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Methodology for elevation and regolith modelling of the Forsmark site

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Preface

A series of methodology reports support the programmes for investigation and modelling during the execution of planned underground constructions at Forsmark. The series includes the following disciplines: geometric modelling of ground elevation and regolith, deterministically modelled geological structures, discrete fracture network (DFN) modelling (stochastic, semi-stochastic and deterministic modelling of structural-hydraulic fracture data), rock mechanics modelling, thermal properties modelling, integrated hydrological and hydrogeological modelling, hydrogeochemical modelling, and transport modelling. Report numbers (ID), acronyms, and titles are shown below. The acronyms are recommended for internal referencing.

ID	Acronym	Title
R-20-10	DGMM	Methodology for deterministic geologic modelling of the Forsmark site.
R-20-11	DFNMM1	Methodology for discrete fracture network modelling of the Forsmark site. Part 1 – Concepts, Data and Interpretation Methods.
R-20-12	DFNMM2	Methodology for discrete fracture network modelling of the Forsmark site. Part 2 – Application examples.
R-20-13	RMMM	Methodology for rock mechanics modelling of the Forsmark site.
R-20-14	HGMM	Methodology for hydrological and hydrogeological modelling of the Forsmark site.
R-20-15	HCMM	Methodology for hydrochemical modelling of the Forsmark site.
R-20-16	ERMM	Methodology for elevation and regolith modelling of the Forsmark site.
R-20-17	TRPMM	Methodology for site descriptive and safety assessment transport modelling of the Forsmark site.
R-20-18	THPMM1	Methodology for modelling of thermal properties of the Forsmark site. Part 1 – Recommended data and interpretation methods.
R-20-19	THPMM2	Methodology for modelling of thermal properties of the Forsmark site. Part 2 – Background and methodology development.

This report describes the methodologies used for geometric modelling of ground elevation and regolith in the Forsmark area. Furthermore, methods for determining properties of the most commonly occurring regolith types are described. The report also discusses further development and improvement of the models. The models presented here reflect the baseline conditions in Forsmark, i.e., the conditions before the start of the building of the repository for spent nuclear fuel and the extension of SFR. The method for modelling the ground elevation, the Digital elevation model (DEM), has earlier been reported by Petrone and Strömgren (2020), and the method for modelling the geometrical distribution of regolith, the Regolith depth model (RDM) has been reported by Petrone et al. (2020).

The report has been developed by Gustav Sohlenius (SGU) and Matilda Svensson (SKB) with support from Mårten Strömgren (Umeå university) and Johan Nyberg (SGU). The report has been reviewed by Jean Marc Mayotte, Robert Earon and Mathias Andersson.

Summary

SKB plans to build a repository for spent nuclear fuel and to extend the storage for low radioactive waste SFR in the Forsmark area. The distribution of regolith and the elevations in that area are shown in two separate models one regolith depth model (RDM) and one digital elevation model (DEM). The models represent 500 and 700 km^2 land, lakes and marine areas respectively, and show the baseline conditions prevailing before the construction of the new repositories in Forsmark.

The DEM shows the height of the ground and sea floor in relation to the sea level. The DEM has highest spatial resolution in the terrestrial areas (1 × 1 m) and lower resolution in water covered areas. For marine areas the DEM is restricted by security but there is a public available model with a 20 × 20 m resolution.

The RDM shows the vertical and horizontal distribution of the most commonly occurring regolith layers. The term regolith refers to all loose deposits overlying the bedrock. The model shows the different regolith layers topographical position in relation to the sea level and has a 20 × 20 m resolution in the whole model area. There is an additional RDM with higher resolution for the area where the entrance for the repository of nuclear waste will be situated.

The DEM and RDM are used for a number of other modelling purposes, within e.g. hydrology. The models are used both for SKB's safety assessment and for the environmental impact assessment (EIA). For the former the models are used to predict where radionuclides from the storages in the future might reach the surface. For the EIA it is important to predict if the storages might affect areas in Forsmark with high nature values.

A large part of the data used for the models was obtained during SKB's site investigations. In terrestrial areas newer LiDAR data from Lantmäteriet was used, giving the DEM a very high accuracy in those areas. Water depth data from the marina areas was mainly obtained during the site investigations, which to a large extent were focused on the central parts of the model area, situated close to the planned storages. The earliest investigations were made using older methods that don't give full-cover water depth information of the sea floor. The largest uncertainties in the DEM are therefore in parts of the marine areas, especially in shallow areas and in peripheral parts of the model area. Also, the lakes in the central parts of the model area are well studied whereas more peripheral lakes in many cases lack depth data. The accuracy of the DEM has been validated to quantify uncertainties, and the uncertainties in terrestrial areas are less than one meter but up to several meters in the marine areas.

Maps of regolith and depth information from coring's and geophysics were used as input to the RDM. The methods used for obtaining these data are shortly described in this report. There are generally few depth data, as well as low resolution regolith maps in the peripheral parts of the model area. These areas have consequently relatively large uncertainties in the RDM. The uncertainties in the RDM have, however, not been quantified and are only roughly estimated. It is today possible to improve the regolith map both in terrestrial and water covered areas using new techniques. An improved regolith map is important for improving the quality of the RDM.

Since there are lakes and marine areas with a relatively low density of depth data more data will be collected in prioritised areas. That data will be used for an updated DEM, which in turn will be used for updating the regolith map. Additional probing's have been performed since the RDM was produced. That information will be used for a new improved RDM. In addition, the new DEM and regolith map will be used to improve the RDM. The uncertainties in the new RDM will be thoroughly quantified.

Sammanfattning

Forsmarksområdets fördelning av olika regolittyper samt höjdförhållanden redovisas i två modeller, en jorddjupsmodell (RDM) respektive en höjdmodell (DEM). Modellerna omfattar land, sjöar och hav i ett 500 respektive 700 km^2 stort område i Forsmark där SKB planerar att slutförvara radioaktivt avfall samt att bygga ut det befintliga förvaret för lågradioaktivt avfall (SFR). Modellerna avser att visa, ”baseline”, dvs de förhållanden som råder innan bygget av slutförvaren påbörjas.

Höjdmodellen redovisar mark- och bottenytans höjd i förhållande till höjd över havets yta. Modellen finns i flera olika upplösningar med den högsta i landområdena (1 × 1 m) och lägre i områden som täcks av vatten. I de marina områdena är höjddata belagt med sekretess men det finns en allmänt tillgänglig modell med en upplösning på 20 × 20 m.

Jorddjupsmodellen (RDM) redovisar vertikal och horisontell utbredning av nio regolitlager. Termen regolit avser alla lösa avlagringar som överlagrar berggrunden. Ibland används även termen jordarter för att beskriva dessa avlagringar. Modellen redovisar den de olika jordlagrens topografiska läge i förhållande till havsytenivån och finns i en upplösning på 20 × 20 m, som omfattar hela området. En mer högupplöst RDM finns också för ett mindre område vid nedfarten för det planerade slutförvaret för använt kärnbränsle.

