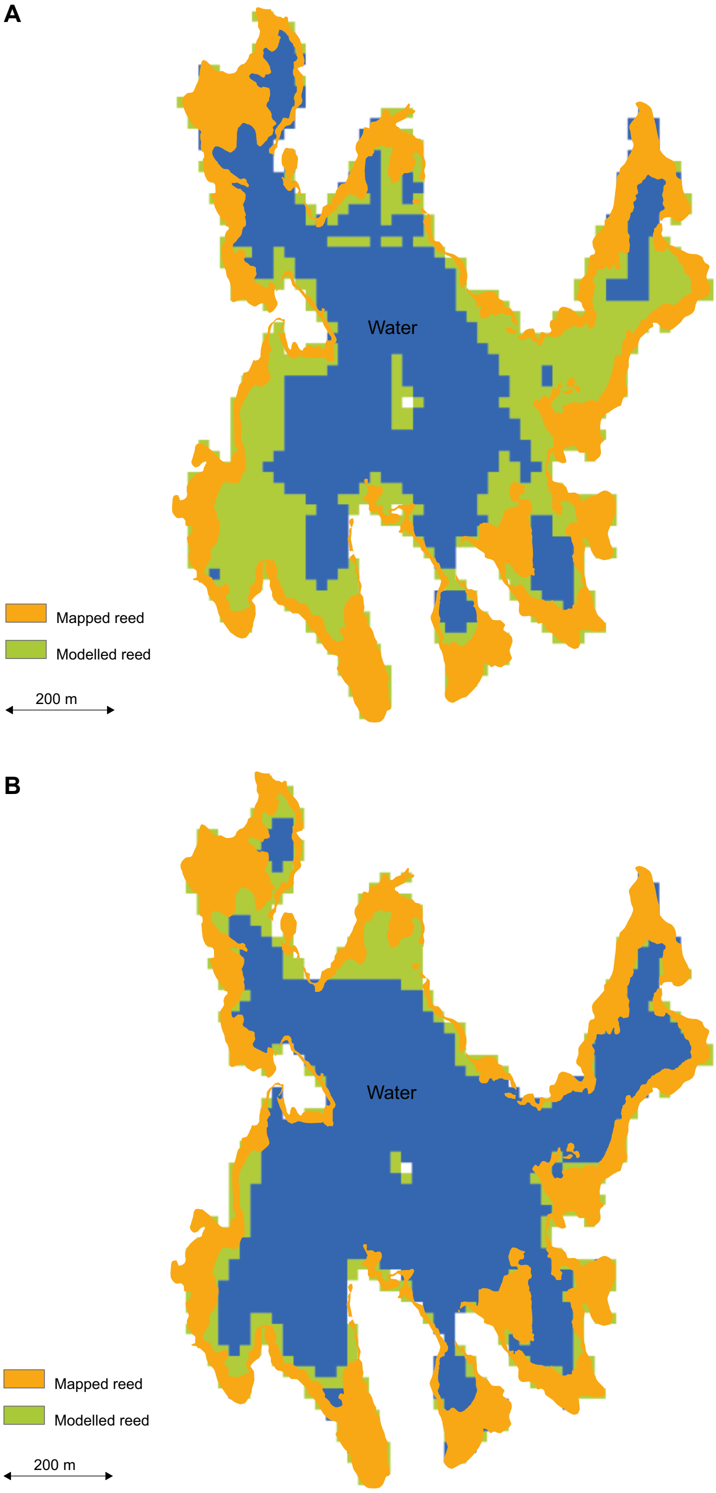

Figure 2-7. *The difference between modelled and mapped reed in Lake Bolundsfjärden at 2000 AD. A) The algorithm for the infilling of vegetation in the lake phase is also used in the shallow sea bay phase (used in the previous RLDM, see Brydsten and Strömgren (2010). B) A new algorithm is used for the infilling of vegetation in the shallow sea bay phase (used in this version of the RLDM). The agreement between modelled and mapped lake surface is better in B.*

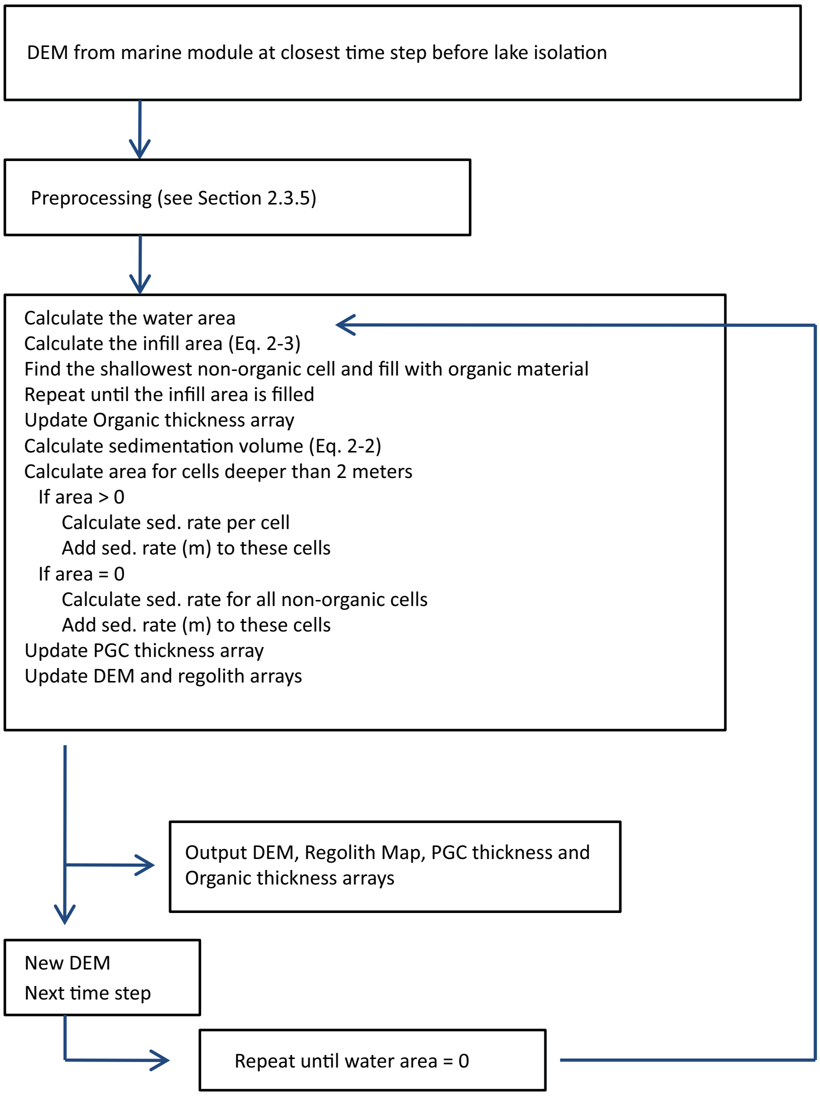

Figure 2-8. *Calculation scheme for the lake module. PGC stands for postglacial clay.*

The type of regolith at each lake threshold was checked against the results from the marine module in the RLDM for the time step before the lake was formed. This test showed that the thresholds of lakes 105 and 114 consisted of erodible material. Consequently, the levels of these lake thresholds were adjusted to the upper surface of the till in the RDM (Sohlenius et al. 2013). Finally, the extents and bathymetries of these lakes were adjusted in the present-day DEM (Strömgren and Brydsten 2013) using the new levels of the lake thresholds. The result of the adjustment of the threshold levels is somewhat shallower and smaller lakes. The number of lakes being modelled is 48, of which 39 are future lakes and 9 existing lakes (Figure 2-9). The physical characteristics of these lakes are summarised in Appendix 2.