Jorddjupsmodellen och höjdmodellen används för en rad andra modelleringar inom t ex hydrologi. Modellerna används både inom säkerhetsanalys och för miljökonsekvensbeskrivningar (MKB). För säkerhetsanalys är modellerna viktiga för att förstå var radionuklider i framtiden eventuellt skulle kunna nå markytan. Inom MKB är det av vikt för att kunna bedöma förvarens eventuella påverkan och konsekvens på områden i Forsmark med höga naturvärden.

Modellerna bygger till stor del på data som tagits fram under SKB:s platsundersökningar. I de terrestra delarna finns också LiDAR-data (Light Detection and Ranging) som samlats in av Lantmäteriet, vilket gör att höjdmodellen i dessa delar har en mycket hög tillförlitlighet. I de marina områdena har främst djupdata från platsundersökningarna använts, vilka till största del var fokuserade på de centrala delarna av modellområdet, närmast de planerade förvaren. De tidigaste undersökningarna utfördes med äldre metoder vilka inte ger heltäckande djupinformation från botten. De största osäkerheterna hos höjdmodellen finns därför inom vissa delar av de marina områdena, framför allt i perifera områden samt i områden med vattendjup grundare än 2–3 meter. Samma sak gäller för sjöarna där de som ligger centralt är väl undersökta medan mer perifert belägna sjöar i vissa fall saknar djupdata.

Gällande höjdmodellen har en validering gjort som kvantifierar osäkerheterna i modellen, och som visar att osäkerheten i landområdena är mindre än 1 m medan den i vissa marina områden är upp till flera meter.

Jordartskartor samt djupdata från borrningar och olika typer av geofysik användes som inputdata till jorddjupsmodellen. I rapporten beskrivs vilka metoder som använts för att ta fram dessa data. I de områden som ligger längst från de planerade förvaren är det generellt glest med djupdata och jordartskartorna är av en översiktlig karaktär. Jorddjupsmodellen har därmed större osäkerhet i dessa områden. Osäkerheter i jorddjupsmodellen har inte kvantifierats utan endast bedömts översiktligt. Idag finns möjlighet att med nya tekniker förbättra jordartskartor både i sådana områden som utgör land och sådana som täcks av vatten. En förbättrad jordartskarta är en viktig input för en framtida jorddjupsmodell.

Eftersom det finns sjöar och marina områden med relativt lite höjddata kommer mer data samlas in i prioriterade områden, varefter en uppdaterad DEM tas fram. Denna information kommer även att användas för att ta fram bättre underlag som visar jordarternas fördelning. Sedan jorddjupsmodellen togs fram har och kommer ytterligare borrningar att utföras. Den informationen kommer användas för att ta fram en förbättrad jorddjupsmodell. Dessutom kommer den förbättrade jordartskartan och DEMen användas för att uppdatera jorddjupsmodellen. Det arbetet kommer även inkludera en kvantifiering av jorddjupsmodellens osäkerheter.

Contents

1 Introduction

This report describes the methodologies used for geometric modelling of ground elevation and regolith in the Forsmark area. Furthermore, methods for determining properties of the most commonly occurring regolith types are described. The report also discusses further development and improvement of the models. The models presented here reflect the baseline conditions in Forsmark, i.e. the conditions before the start of the building of the repository for spent nuclear fuel and the extension of SFR.

Most data used for the models were obtained during the two site investigations SR-Site (SKB 2008, Lindborg 2008a) and SR-PSU (SKB 2013). Some additional studies were, however, carried out after the site investigations, and data from these models will be included in future models. The methods used for obtaining new data and for modelling have changed since the first site investigations. New methods have consequently been introduced, but there are also other investigation methods that up to now have not been used in the Forsmark area. The report ends with an overview of new methods that can be used for future investigations and models.

Two types of geometrical models are discussed in the report, one for the depth and thickness of different regolith layers, the Regolith depth model (RDM), and one for the altitude of terrestrial and land areas, the digital elevation model (DEM). Furthermore, methods for mapping and determining regolith properties are discussed. The model area represented by the DEM is almost 700 km^2 whereas the RDM represent almost 500 km^2 of the same area (Figure 1-1). Both areas are larger than the area for baseline understanding in Forsmark (Baseline Forsmark Area (Earon 2022). The modelled areas include terrestrial areas as well as lakes and the sea bay between the mainland and the Gräsö Island (Öregrundsgrepen). In addition, a more detailed RDM representing the access area for the storage of spent nuclear fuel has been produced (Figure 1-1).

The models described in this report are used for several issues important for SKB's safety assessments as well as for environmental impact assessments (EIA). For the safety assessment, both regolith properties and topography are used to model the spatial distribution of radionuclides that might emit from the two repositories (SKB 2010). These properties are also used to model how the landscape will develop in the future. That is important for assessing the future environment and how humans might be exposed to radionuclides. For the EIA, properties of regolith and topography is used to model hydrology. The wetlands in Forsmark with high nature values are of special interest for the EIA, since they might be affected by the repository for used nuclear waste (Werner et al. 2014). The geometrical models are therefore important in understanding these environments and how to mitigates effects of potential lowering of the groundwater table. In addition, the models give a good understanding of the regolith and topography, which will be of large use for the construction of the repositories built in Forsmark.