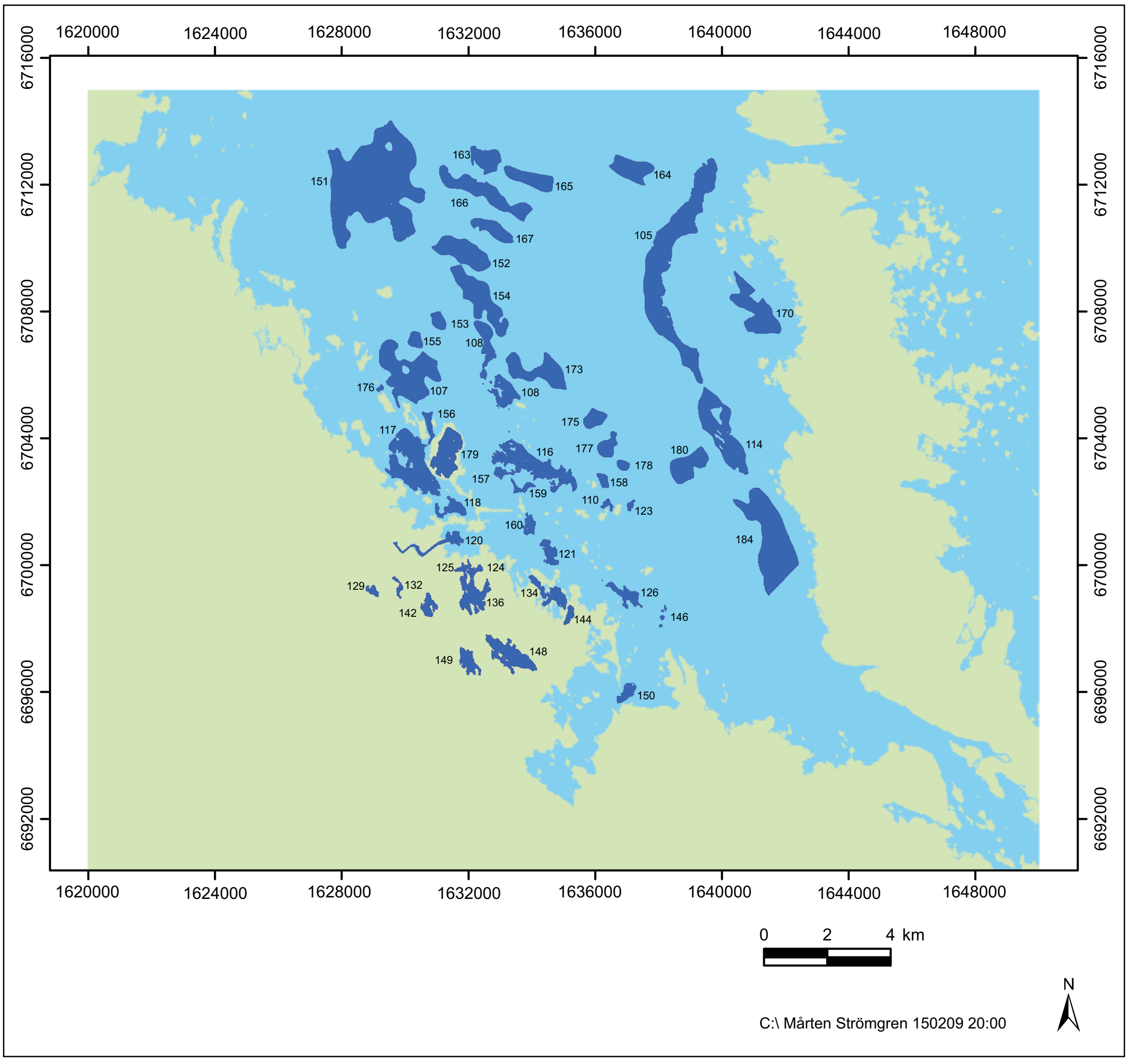

Figure 2-9. *Existing and future lakes as given by output from the RLDM. The numbers are the lake identification numbers used in all modelling (e.g. Appendix 2).*

2.6 Merging data from the two modules

As mentioned earlier, the marine module is processed in one single run and results in four raster data sets for each time step (DEM, surface regolith, and thickness of glacial clay and postglacial clay). The lakes are processed one by one and the resulting data sets are merged to obtain combined single raster data sets for each time step for the modelled lakes. This was done manually in the ArcGIS program. In this process, the thickness of the postglacial clay is split into a marine and a lacustrine stratum. A fifth raster data set referring to the thickness of fen peat is also produced. The marine module stops at 7000 AD and the result is used for all later time steps.

2.7 Post-processing the GIS datasets

2.7.1 Infilling of small lakes

Since only the largest lakes are processed in the lake module, the DEM for each time step contains small local depressions that are the non-processed lakes. These small lakes are assumed to be filled up to the threshold with peat during one time step (500 years). This post-processing is performed using the GIS function “fill” on the DEM for 40,000 AD from the merged data sets from the marine and lake modules described above. At 40,000 AD all lakes processed in the lake module are infilled and due to the land upheaval no part of the model area is situated below sea level. The fill function gives the thickness of peat at all cells in the model area in 40,000 AD. To identify peat to be included in the RLDM for each time step, a land/sea layer for each time step is used, i.e. only cells situated on land are included. The land/sea layers are produced using the DEM for each time step. Since this can be done with different methods with different outcomes, the method used here is described below.

2.7.2 Classification of land and sea

In order to determine which surfaces are land or sea, the DEM for each time step is reclassified into two classes – positive and negative values. This new layer is converted into shape file format keeping the raster structure intact. The largest continuous surface with negative values in the Shape file is classified as sea and the rest of the model area as terrestrial. With this method, the lake bottoms lower than the sea level are classified as terrestrial, but also small surfaces adjacent to the surface classified as sea where the contact between the two are cell-corner against cell-corner.

Some of these small surfaces are probably sea bays and some are small lakes, but it is difficult with the information from the DEM only to make a correct classification. Using this method, the sea is set to its minimum extent; since the same method is used in the sediment dynamic model, there is less risk of getting confusing results in near-shore cells. The layers with thickness of "additional peat" were used to update the peat thickness layers for each time step.

2.7.3 Hanging wetlands

A final post-processing step deals with wetlands not emanating from infilled lakes. These so-called hanging wetlands are modelled with the Topographical Wetness Index (TWI) calculated in GIS using 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 (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 are not lakes are classified as hanging wetlands.

Peat layers in hanging wetlands are generally thin. The thickness is therefore approximated to zero and consequently this peat is not included in the peat thickness layers for each time step in the RLDM. Instead, the TWI-modelled peat is delivered in one separate layer and is used in the landscape development model (LDM, see SKB 2014c).

2.7.4 Stream locations

The locations of streams were modelled by using the present-day DEM (Strömgren and Brydsten 2013) and do not change in time. No erosion adjustment between time steps was taken into account. Using the GIS-program ArcView Hydrology extension, the DEM was "filled", which means that all negative features were filled up to their threshold levels before the actual modelling started. Streams passing through lake areas were adjusted by connecting the small ponds that exist in the later stages of the lake infilling process. Upstream of the highest situated lakes, the streams were removed when they became too small to have flow all year around. This was based on the Hydrology extension flow accumulation value being < 7,000, which corresponds to a mean runoff 0.02 $m^3 s^{-1}$.

Basins for all 48 lakes shown in Figure 2-9 are established by mapping the water divides on the parts that are on land (Brunberg et al. 2004) and modelled with GIS using the present-day DEM (Strömgren and Brydsten 2013) for the water divides that presently are in the sea. The extensions of these basins are shown in Figure 2-10. Each basin holds a single lake (existing or future) and the basin is defined as the catchment of the outlet of the lake minus the catchment of the outlet of the next upstream lake.