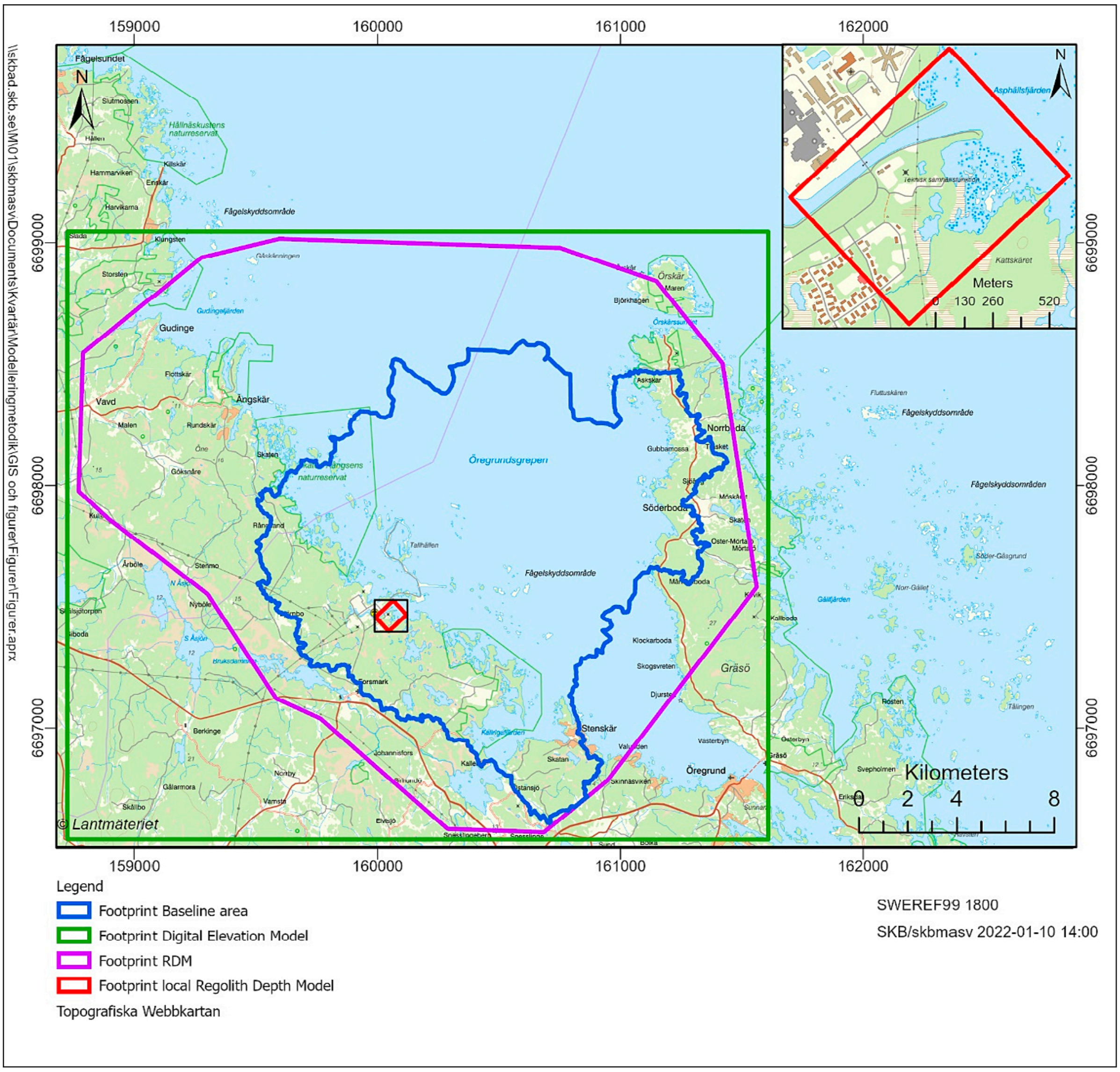

Figure 1-1. The aerial distribution of the Regolith depth model (RDM) and the Digital elevation model (DEM). The local RDM represent the access area for the planned repository for spent nuclear fuel. Both the DEM and RDM represent areas larger than the Baseline area.

2 Digital elevation model (DEM)

2.1 Introduction

The DEM was produced by Petrone and Strömgren (2020) represents the area shown in Figure 1-1 including the floor of areas covered by water, which contrasts with most used DEM's where the surfaces of lakes and sea are represented by constant values. Petrone and Strömgren (2020) produced several DEMs with different resolutions (Table 2-1). The DEM in the terrestrial area has the highest resolution, with 1 m cell size, whereas the DEM in the marine has a 10 m or in some areas 20 m resolution (Table 2-1). Furthermore, a DEM with 5 m resolution has been produced for the terrestrial areas. In the marine area the DEM with the highest resolution is not freely available since bathymetric information is restricted by a law that aims at protecting geographical information (SFS 2016:319). One common DEM for the whole area with 20 m cell sizes is, however, not restricted. The methodology for producing the DEM is summarised in Figure 2-1.

Table 2-1 The different DEMs presented in Petrone and Strömgren (2020). The geographical extension of the DEMS are shown in Figure 1-1.

Product	Resolution	Geographical extention	Reference to SKB model database
DEM 20 × 20 m	20 × 20 m	The whole model area for the DEM	1954772
DEM 10 × 10 m	10 × 10 m	The whole model area for the DEM	1969401
DEM 1 × 1 m	1 × 1 m	The terrestrial part of the model area (DEM)	1859072
DEM 5 × 5 m	5 × 5 m	The terrestrial part of the model area (DEM)	1859070

The DEM aims at describing the topography and bathymetry as accurately as possible, whether it is the land surface, the lake floor or the sea floor. The model represents baseline conditions i. e. the conditions before the start of building of the repository for used nuclear fuel. A small part of the DEM for the access area for the planned spent nuclear fuel repository is presented in Follin (2019).

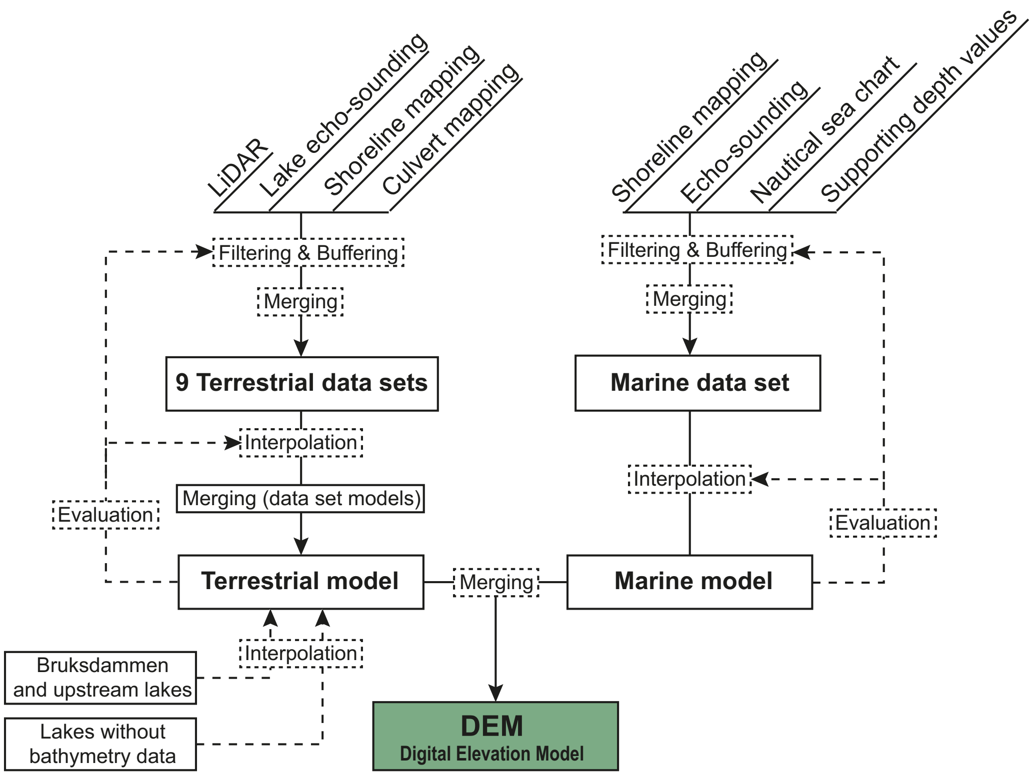

Figure 2-1. The workflow for producing the DEM. The marine and terrestrial areas were modelled separately (Petrone and Strömgren 2020).

The present DEM was proceeded by other DEMs that have considerably lower geographical resolution (Brydsten and Strömgren 2004a, Strömgren and Brydsten 2013). The main reason for the improvement is that high resolution laser scanning data (LiDAR) now is available in the whole terrestrial part of the model area.

One difficulty when producing the DEM was that the density and quality of elevation information varies considerably within water covered areas. Furthermore, the quantity of data is considerably higher in the terrestrial areas compared to the water covered areas. The final DEM has consequently a heterogenous accuracy within areas covered by water.