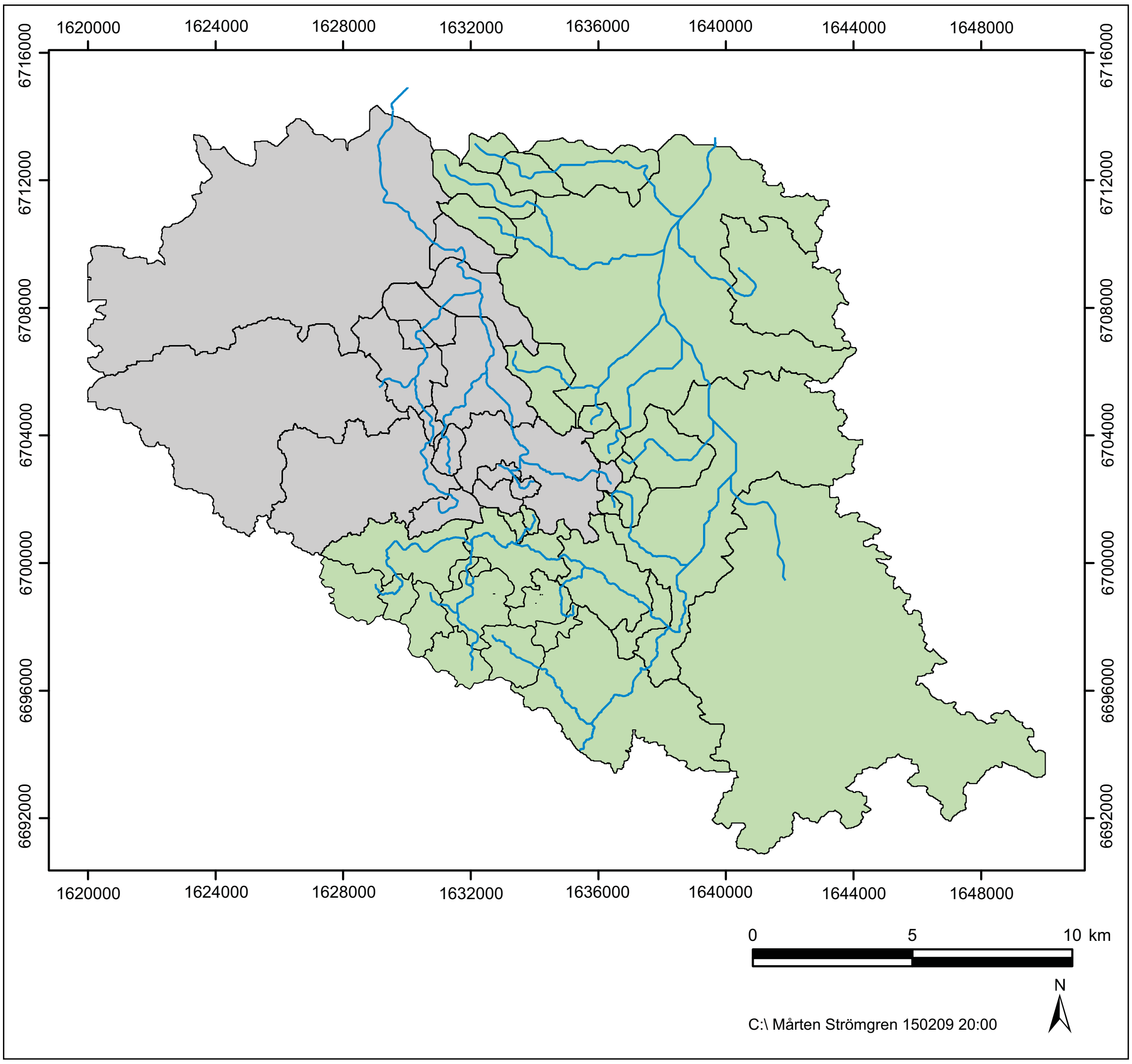

Figure 2-10. *All basins modelled in the RLDM. The basins are linked together by streams. The basins are grouped into two major branches: a western branch with 17 basins (grey) and an eastern branch with 33 basins (green).*

The identification and succession of biosphere objects in SR-PSU is thoroughly described in Chapter 6 of the Biosphere synthesis report (SKB 2014c). A biosphere object is an area in the present and/or future landscape that potentially, at any time during the considered assessment period, could receive a discharge of radionuclide-containing groundwater associated with the SFR repository. Specifically, a division into two types of object succession was made: objects that go through a future lake succession stage and objects that do not go through a lake stage.

Altogether, seven biosphere objects were identified. The biosphere object basins are shown in Figure 2-11. Note that these are the biosphere objects used in the modelling of temperate climates, such as the global warming climate case. Five of these are basins and associated lakes modelled in the RLDM, i.e. objects that go through a future lake succession stage. Two of the potential discharge areas are not associated to lakes modelled in the RLDM and consequently these areas were handled as biosphere objects without a lake stage, i.e. a wetland is formed directly after the sea stage. The two biosphere objects without a lake stage were situated in basins 121 and 157, i.e., these two basins were divided in two sub-basins, one for the original lake and one for the biosphere object without a lake stage. These basins were numbered 121_1 and 157_1 for the biosphere objects with a lake stage and 121_2 and 157_2 for the biosphere objects with wetlands not passing through a lake stage.

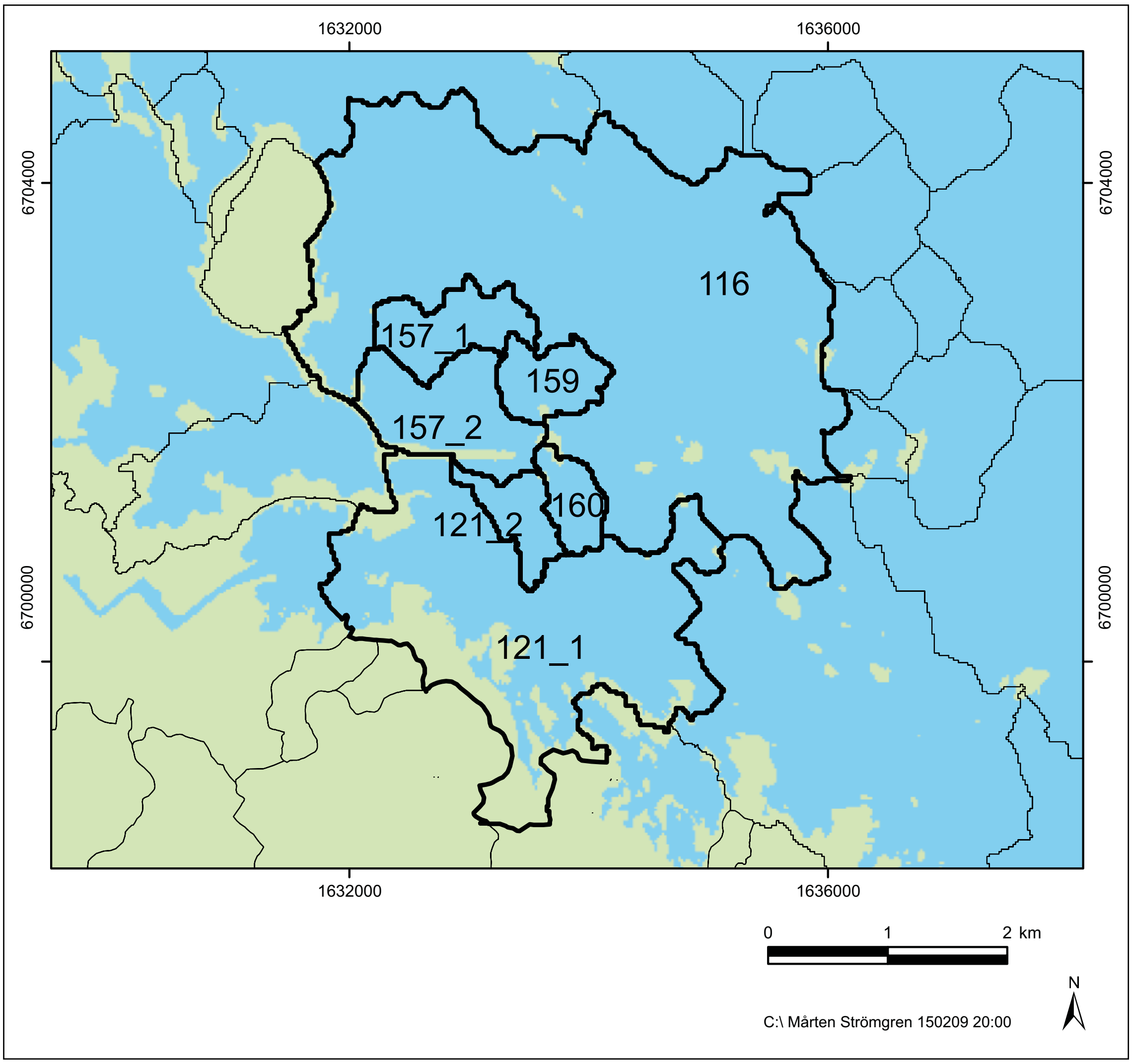

Figure 2-11. *Parts of the basins modelled in the RLDM. Basins 114, 121, 157, 159, 160 are future biosphere objects. Object 121 and 157 are divided into two objects each where 121_1 and 157_1 contain the lake basins and 121_2 and 157_2 contain wetlands not passing through a lake stage.*