2.2 Data sources

Data from several different sources was used for interpolation of the DEM (Figure 2-2). Some data was obtained during the site investigations and other data was retrieved from external sources. Most data over lakes and marine areas were obtained during SKB's site investigations (Tables 2-1 and 2-2 in Petrone and Strömgren 2020). Different types of data were used in different parts of the model area, and the distribution of data is shown in Figures 2-2 and 2-3.

2.2.1 The terrestrial area

In several grids the classification has been enhanced by Lantmäteriet using the software TerraScan. For the terrestrial area airborne LiDAR data (Light Detection And Ranging) from Lantmäteriet was used. LiDAR data is used to determine the altitude of the ground surface but can also be used to determine e.g. tree height (Lantmäteriet 2009, 2020). The height model presented by Lantmäteriet has a vertical resolution of 0.25 m and a 2 m horizontal cell size. The model by Petrone and Strömgren (2020) used Lantmäteriets raw data to produce a DEM for the terrestrial areas with a 1 m horizontal cell size. Data was delivered to SKB by Lantmäteriet in the coordinate system SWEREF 99 18 00 and the height system RH 2000. The average point spacing within the grids ranges from around 0.7 to a little more than 1.5 points per m^2. Each point has been classified as either ground or water, or where no classification has been determined, as unassigned. The vertical accuracy of the delivered data has been determined by Lantmäteriet to be between 0.053 and 0.062 m and the horizontal accuracy approximately 0.3 m. Further information regarding methods and technical specifications of the laser survey is presented in Lantmäteriet (2009, 2020).

However, the Lantmäteriet height model partly classifies particularly thick vegetation (e.g. reed) as ground which may cause incorrect elevation values of up to several meters especially in areas with a dense high reed coverage. These errors were, however, to a large extent corrected in the DEM produced by SKB (Petrone and Strömgren 2020). The elevation data available for the terrestrial area have a higher density and is more evenly distributed compared to data from water covered areas. In the marine area most depth measurements are distributed along survey lines with no depth measurements at all in large areas between the survey lines. As a result of the large difference in the density and spatial distribution of data the modelling of the DEM was performed separately for the marine and terrestrial areas.

2.2.2 Lakes

During the SR-Site (SKB 2008), depth values were obtained from lakes in the central part of the model area (Brunberg et al. 2004) and that data was used for the DEM. Additional depth data from investigations of lakes that haven't been performed by SKB was included in the model (Brunberg and Blomqvist 1998). These lakes include Bruksdammen and upstream lakes from which water depths were digitalised by (Petrone and Strömgren 2020). In addition, unpublished results from SKB's depth soundings in Bruksdammen and estimated depths from Bruksdammen and upstream lakes were included in the model (see Table 2-1 in Petrone and Strömgren 2020).

There are, however, other lakes within the model area but outside the area investigated during SR-Site where no bathymetric surveys have been performed. Lakes lacking data with areas between 2.9 and 5.0 ha have been assigned a generic depth value of 0.59 m and larger lakes lacking data have been assigned a depth of 0.96 m. These values are based on mean depth in lakes studies during the site investigation (Brunberg et al. 2004). Smaller lakes and ponds lacking data were not assigned with depth data. In addition, depth data collected during 2014 by using echo sounding in Lake Eckarfjärden was used fort the DEM (see Petrone and Strömgren 2020).

2.2.3 Streams

The LiDAR data sometimes fails to register the stream bed in brooks due to vegetation and/or water. Additional measurements have therefore been made in the central part of the area (Brydsten and Strömgren 2005).

Culverts under roads cannot be detected in LiDAR data but is of importance for hydrological modelling. In and around the site investigation area the x and y position of culverts has therefore been measured using a handheld GPS device. Data representing the bottom levels of the culverts, were calculated based om LiDAR data from the in- and outgoing stream or ditch. The calculated values were used for the DEM (see Table 2-1 in Petrone and Strömgren 2020).

2.2.4 Wetlands

Water depths obtained during investigations of wetlands (Sohlenius and Hedenström 2009) around the access area for the spent nuclear fuel, Söderfjärden, were used. Most water covered wetlands lack, however, depth data. Large wetland areas are covered by reed, e.g. around Lake Bruksdammen, making it difficult to use LiDAR data for modelling the ground surface. These areas were processed and worked on extensively to obtain a satisfactory topography within these areas. However, these areas are partly covered by water with unknown depth.

2.2.5 Shoreline

A new shoreline was created for to separate the marine and terrestrial domains. A first evaluation shows that the shoreline model from Lantmäteriet has relatively large uncertainties in some areas (Brydsten and Strömgren 2004a), and a new model for the central part of the model areas has therefore been made. The uncertainties in the shoreline model have not been evaluated but data presented in Brydsten and Strömgren (2004a) shows that 95 % the DGPS measurements have an error that is less than 1 m.

The shoreline used for the DEM has four main data sources:

- In parts of the central studied area (Figure 2-2) the shoreline was measured using differential GPS (Brydsten and Strömgren 2004a).
- In areas with a well defined shoreline manual digitising of shoreline using aerial photos was used (Brydsten and Strömgren 2004a).
- Base maps from Lantmäteriet.
- The raw LiDAR data that differentiates between land and water (Petrone et al. 2020). It is difficult to identify the shoreline where there is significant vegetation between the solid ground and the open water surface. In such areas, the top of certain vegetation is identified as solid ground in LiDAR data, when it should be classified as water. For this reason, it was necessary to correct the shoreline further inland in many shallow sea bays where thick reed vegetation exists. For areas with reed the shoreline was therefore defined in areas lacking reed and thereafter extrapolated into the reed covered areas. That method was used by Petrone et al. (2020) in several lakes as well as in many sea bays to correct the shoreline from Lantmäteriet.

2.2.6 Marine area

Most bathymetric data from the marine area was obtained during SKB's site investigations. Data from digital nautical charts from the Swedish Maritime Administration (Sjöfartsverket 2015) was, however also used. The data from the marine area are shown in Table 2-2 in Petrone and Strömgren (2020).

Data from the site investigations

The areas represented by the different data sets used in the marine model are shown in Figure 2-2. The density and quality of data varies between the data sets (Figures 2-2 and 2-3). A large part of the data was obtained along lines (Figure 3-2) using a single-beam echo sounder (Elhammer and Sandkvist 2005) and the density of data is therefore high along these lines but considerably lower between the lines (Figure 2-3). In the detailed survey area (10 km^2), above SFR, (see Figure 2-2) a Swath sonar (Nyberg et al. 2011) was used for collecting depth data. The Swath sonar gives full cover bathymetric information along the measured lines with different widths depending on water depths and settings for the instrument. In this study, the widths were overlapping with nearest measured lines giving a full cover bathymetric map. However, the further out from the lines the less dense data. The water depth measurements were obtained simultaneously as backscatter from the Swath sonar. The backscatter gives information on horizontal regolith distribution. The sound pulses reflected from the seabed are used to calculate the water depth and the energy content (backscatter) is used to record the hardness and roughness of the seabed. The last information was used to interpret the distribution of different regolith types at the seabed.

The surface regolith maps were produced by combining the backscatter and bathymetric data and using data from seismics, sediment profiles and sampling. The survey methods are described further below in the text describing methods for investigating regolith (Section 3.1).

The distance between survey lines in the original data within the regional survey area is sometimes more than 1 000 m (Elhammer and Sandkvist 2005, Nyberg et al. 2011) with depth values at about 3 m distance between them along these survey lines. During 2015, SKB carried out additional echo sounding in the regional survey area (Figure 2-2) to improve the quality of the bathymetry data set (Petrone and Strömgren 2020). During the bathymetric survey, the distance between survey lines in the area was halved, but the distance between the lines is still long compared to the distance between measured depth values along the lines. Additional data from the digital depth chart was also used for modelling this area (see below).

Depth from the detailed survey area (10 km^2) were extracted from the processed Swath sonar water depth image of the sea floor (Nyberg et al. 2011). The images have a resolution of 5 × 5 m and the distance between depth points is 5 m within this area. No further processing was done on this data set. In the detailed survey area investigated by Elhammer and Sandkvist (2005) water depths were interpreted within that investigation, and no further processing was necessary. The interpreted data set consists of depth values extracted from interpreted depth contours based on the bathymetric measurements (Elhammer and Sandkvist 2005).

Depths in shallow bays have been measured by Brydsten and Strömgren (2004b). In certain of the shallow bays, depth values have been estimated since no measurements could be performed. These depth values are often found close to the shoreline or in areas where there is a lot of subsurface vegetation (i.e. *Chara algae*), which makes it impossible to make proper depth measurements. To increase the quality of the bathymetry data set for Asphällsfjärden and Söderviken, a complementary bathymetric survey was performed in 2015 (Table 2-2 in Petrone and Strömgren 2020).

A previously rectified and digitised depth chart map was used for Biotestsjön (see Table 2-2 in Petrone and Strömgren 2020). No additional measurements or processing were made for that area.

Digital depth chart

A digital depth nautical chart from the Swedish maritime administration (Sjöfartsverket 2015) was used in the construction of the DEM in some coastal areas (Figure 2-2). The main purpose of the digital depth chart is to support any areas where little or no other depth data exists.

The following processing was made to this data set:

- Depth point values were extracted every 25 m along the 3, 6 and 10 m depth contours.
- Depth point values were extracted every 50 m along the 15, 20 and 30 m depth contours.

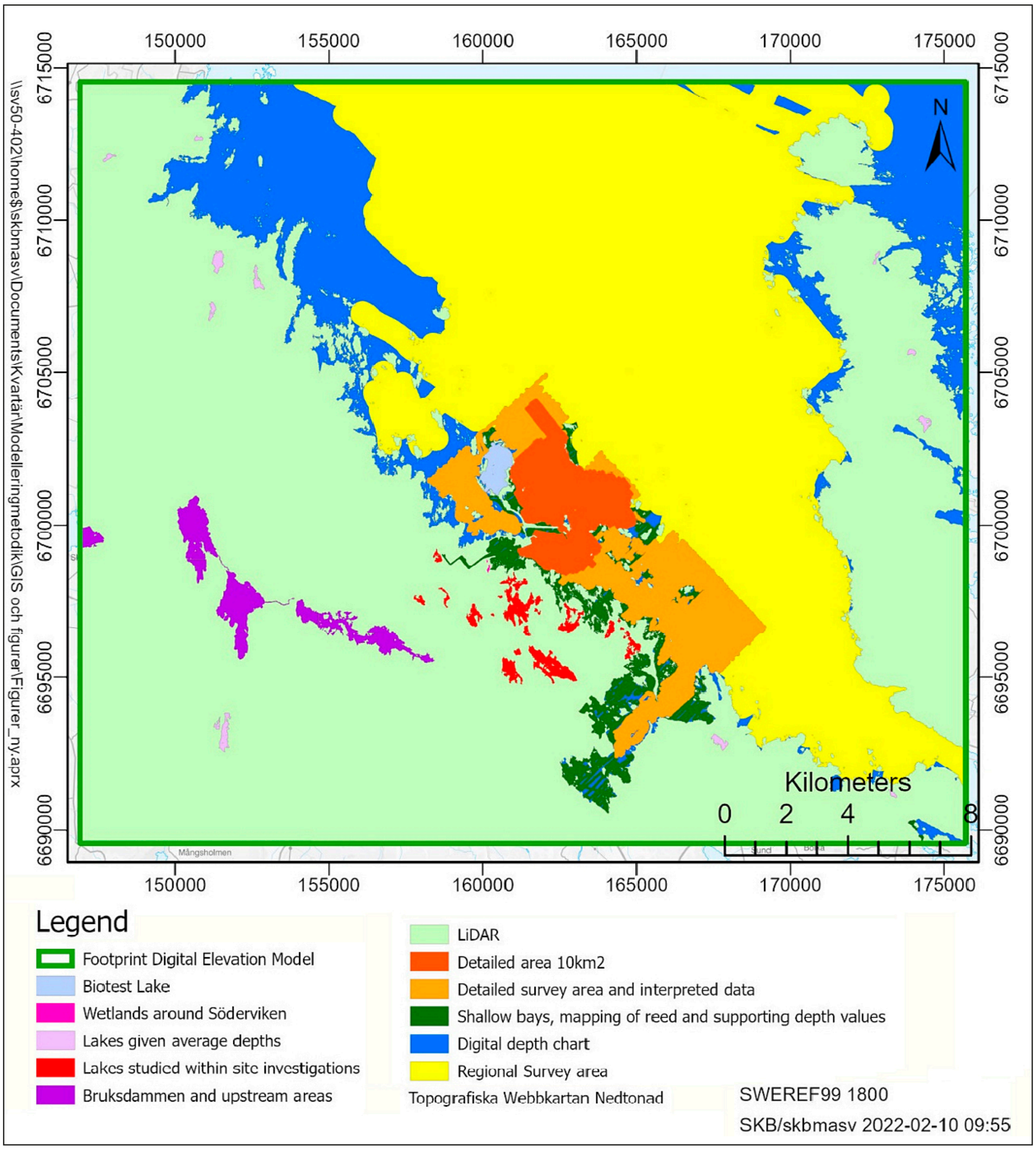

Figure 2-2. *Different data sets were used for interpolating the marine bathymetry. Most data were collected during SKB's site investigations.*