3 Results

3.1 Delivered data

The RLDM is delivered for the global warming, the early periglacial and Weichselian glacial cycle climate cases. The models are delivered to SKB in a set of GIS-projects (in ArcGis mxd-format) together with layers representing regolith from the RDM (Sohlenius et al. 2013), which are not assumed to be exposed to erosion processes. A conceptual model for the distribution of these layers is shown in Figure 2-6. The postglacial clay shown in this figure is separated into marine and lacustrine strata in the RLDM. Individual projects for each time step consist of the following layers:

(i) thickness of organic sediments (peat),

(ii) thickness of lacustrine postglacial fine-grained sediments,

(iii) thickness of marine postglacial fine-grained sediments,

(iv) thickness of glacial clay,

(v) sand/gravel, glaciofluvial sediment or artificial fill from the RDM (Sohlenius et al. 2013),

(vi) till (Sohlenius et al. 2013),

(vii) bedrock adjusted for the shoreline displacement.

For the RDLM of the global warming climate case, the upper surface of peat for each time step is also delivered. These layers correspond to the DEM for each time step and were produced after the RLDM was delivered and are for that reason delivered separately from the RLDM. Table 3-1 shows references at SKB for the delivered regolith-lake development models (RLDM), data extracted from the RLDM and some data produced during the work with the RLDM.

The time steps in the GIS projects are in 500-year intervals for the period 8500 BC–12,000 AD, and 5,000-year intervals for the period between 15,000 AD and 40,000 AD when all lakes are completely infilled. As mentioned earlier, time steps of the lake module are in 100-year intervals; thus, some results regarding the lakes from the RLDM are not presented in the GIS projects. All results from the lake module are merged into Excel documents with 48 sheets for the RLDM for the Weichselian glacial cycle, the early periglacial and the global warming climate cases, respectively. Each lake is presented with the time steps in rows and the parameters in columns in the data sheets.

For the seven biosphere objects (SKB 2014c, Chapter 6) used in the radionuclide transport model for the biosphere (Saetre et al. 2013), 32 parameters are calculated and delivered in a separate Excel document. 20 of these parameters are results extracted directly from the RLDM for the global warming climate case and the remaining 12 parameters are calculated from these 20 parameters. The parameters are defined in one sheet and each biosphere object is presented with the time step in rows and parameters in columns in other sheets. For a further explanation of these parameters, see Grolander (2013).

An additional Excel document is delivered with 5 parameters concerning the transition of biosphere objects from marine basins to shallow sea bays, lakes and mires. For a description of the succession of the biosphere objects, see SKB (2014c, Chapter 6), and for a description of the delivered parameters, see Grolander (2013).

Table 3-1. Delivered data. The table gives a short description of the delivered data and the associated references at SKB.

Description	Reference at SKB
RLDM for the global warming climate case.	C245 (GIS, Delivery ID)
RLDM for the early periglacial climate case.	C297 (GIS, Delivery ID)
RLDM for the Weichselian glacial cycle climate case.	C298 (GIS, Delivery ID)
Upper surfaces of peat in the RDLM for the global warming climate case. These surfaces correspond to the DEM for each time step.	C296 (GIS, Delivery ID)
Basins modelled in the RLDM.	SDEADM.UMEU_FM_GEO_10168
Lakes modelled in the RLDM.	SDEADM.UMEU_FM_GEO_10327
Streams modelled in the RLDM.	SDEADM.UMEU_FM_GEO_10171
TWI-modelled peat.	C309 (GIS, Delivery ID)
Biosphere objects.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/Objects_130306
Parameters for biosphere objects used in the Radionuclide model for the biosphere.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/Ecolego_SFR_7_basins.xlsx
Additional parameters for the transition of biosphere objects from marine basins to shallow sea bays, lakes and mires.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/lake_isolation_start_stop_psu_v4.xlsx
Additional parameters for the lengths of the streams when the biosphere objects have turned from lakes to mires.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/Lakes_stream_length.xls
Areas of the sub-catchments of the biosphere objects.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/sub_catch.xlsx
Parameters of the area where a well would receive the highest concentrations of radionuclides from the repository.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/well_Interaction_Area
Parameters for all lakes in the RLDM for the Weichsel climate case.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/leverans av landskapsparametrar/Result_all_lakes_weichsel.xlsx
Parameters for all lakes in the RLDM for the early periglacial climate case.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/leverans av landskapsparametrar/Result_all_lakes_early.xlsx
Parameters for all lakes in the RLDM for the global warming climate case.	svn://svn.skb.se/projekt/SFR/SR-PSU/Landscape/leverans av landskapsparametrar/Result_all_lakes_green.xlsx

3.2 Overview of the RLDM results

The Weichselian ice sheet receded from the model area around 8500 BC and the last sea bay will be isolated and form a lake around 9400 AD. This makes the marine stage calculated by the RLDM about 17,900 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 35,700 AD in the RLDM for the global warming climate case and at almost 37,900 AD in the RLDM for the early periglacial climate case. Thus the terrestrial stage will be about 39,400 years. The first lake in the model area is isolated about 600 AD, so the limnic stage in the RLDM is about 37,300 years for the early periglacial climate case (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 (5%). To illustrate the importance of the relative sea level (RSL) change for the 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 describes the change in thickness of glacial clay, postglacial clay and peat. The changes in the DEM and the regolith map are then calculated using the thickness of postglacial clay and peat as input. Modelling results for each lake, in the form of volumetric fractions and thicknesses of different sediments (lacustrine and marine) and peat at the time when the lake is totally infilled, are presented in Appendix 3 (volumes) and Appendix 4 (thicknesses).

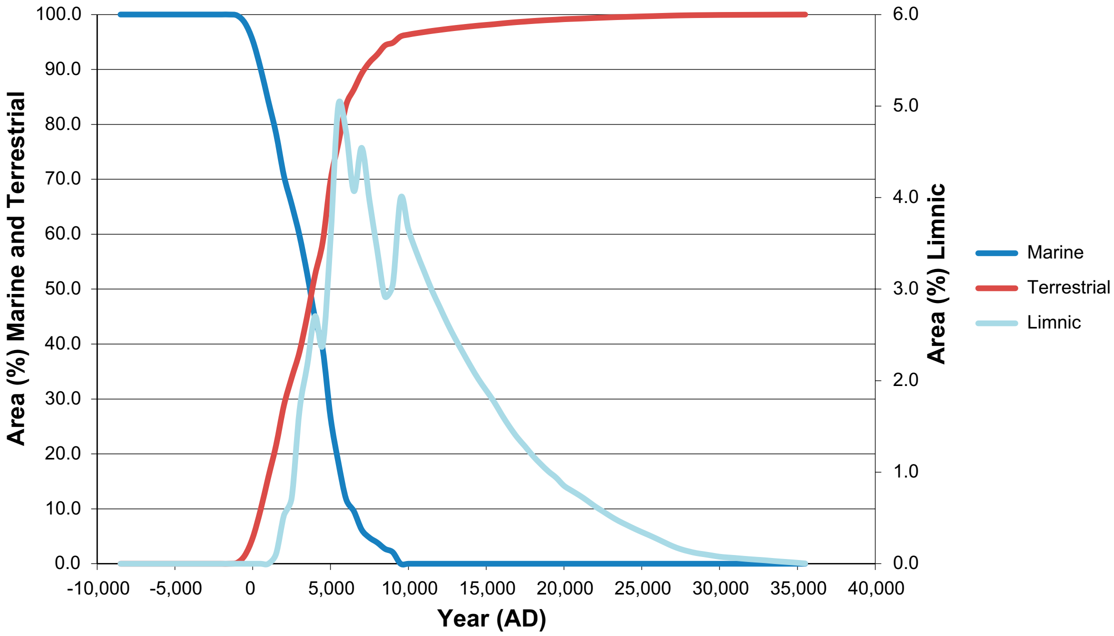

Figure 3-1. *The temporal area development of the three main ecosystems: marine, terrestrial and limnic in the Forsmark model area during a global warming climate case.*

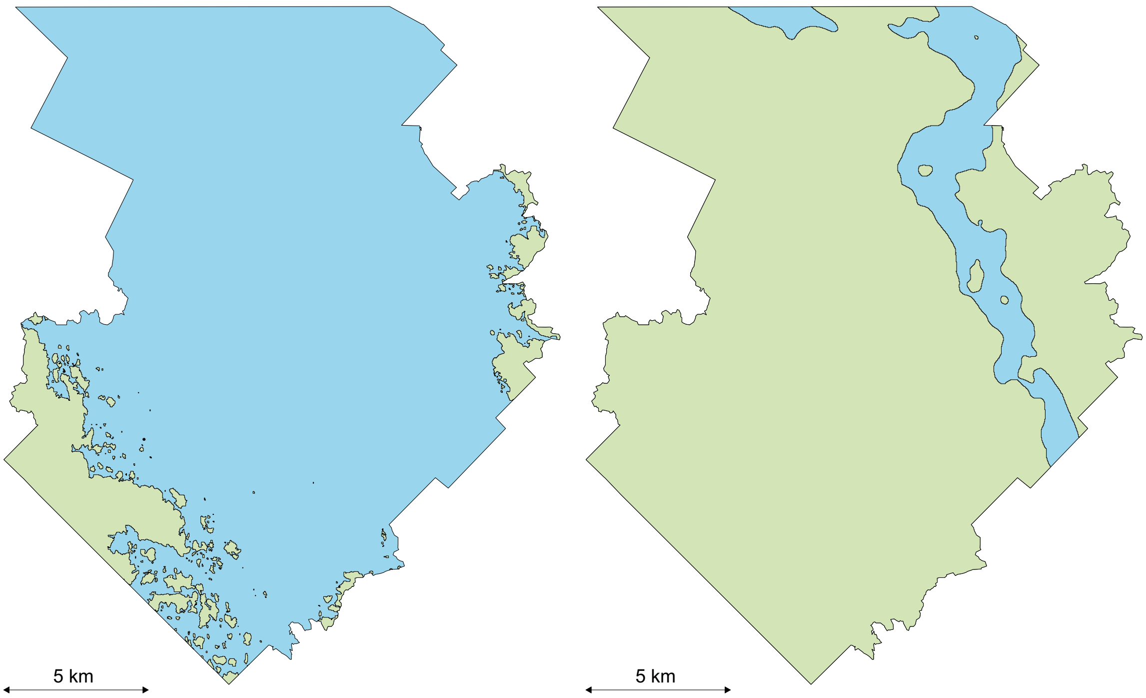

Figure 3-2. *The distribution of sea and land at two chosen time steps: 500 AD with about 90% sea (left) and 6500 AD with about 90% land (right).*

The increase in marine postglacial clay volume between 8500 BC and 6000 BC is caused by large areas of accumulation bottoms during that period (Figure 3-3). The decrease in volume during the period 6000 BC–3000 BC is caused by successively more sea bottoms being situated above the wave base and thus shifting from accumulation bottoms to transport bottoms. The figure also shows that more than 34 million m^3 of postglacial clay is exported out of the model area during this period. From 2500 BC, the volume increases continuously. At the end of the modelled period (around 36,000 AD), when all lakes are totally infilled and the development of the landscape is stabilised, the volume of the marine part of the postglacial clay is about 55% of the total volume.

The lacustrine postglacial clay starts to accumulate from 600 AD when the first lake is isolated and the volume increases until around 36,000 AD when all lakes are totally infilled (Figure 3-3). The organic sediment (which end up as peat) is also associated with infilled lakes and is in the RLDM treated as permanent accumulations, always increasing over time. The total peat volume is dominated by organic material generated by the lake infill processes; therefore, the peat volume increase rate (Figure 3-3) is closely associated with the number of lakes with ongoing infill processes. At the end of the RLDM period (40,000 AD), the total fen peat volume is about 90 million m^3, i.e. about half of the volume of postglacial clay at the same time.

The continued development of regolith in the Forsmark model area in the global warming climate case is presented in Figure 3-4. 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 2500 BC when the area of postglacial clay is at a local minimum (0.3% of the model area). Then, the postglacial clay area increases to reach 59.0% of the model area at 4500 AD.

From about 7000 AD, changes in the regolith surface distribution are limited. The postglacial clay area decreases continuously, mostly as a result of the infilling of lakes when postglacial clay is overlaid with peat. At 36,000 AD, the last lake within the model area is totally infilled. The landscape has come to a maturity stage.

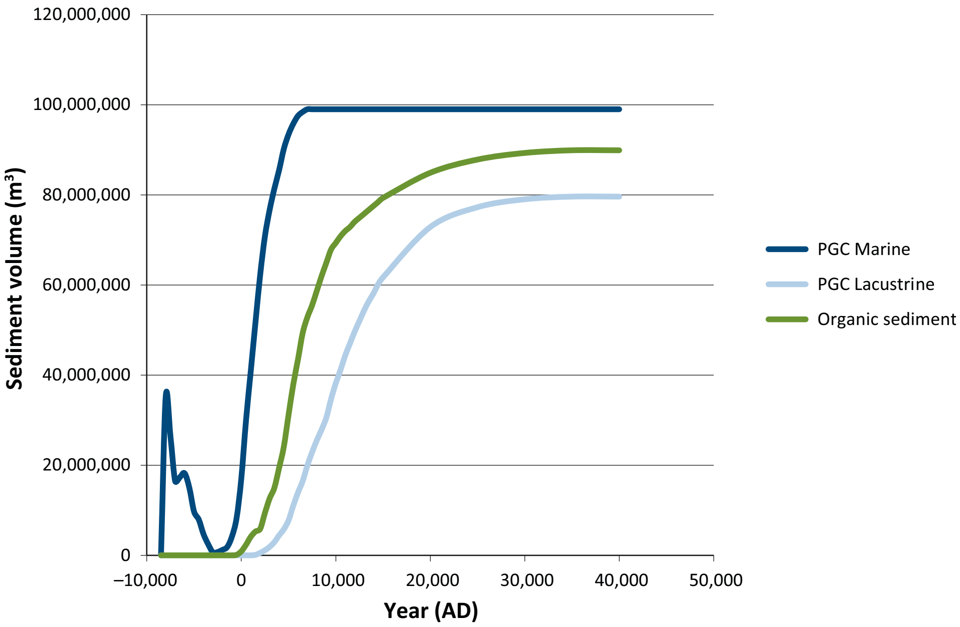

Figure 3-3. *The temporal variation of marine and lacustrine postglacial clay (PGC) volume (dark blue and light blue, respectively) and organic sediment (green, ends up as peat) in the Forsmark model area for the global warming climate case.*