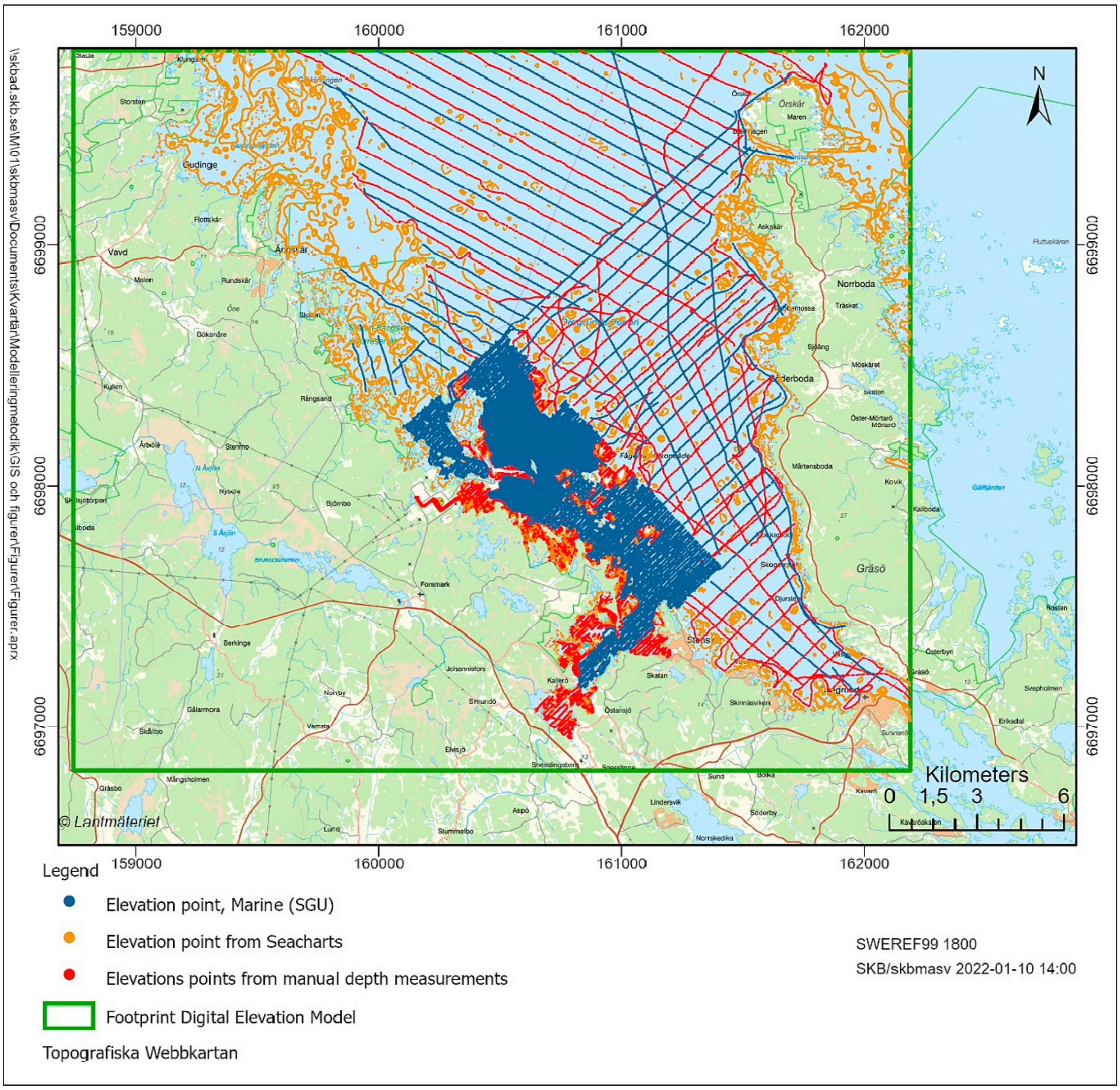

***Figure 2-3.** Data points used in the interpolation of the marine model. A large part of the data was collected along lines during SKB's site investigations. Data from the digital depth nautical chart has also been used (Sjöfartsverket 2015). It is obvious that the data is not evenly distributed in the area.*

2.3 Method

2.3.1 Modelling

The methodology for producing the DEM is summarised in Figure 2-1. The terrestrial part of the model area is c 352 km^2 and more than 150 million elevation points are used in the interpolation performed to produce this part of the DEM, i e almost one point for each 2 m^2. The marine part of the model covers a slightly smaller area, c 322 km^2, but only 1.1 million elevation points are available for the interpolation providing the basis for this part, i e in average one point per 300 m^2. The fact that more than 99 % of elevation data are in the terrestrial part of the model area made it necessary to divide the model into two sub-models, one for the terrestrial area and one for the marine area. This made it possible to run kriging modelling separately for the two sub-models, thereby obtaining better and more realistic results than if the whole area had been handled in the same modelling exercise. In the integrated model, the two sub-models are merged without overlap and with a smooth transition that could be achieved since elevation data from the shoreline was used when modelling both areas. Lakes with bathymetrical data and measurement from streams were added to the terrestrial dataset whereas Bruksdammen and upstream lakes as well as lakes with no data were modelled separately.

The DEM was produced by using kriging (Davis 1986, Isaaks and Srivastava 1989) interpolation in ArcGIS 10.3 Geostatistical Analysis extension. The kriging method used for this interpolation is thoroughly described in Petrone and Strömgren (2020).

In kriging, regularly spaced digital elevation models are produced from irregularly spaced point values. Ordinary kriging in the software ArcGis 10.3 Geostatistical Analysis extension was used. Several test interpolations were performed to obtain the final data sets used for the interpolation of the DEM. The aim of these tests was to produce a DEM representing the Forsmark area with as high accuracy as possible. However, in the marine part of the DEM a smoother surface was prioritised instead of high accuracy along the survey lines, due to the uneven distribution of depth data. That was decided since a high density of data along the lines might cause an unrealistic imprint along the lines, something that has been observed in an earlier version of the DEM (Strömgren and Brydsten 2008). As mentioned above, the interpolation was done in two main domains due to the big difference in density and spatial distribution of elevation data. Land, including lakes in the central part of the area, and the marine area were therefore modelled separately. Digital elevation models with 1 and 5 m resolutions were produces in models covering the terrestrial area. In the marine area 10 and 20 m resolutions were produced. Furthermore, models with 10 and 20 m resolutions were produced for the whole modelled area. The DEM was constructed in two projected coordinate systems, RT 90 2.5 gon V and SWEREF 99 18 00 with the associated height systems RHB 70 and RH 2000, respectively.

Lantmäteriets height model is, as mentioned above, based on LiDAR data. In some areas with dense vegetation (e.g. bushes or reed) the ground surface can, however, be misinterpreted when modelling the ground surface. Petrone and Strömgren (2020) therefore processed the LiDAR-data in large areas with reed and at the outlets of certain lakes to obtain a correct topography. This was important to secure that water will exit lakes at the correct locations in hydrological models built on the DEM. Furthermore, Petrone and Strömgren (2020) processed the LiDAR data to obtain a DEM with 1 m horizontal cell size compared to the 2 m model presented by Lantmäteriet.

In most parts of the marine area depth data was, as mentioned above, collected along survey lines using a single-beam echo sounder. In some cases, there are elevation points every 3 to 5 m along these survey lines. However, the distances between survey lines are in some areas 500 m, and between these lines the density of data from the nautical chart is low. This is a challenge for the kriging interpolation as the interpolation is unable to predict a realistic surface in areas with such long distances between data points. As a result, the modelling could produce interpolation artefacts forming false topographical linear structures along the investigated lines. Furthermore, data from the nautical chart have too low weight compared to the data from the survey lines, and structures between the lines may therefore be omitted in the final DEM. To minimise these effects, it was decided to modify the modelling procedure as follows:

1. Increase the distance between elevation points along survey lines to avoid false linear structures along these lines (decreased number of points).
2. Increase the weight of specific elevation points from the digital nautical chart (increased number of points). These points are situated between the survey lines and the increased numbers are used to improve the quality of the DEM in areas situated between the survey lines.
3. Adjust the kriging model parameters to include distant data points (Petrone et al. 2020).

Therefore, only a few linear structures along the survey lines were obtained in the final DEM and in total the surface in the marine sub-model has a smooth appearance. The disadvantage is that the accuracy along survey lines decreases due to the smoothing. However, this compromise was considered to give a more realistic bathymetry, avoiding artefacts produced by the uneven distribution of depth data.

The models for the land and sea domains were merged into one DEM, representing the whole Forsmark area. A raster layer representing the bathymetry in Lake Bruksdammen and for lakes lacking depth data was produced separately (see Figure 2-2), That raster was thereafter merged into the DEM.

2.3.2 Validation

The uncertainties in the model have been evaluated and are thoroughly described in Petrone and Strömgren (2020). Both the terrestrial and marine parts of the model have been evaluated and validated, but there are still areas for which no validation data exists. These areas include Lake Bruksdammen and upstream lakes with surrounding wetlands, lakes without bathymetry data, lakes studied during the site investigation, the nuclear power plant inlet canal and Lake Biotestsjön. It would be possible to validate bathymetry for the lakes studied during the site investigation. The area defined as the lake boundary for these objects also includes large areas of wetlands surrounding the lakes.

Unfortunately, there are no depth data in these wetland areas and validation, only using existing data, of the lakes would therefore be misleading. This is because it would only be possible to validate the open water surface where actual measured depth values exist. More data from wetlands surrounding the lakes is needed to do a prober validation of these areas.

The terrestrial area

To evaluate the accuracy of the terrestrial part of the DEM, measured elevations were collected from 264 locations in central terrestrial parts, of the model area. These points were not used when modelling the DEM but were instead used for validation of the model. The distribution of the validation points is shown in Petrone and Strömgren (2020). A statistical analysis of the differences between the measured elevations and modelled elevations was made (Table 2-2). The results of the validation show a generally good agreement between measured and modelled elevations. As expected, the best agreement is found for the 1-m model, followed by the 5-, 10- and 20-m models (in order of declining agreement). The larger difference between measured and modelled elevations in the 20-m model compared to the models with higher resolution reflects the larger variation in elevation for LiDAR data within a 20-m cell compared to the smaller cell sizes. The statistics from the validation also show that no differences larger than 1 m between measured and modelled elevations are found in the 1-m model, whereas differences larger than 1 m are unusual in the 5- and 10-m models and differences larger 2 m are unusual in the 20-m model. One reason for the relatively low differences between the model and validation data is the relative flatness (small height variations) of the model area.

Table 2-2. Statistical analysis of differences between measured and modelled elevations at selected locations within the terrestrial part of the model area (from Petrone and Strömgren 2020). No test of normal distribution was performed.

Model	N	RMS	Mean	STDV	Min	Max	5 %	95 %
1 m	264	0.19	−0.08	0.18	−0.56	0.54	−0.35	0.21
5 m	264	0.27	−0.08	0.25	−1.03	1.17	−0.43	0.30
10 m	264	0.37	−0.05	0.37	−1.55	1.68	−0.62	0.51
20 m	264	0.67	0.01	0.67	−1.87	2.57	−1.13	1.33

N = number of points used for the calculation, RMS = root mean square, mean = mean difference, STDV = standard deviation, min = minimum difference, max = maximum difference. The two columns to the right show the 5th and 95th percentiles.

The marine area

The accuracy of the DEM varies within the marine area, due to the variation in quality and spatial density of depth data. To validate and evaluate the model, the marine area was divided into five subareas with internally similar distributions of depth data: the regional survey area, the detailed survey area, the detailed survey area (10 km^2), the shallow bays and the digital nautical chart (shallower than 10 m), see Figure 2-2. Almost 1 000 depth measurements were used for the validation of these five areas. A statistical analysis of the differences between measured and modelled depths was made (Table 2-3). The results of the statistical analysis of the difference between measured and modelled depths are often around 0.5 m in the shallow bays and in the detailed survey areas. Differences larger than 1 m are unusual in in these areas. In the regional model area and in areas where only digital nautical charts are available the differences between measured and modelled depth values are considerably larger. The differences are especially large in the areas that only has data from the nautical chart as input to the model, where the average difference between measured and modelled values is over 2 m, whereas the average difference is c 1 m in the regional survey area. Differences between measured and modelled water depths larger than 3 and 4 m are not unusual in the regional survey area and in the area only produced from the digital nautical chart, respectively.

Table 2-3. Statistical analysis of differences between measured and modelled depths at selected locations within the marine part of the model area (from Petrone and Strömgren 2020). No test of normal distribution was performed.

Area	N	RMS	Mean	STDV	Min	Max	5 %	95 %
Regional survey area	266	1.18	−0.55	1.77	−6.80	3.86	−3.71	2.02
Detailed survey area	252	0.58	0.19	0.48	−1.42	1.98	−0.60	1.04
Detailed survey area (10 km^2)	185	0.61	0.34	0.51	−0.54	2.26	−0.21	1.43
Shallow bays	58	0.49	−0.16	0.46	−0.97	1.72	−0.70	0.72
Digital nautical chart	219	2.63	−2.21	1.43	−6.10	1.80	−4.80	0.08

N = number of points used for the calculation, RMS = root mean square, mean = mean difference, STDV = standard deviation, min = minimum difference, max = maximum difference. The two columns to the right show the 5th and 95th percentiles.

2.3.3 Discussion

The DEM representing the terrestrial areas has a high quality and is based on data with a dense and even distribution. This part of the DEM probably has enough accuracy for most or all users. The areas covered by water on the other hand generally have an uneven distribution of data (Figure 2-3) and the density of data is in some areas low. It is therefore recommended that future updates of the Forsmark DEM should focus on areas covered by water and in particular parts of the coastal zone and the regional survey area. One area of special interest is the bay Söderviken situated close to the place where the planned repositories will be situated. Technology not used during the site investigations could be used to drastically increase the quality of the bathymetry model, as was done here for the detailed survey area situated above SFR (Detailed area 10 km^2 in Figure 2-2). Future updates of the DEM are discussed in Section 3.5.

3 Regolith data and models

Regolith data has been used for models showing the distribution and properties of the most commonly occurring regolith types (Table 3-1). These models will be further developed by using additional data and new modelling tools.

Table 3-1. The regolith models.

Product	Resolution	Description	Reference	Reference to SKB model database
Regolith Depth Model (RDM)	20 × 20 m	Depth and surficial distribution of the most common regolith types.	Petrone et al. (2020)	1933818
Regolith Depth Model (RDM) for the area Söderviken	1 × 1 m	Depth and surficial distribution of the most common regolith types in the area Söderviken (Forsmark).	Follin (2019)	1933838
Regolith map	The resolution is differing between different areas and is described in the text below and in several reports (see Table 3-3 and Figure 3-1).	The surficial distribution of different types of regolith.	Petrone et al. (2020), Sohlenius et al. (2019)	Waiting to be uploaded
Regolith map local for the area Söderviken	This map has a high resolution and show the distribution of regolith at the ground surface.	The surficial distribution of different types of regolith in the area Söderviken (Forsmark)	Follin (2019)	1859082

Regolith refers to the unconsolidated deposits overlying the bedrock. The vertical and horizontal distribution of regolith in the Forsmark area have been investigated within several studies (Table 3-2). Most studies were carried out during the site investigations. Furthermore, numerous samples have been analysed for different chemical and physical properties. Most data were collected during SKB's site investigations, but data has also been collected by other actors. In addition, some studies have also, been carried out after the site investigations.