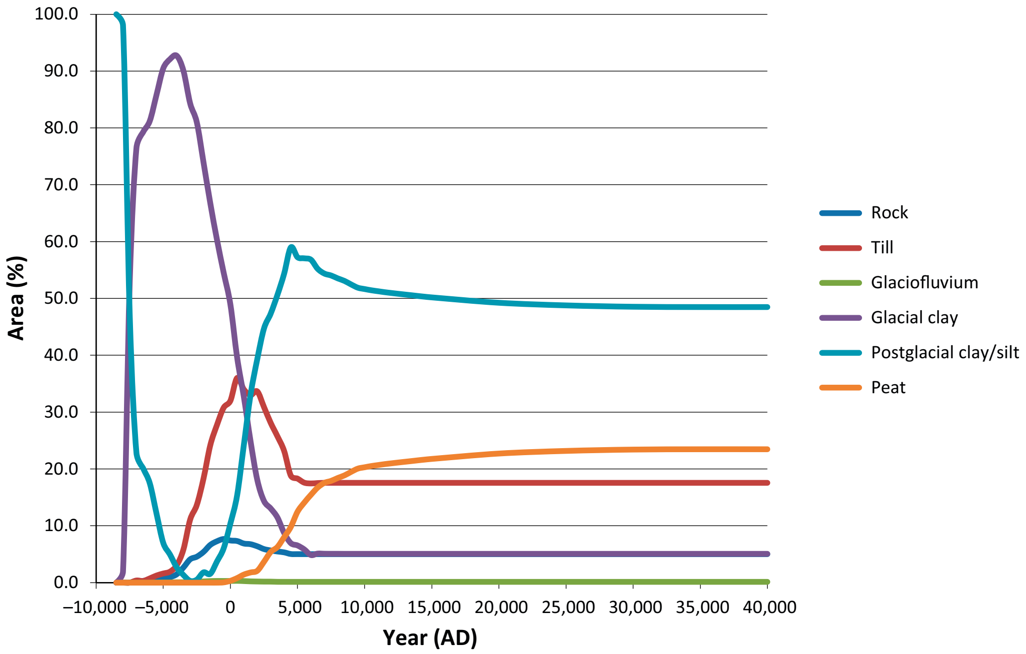

Figure 3-4. *Development of the surface regolith distribution in the Forsmark model area (in % of the whole model area) for the global warming climate case.*

4 Discussion

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

(i) the modelling of the wave base depth in the sediment dynamic model depends on an accurate DEM, and errors in the sediment dynamic model results give errors in the accumulation and erosion rates in the RLDM,

(ii) the DEM is used for modelling the extents of future lakes, and small errors in the DEM at the lake thresholds give 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 analysed in Strömgren and Brydsten (2009) and Strömgren and Brydsten (2013) based on the 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 infilling processes. In the sediment dynamic model, the 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 sediment dynamic model, it would be more correct to use the upper surface of the regolith depth model. This should lead to increased water depths, larger areas with accumulation bottoms, and thicker postglacial clay strata. The optimal method should run the sediment dynamic model and the RLDM in parallel.

The RLDM applied to permafrost conditions showed that the model is very sensitive to the chosen reduction of the lake infill rate (Brydsten and Strömgren 2010). A mean reduction of 75% was chosen for all permafrost periods. Instead, it would be more accurate to use a variable reduction based on, for example, the mean permafrost depth. However, this requires more accurate climate data (e.g. air temperature, permafrost depth) from the reference sites or more precise climatic definitions of the arctic zones (subarctic, high subarctic, low arctic, and high arctic zones). If radionuclide modelling is sensitive also to the result from the RLDM permafrost variant, it would be possible to update the RLDM with a variable reduction of the infill rate under 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 (Brydsten and Strömgren 2010). The infill rate occurs in two places in the model: in modelling vegetation colonisation in shallow sea bays that later will become lakes and in the lake module. Both rates are reduced under 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.

Another major source of error is the resolution of the results from the sediment dynamic model. The SDM was modelled in 500-year time steps. It was therefore necessary to use the same temporal 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 0.39–0.06 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 occurs only for a particular cell at one time step during the modelled period. This error probably has limited significance for the modelling of radionuclide dynamics but can cause substantial errors on regolith maps 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 temporal resolution of 500 years also means that the time scales in figures should not be viewed as absolute, rather as time periods +/– 250 years around the given time.

The uncertainty in the modelled glacial clay thickness is probably quite large during several thousand years after the Weichselian ice sheet has receded from the area. A minimum thickness of 2 m was assumed at 8500 BC. Most certainly, there should be a larger variation in the glacial clay thickness depending on the variation in the geological conditions in the Forsmark model area, but to use a dynamic approach would have been very difficult. However, the good agreement between the glacial clay modelled in the RLDM for 2000 AD and the glacial clay from the RDM (Sohlenius et al. 2013) shows that the uncertainty in the modelled glacial clay is much less from at least 2000 AD and onwards.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Beven K J, Kirkby M J, 1979. A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin 24, 43–69.

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

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

Brydsten L, 2006a. A model for landscape development in terms of shoreline displacement, sediment dynamics, lake formation, and lake choke-up processes. SKB TR-06-40, Svensk Kärnbränslehantering AB.

Brydsten L, 2006b. Modelling groundwater discharge areas using only digital elevation models as input data. SKB TR-06-39, Svensk Kärnbränslehantering AB.

Brydsten L, 2009. Sediment dynamics in the coastal areas of Forsmark and Laxemar during an interglacial. SKB TR-09-07, Svensk Kärnbränslehantering AB.

Brydsten L, Strömgren M, 2010. A coupled regolith-lake development model applied to the Forsmark site. SKB TR-10-56, Svensk Kärnbränslehantering AB.

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

Grolander S, 2013. Biosphere parameters used in radionuclide transport modelling and dose calculations in SR-PSU. SKB R-13-18, Svensk Kärnbränslehantering AB.

Hedenström A, 2004. Forsmark site investigation. Investigation of marine and lacustrine sediment in lakes. Stratigraphical and analytical data. SKB P-04-86, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, 2008. Description of the regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-04, Svensk Kärnbränslehantering AB.

Kokfelt U, Reuss N, Struyf E, Sonesson M, Rundgren M, Skog G, Rosén P, Hammarlund D, 2010. Wetland development, permafrost history and nutrient cycling inferred from late Holocene peat and lake sediment records in subarctic Sweden. Journal of Paleolimnology 44, 327–342.

Lindborg T (ed), 2010. Landscape Forsmark – data, methodology and results for SR-Site. SKB TR-10-05, Svensk Kärnbränslehantering AB.

Lindborg T, Brydsten L, Sohlenius G, Strömgren M, Andersson E, Löfgren A, 2013. Landscape development during a glacial cycle: modeling ecosystems from the past into the future. Ambio 42, 402–413.

Odén M, Follin S, Öhman J, Vidstrand P, 2014. SR-PSU Bedrock hydrogeology. Groundwater flow modelling methodology, setup and results. SKB R-13-25, Svensk Kärnbränslehantering AB.

Saetre P, Nordén S, Keesmann S, Ekström P-A, 2013. The biosphere model for radionuclide transport and dose assessment in SR-PSU. SKB R-13-46, Svensk Kärnbränslehantering AB.

SKB, 2008. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. SKB TR-08-05, Svensk Kärnbränslehantering AB.

SKB, 2014a. Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU. SKB TR-14-01, Svensk Kärnbränslehantering AB.

SKB, 2014b. Climate and climate related issues for the safety assessment SR-PSU. SKB TR-13-05, Svensk Kärnbränslehantering AB.

SKB, 2014c. Biosphere synthesis report for the safety assessment SR-PSU. SKB TR-14-06, Svensk Kärnbränslehantering AB.

Sohlenius G, Strömgren M, Hartz F, 2013. Depth and stratigraphy of regolith at Forsmark. SR-PSU Biosphere. SKB R-13-22, Svensk Kärnbränslehanering AB.

Strömgren M, Brydsten L, 2013. Digital elevation model of Forsmark. Site descriptive modelling. SR-PSU biosphere. SKB R-12-03, Svensk Kärnbränslehantering AB.

Strömgren M, Lindgren F, 2011. Mapping of reed in shallow bays. SFR-Site Forsmark. SKB P-11-09, Svensk Kärnbränslehantering AB.

Söderbäck B (ed), 2008. Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling. SDM-Site. SKB R-08-19, Svensk Kärnbränslehantering AB.

van Dijk D, Law J, 1995. Sublimation and aeolian sand movement from a frozen surface: experimental results from Presqu'ile Beach, Ontario. Geomorphology 11, 177–187.

Werner K, Sassner M, Johansson E, 2014. Hydrology and near-surface hydrogeology at Forsmark – synthesis for the SR-PSU project. SR-PSU Biosphere. SKB R-13-19, Svensk Kärnbränslehantering AB.

Appendix 1

Relative sea level

The table below shows the relative sea level at Forsmark for the Weichselian glacial cycle climate case and the global warming climate case (altitude in the RH70 elevation system).

Year	Weichselian glacial cycle climate case Altitude (m)	Global warming climate case Altitude (m)
9500 BC	171.12	171.12
9000 BC	148.47	148.47
8500 BC	131.62	131.62
8000 BC	104.22	104.22
7500 BC	82.92	82.92
7000 BC	74.04	74.04
6500 BC	71.83	71.83
6000 BC	68.90	68.90
5500 BC	64.83	64.83
5000 BC	59.98	59.98
4500 BC	54.74	54.74
4000 BC	49.40	49.40
3500 BC	44.11	44.11
3000 BC	38.97	38.97
2500 BC	34.04	34.04
2000 BC	29.33	29.33
1500 BC	24.87	24.87
1000 BC	20.64	20.64
500 BC	16.65	16.65
0 AD	12.88	12.88
500 AD	9.32	9.32
1000 AD	5.97	5.97
1500 AD	2.81	2.81
2000 AD	–0.17	–0.17
2500 AD	–3.08	–3.08
3000 AD	–5.92	–5.92
3500 AD	–8.69	–8.69
4000 AD	–11.40	–11.40
4500 AD	–14.03	–14.03
5000 AD	–16.60	–16.60
5500 AD	–19.09	–19.09
6000 AD	–21.52	–21.52
6500 AD	–23.88	–23.88
7000 AD	–26.16	–26.16
7500 AD	–28.38	–28.38
8000 AD	–30.53	–30.53
8500 AD	–32.61	–32.61
9000 AD	–34.62	–34.62
9500 AD	–36.56	–36.56
10,000 AD	–38.44	–38.44
10,500 AD	–40.24	–40.24
11,000 AD	–41.97	–41.97
11,500 AD	–43.64	–43.64
12,000 AD	–45.23	–45.14
12,500 AD	–46.76	–46.06
13,000 AD	–48.22	–46.98
13,500 AD	–49.60	–47.89

Year	Weichselian glacial cycle climate case Altitude (m)	Global warming climate case Altitude (m)
14,000 AD	–50.92	–48.81
14,500 AD	–52.17	–49.73
15,000 AD	–53.35	–50.65
15,500 AD	–54.46	–51.57
16,000 AD	–55.51	–52.48
16,500 AD	–56.48	–53.40
17,000 AD	–57.38	–54.32
17,500 AD	–58.22	–54.83
18,000 AD	–58.98	–55.35
18,500 AD	–59.68	–55.86
19,000 AD	–60.30	–56.37
19,500 AD	–60.86	–56.89
20,000 AD	–61.35	–57.40
20,500 AD	–62.44	–57.91
21,000 AD	–63.00	–58.43
21,500 AD	–63.56	–58.94
22,000 AD	–64.12	–59.45
22,500 AD	–64.68	–59.75
23,000 AD	–65.24	–60.04
23,500 AD	–65.80	–60.34
24,000 AD	–66.13	–60.63
24,500 AD	–66.46	–60.93
25,000 AD	–66.78	–61.23
25,500 AD	–67.11	–61.52
26,000 AD	–67.43	–61.82
26,500 AD	–67.76	–62.11
27,000 AD	–67.93	–62.41
27,500 AD	–68.10	–62.58
28,000 AD	–68.27	–62.76
28,500 AD	–68.45	–62.94
29,000 AD	–68.62	–63.11
29,500 AD	–68.79	–63.29
30,000 AD	–68.81	–63.46
30,500 AD	–68.83	–63.64
31,000 AD	–68.85	–63.82
31,500 AD	–68.87	–63.99
32,000 AD	–68.88	–64.17
32,500 AD	–68.90	–64.28
33,000 AD	–69.01	–64.39
33,500 AD	–69.12	–64.49
34,000 AD	–69.22	–64.60
34,500 AD	–69.33	–64.71
35,000 AD	–69.43	–64.82
35,500 AD	–69.54	–64.93
36,000 AD	–69.32	–65.04
36,500 AD	–69.11	–65.15
37,000 AD	–68.90	–65.25
37,500 AD	–68.68	–65.32
38,000 AD	–68.47	–65.38
38,500 AD	–68.26	–65.44
39,000 AD	–68.35	–65.50
39,500 AD	–68.44	–65.57
40,000 AD	–68.53	–65.63

Appendix 2

Physical properties of lakes

The table summarises physical properties of the 48 lakes that are treated in the RLDM. The time for isolation (Isolation) and infill time (Infilled) are shown as closest 100 year after the event occurred and are only shown for the global warming climate case. The rest of the properties are identical for the Weichselian glacial cycle, early periglacial and global warming climate cases. The Lake Id refers to the labels in Figure 2-9.

Lake Id	Area (m^2)	Volume (m^3)	Altitude (m)	Mean depth (m)	Max depth (m)	Isolation (Year AD)	Infilled (Year AD)	Name
105	4,244,800	12,212,290	–35.901	2.877	18.396	9400	35,700	Nameless future lake
107	1,970,800	3,509,995	–6.24	1.781	6.719	3100	14,600	Nameless future lake
108	1,276,800	1,357,238	–15.225	1.063	5.149	4800	9100	Nameless future lake
110	58,000	30,392	–6.054	0.524	2.012	3100	3700	Nameless future lake
114	1,654,400	4,412,285	–33.493	2.667	11.666	9000	28,700	Nameless future lake
116	1,491,600	1,871,958	–14.238	1.255	4.174	4600	9900	Nameless future lake
117	1,775,600	3,261,777	–5.721	1.837	4.124	3000	8700	Nameless future lake
118	266,400	298,102	–5.135	1.119	2.874	2900	8800	Nameless future lake
120	275,200	476,922	–2.602	1.733	7.69	2500	5200	Nameless future lake
121	270,000	196,560	–10.416	0.728	2.32	3900	6400	Nameless future lake
123	87,600	65,350	–10.913	0.746	2.547	4000	6000	Nameless future lake
124	82,741	30,614	0.48	0.37	1.29	1900	4300	Puttan
125	76,070	23,582	0.4	0.31	0.88	1900	2600	Norra Bassängen
126	538,000	806,462	–12.245	1.499	3.969	4200	6400	Nameless future lake
129	67,453	34,401	5.82	0.51	1.29	1100	4500	Gunnarsboträsket
132	60,042	16,211	3.66	0.27	1.07	1400	4700	Labboträsket
134	352,000	485,760	–1.351	1.38	4.221	2200	9800	Nameless future lake
136	611,311	372,900	0.42	0.61	1.81	1900	5900	Bolundsfjärden
142	187,048	31,798	1.82	0.17	1.51	1700	4300	Gällsboträsket
144	97,663	72,271	0.41	0.74	1.72	1900	5100	Bredviken
146	236,400	200,940	–13.866	0.85	2.254	4500	10,500	Nameless future lake
148	754,302	279,092	0.56	0.37	1.86	1900	6900	Fiskarfjärden
149	283,849	258,303	5.32	0.91	2.12	1100	5500	Eckarfjärden
150	313,600	772,397	–8.216	2.463	5.821	3500	10,700	Nameless future lake
151	7,070,800	21,608,365	–16.834	3.056	7.008	5100	20,000	Nameless future lake
152	1,048,800	1,698,007	–15.406	1.619	5.013	4700	9800	Nameless future lake
153	186,400	96,555	–8.288	0.518	1.604	3500	5600	Nameless future lake
154	1,352,800	1,479,963	–15.359	1.094	3.683	4800	10,200	Nameless future lake
155	171,200	86,970	–6.604	0.508	1.422	3200	5300	Nameless future lake
156	143,600	184,239	–6.058	1.283	2.953	3100	12,500	Nameless future lake
157	103,600	65,061	–13.994	0.628	1.494	4500	5700	Nameless future lake
158	104,800	81,534	–9.109	0.778	1.799	3600	4900	Nameless future lake
159	103,200	105,780	–11.84	1.025	2.644	4100	7600	Nameless future lake
160	158,400	211,939	–7.086	1.338	2.852	3300	8800	Nameless future lake
163	613,600	1509,456	–16.188	2.46	6.85	5000	14,600	Nameless future lake
164	691,600	1148,056	–20.191	1.66	5.61	5800	10,300	Nameless future lake
165	613,600	681,096	–18.617	1.11	2.55	5500	11,600	Nameless future lake
166	1,283,600	2,117,940	–16.204	1.65	6.39	5000	10,200	Nameless future lake
167	488,400	757,020	–16.987	1.55	3.94	5100	10,900	Nameless future lake
170	1,886,000	6,544,420	–10.139	3.47	11.07	3800	16,500	Nameless future lake
173	1,022,800	1,298,956	–10.528	1.27	4.62	3900	13,600	Nameless future lake
175	290,800	360,592	–10.055	1.24	3.51	3800	6700	Nameless future lake
176	2,526,000	3,662,700	–4.949	1.45	4.57	2900	8500	Nameless future lake
177	286,400	343,680	–8.735	1.2	3.1	3600	6700	Nameless future lake
178	94,800	107,124	–7.591	1.13	3.04	3300	5000	Nameless future lake
179	925,600	2,276,976	–1.666	2.46	4.53	2300	6200	Nameless future lake
180	746,000	1,275,660	–20.338	1.71	4.61	5800	15,800	Nameless future lake
184	4,116,400	22,269,724	–24.243	5.41	16.32	6600	29,900	Nameless future lake

Appendix 3

Sediment volume

The table shows the volumetric fractions (in %) of different sediment types at the time each lake is totally infilled.

Lake Id	Marine	Lacustrine	Peat
105	17	62	21
107	7	43	51
108	16	23	61
110	21	4	75
114	32	45	23
116	20	23	57
117	16	34	49
118	13	32	56
120	20	27	53
121	37	14	49
123	38	6	56
124	17	17	66
125	31	20	49
126	30	5	64
129	15	13	72
132	24	21	55
134	10	38	52
136	19	32	49
142	16	11	73
144	9	27	64
146	73	3	24
148	15	31	53
149	11	32	57
150	19	28	53
151	5	43	52
152	9	34	57
153	1	29	71
154	6	35	59
155	6	19	75
156	9	40	51
157	23	9	68
158	18	10	72
159	21	11	69
160	14	28	58
163	5	50	45
164	3	34	62
165	5	45	51
166	4	38	58
167	7	28	65
170	22	40	38
173	4	44	52
175	7	24	69
176	8	64	28
177	10	24	66
178	5	14	82
179	9	30	61
180	13	46	40
184	22	62	17

Appendix 4

Sediment thickness

The table below shows the thickness (in metres) of different sediment types at the time each lake is totally infilled.

	Marine sediments (m)			Lacustrine sediments (m)			Peat (m)		
Lake Id	Mean	Max	STD	Mean	Max	STD	Mean	Max	STD
105	3.57	1.48	0.95	20.59	5.55	4.26	10.26	1.88	0.64
107	0.37	0.21	0.06	6.24	1.34	1.59	2.08	1.59	0.61
108	0.39	0.24	0.08	3.77	0.33	0.56	2.22	0.88	0.65
110	0.29	0.17	0.05	0.26	0.04	0.04	1.91	0.61	0.44
114	3.39	2.53	0.31	12.04	3.54	2.73	8.52	1.85	0.53
116	0.74	0.47	0.13	3.41	0.53	0.68	2.10	1.30	0.54
117	0.57	0.36	0.08	4.41	0.77	0.97	1.68	1.11	0.48
118	0.46	0.32	0.04	3.00	0.80	0.82	2.17	1.40	0.74
120	0.96	0.35	0.14	4.09	0.46	0.75	2.16	0.91	0.66
121	0.61	0.61	0.01	2.12	0.23	0.39	1.86	0.82	0.58
123	0.44	0.30	0.06	0.91	0.05	0.11	2.09	0.44	0.66
124	0.40	0.37	0.07	1.18	0.37	0.33	2.15	1.41	0.81
125	0.40	0.22	0.09	0.20	0.14	0.04	1.03	0.35	0.21
126	0.90	0.66	0.07	4.17	0.12	0.39	3.15	1.41	1.02
129	0.76	0.65	0.17	1.53	0.54	0.44	3.53	3.06	0.45
132	0.62	0.62	0.00	1.66	0.55	0.48	2.00	1.40	0.72
134	0.34	0.30	0.08	3.90	1.16	1.05	2.17	1.60	0.63
136	0.40	0.39	0.04	2.11	0.67	0.59	2.00	1.04	0.73
142	0.79	0.55	0.16	1.22	0.40	0.29	3.14	2.50	0.68
144	0.17	0.17	0.00	1.62	0.52	0.53	2.01	1.25	0.73
146	0.90	0.60	0.17	3.47	0.03	0.22	2.44	0.19	0.44
148	0.79	0.40	0.04	4.63	0.81	0.60	2.00	1.39	0.55
149	0.76	0.39	0.11	2.66	1.10	0.64	2.86	1.95	0.56
150	1.16	0.74	0.17	3.97	1.07	1.35	3.70	2.02	1.56
151	0.34	0.17	0.06	6.82	1.43	1.63	2.08	1.70	0.52
152	0.28	0.18	0.07	4.38	0.71	0.98	2.00	1.18	0.51
153	0.08	0.01	0.02	1.08	0.20	0.19	1.65	0.50	0.39
154	0.19	0.14	0.03	3.98	0.82	0.84	2.03	1.39	0.57
155	0.08	0.08	0.02	0.86	0.26	0.28	1.94	1.03	0.64
156	0.57	0.32	0.13	5.04	1.41	1.23	2.16	1.80	0.42
157	0.50	0.50	0.02	1.11	0.19	0.22	2.09	1.45	0.58
158	0.20	0.20	0.00	0.35	0.11	0.11	1.57	0.79	0.39
159	0.50	0.44	0.09	1.58	0.23	0.32	2.06	1.47	0.58
160	0.54	0.37	0.07	2.80	0.72	0.84	2.00	1.49	0.61
163	0.19	0.13	0.06	5.85	1.35	1.79	2.03	1.19	0.82
164	0.06	0.06	0.02	2.85	0.57	0.67	1.88	1.04	0.45
165	0.26	0.15	0.04	3.66	1.42	1.22	2.04	1.62	0.53
166	0.19	0.08	0.03	4.35	0.88	1.01	2.03	1.35	0.64
167	0.26	0.17	0.04	3.47	0.66	0.90	2.02	1.52	0.63
170	1.23	0.87	0.18	6.98	1.60	1.90	2.21	1.52	0.70
173	0.15	0.11	0.05	5.15	1.21	1.27	2.03	1.45	0.72
175	0.15	0.14	0.03	3.19	0.48	0.81	2.00	1.36	0.64
176	0.29	0.23	0.08	3.13	1.79	1.25	1.17	0.79	0.40
177	0.27	0.14	0.05	1.90	0.36	0.52	1.76	0.98	0.50
178	0.08	0.06	0.04	1.17	0.18	0.27	2.00	1.07	0.66
179	0.34	0.23	0.10	2.93	0.75	0.81	2.17	1.51	0.60
180	1.48	0.58	0.18	5.39	2.03	1.59	2.02	1.77	0.45
184	2.71	2.54	0.20	16.82	7.20	3.49	2.40	1.94	0.19