Table 3-2. Method descriptions used for investigating the distribution of regolith.

SKB method description	Author	SKBdoc id
SKB MD 131.001 Metodbeskrivning för Jordartskartering	Kärstin Malmberg Persson, SGU	1229503
SKB MD 131.002 Metodbeskrivning för torvmarksundersökning	Dag Fredriksson, SGU	1229504
SKB MD 260.001 Metodbeskrivning för maringeologisk undersökning	Anders Elhammer (SGU), Leif Stenberg (SKB)	1229525

3.1 Maps of regolith

Several methods have been used to determine the vertical and horizontal distribution of the different types of regolith (Table 3-3). The map of regolith shows the surficial distribution of regolith and is a compilation of nine maps, originally produced with different methods (Figure 3-1) and adjusted for presentation at different scales. The maps are denoted from "Area 1 (a and b)" to "Area 8". The regolith map covers the whole modelled area and can be used to ascribe properties to the surface layer. The maps show the distribution of regolith at a depth of 0.5 meters. This depth is used to characterise deposits that are more or less unaffected by surface processes (e.g. weathering and bioturbation). Thinner layers of regolith covering large areas are, however, also shown on the maps, e.g. thin layers of sand commonly occurring at the sea floor and thin layers of peat in wetlands. As for the DEM with high resolution the regolith map for the marine area is not public due to safety restrictions (SFS 2016:319).

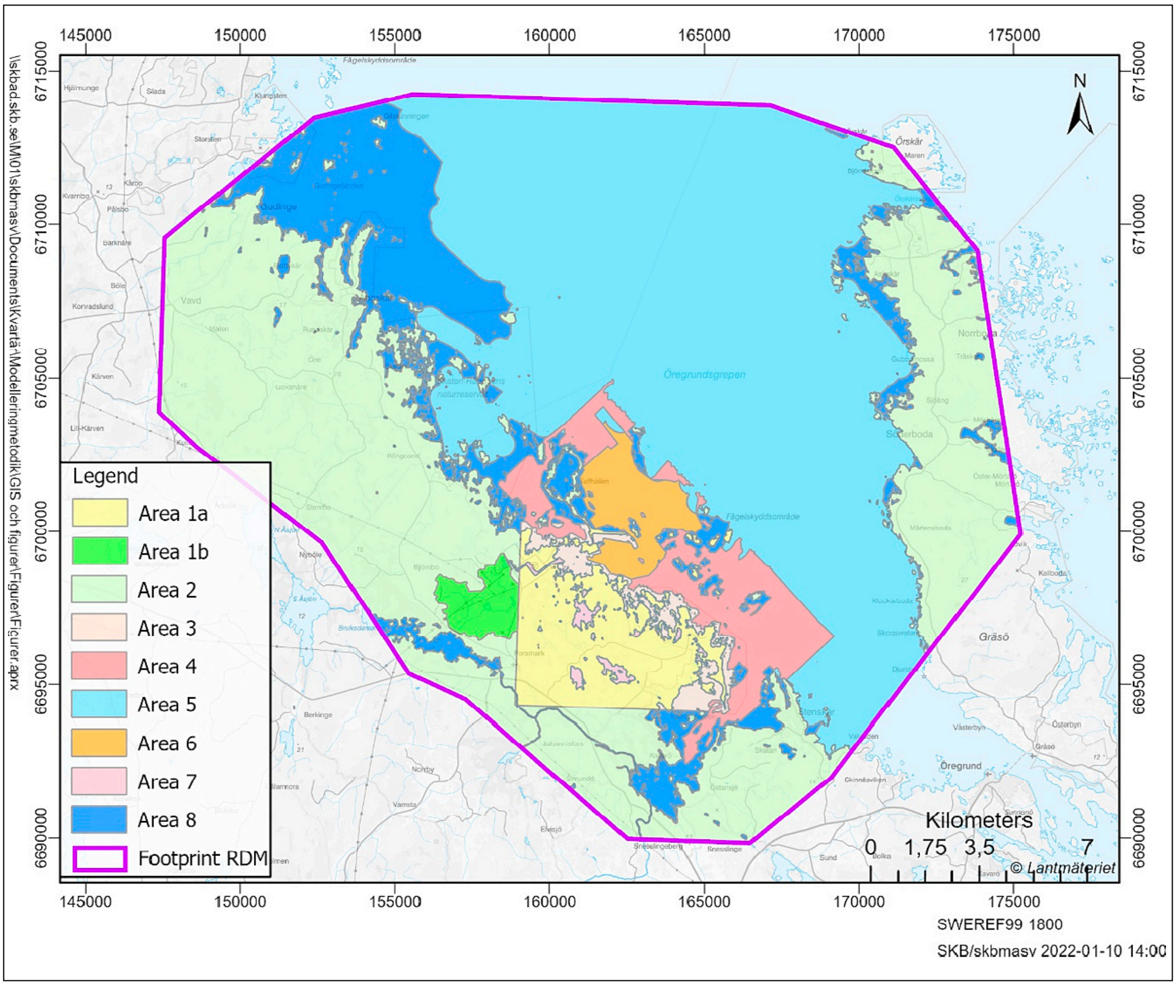

Figure 3-1. The distribution of the areas represented on the nine different maps of regolith. The methods used for mapping the areas are briefly described in Table 3-2 and in the text.

Table 3-3. Short description and references to the methods used to produce the regolith map. The geographical distribution of the different areas is shown in Figure 3-1.

Area	Area km²	Type of data	Reference
1a (Terrestrial)	23.42	Detailed regolith map for presentation in 1:10 000.	Sohlenius et al. (2004)
1b (Terrestrial)	4.79	Detailed regolith map for presentation in 1:10 000.	Sohlenius et al. (2019)
2 (Terrestrial)	165.72	SGU map of regolith for presentation in 1:50 000.	Persson (1985, 1986)
3 (Marine)	3.31	Distribution of regolith in shallow coastal areas.	Ising (2006)
4 (Marine)	21.66	Detailed distribution of regolith in coastal areas with water depths between 3 and 6 m. Depth and stratigraphy of regolith obtained along lines with a spacing of 100 m.	Elhammer and Sandkvist (2005)
5 (Marine)	195.49	Distribution of regolith at the sea floor in areas with water depths > 6 m. Depth and stratigraphy of regolith obtained along lines with a spacing of 1 000 m with data from some additional crossing lines.	The central part of the area was interpreted by Elhammer and Sandkvist (2005) and reinterpreted by Nyberg et al. (2011). The map representing the whole area is available in the SGU database. Data for parts of the area are only available in the SGU database.
6 (Marine)	10.04	Detailed distribution of regolith in coastal areas with water depths between 3 and 6 m = Depth and stratigraphy of regolith obtained along a network of lines with a spacing of 100 m.	Nyberg et al. (2011)
7 (Lakes in the central part of the model area)	1.60	Interpretation from corings in lakes.	Hedenström (2003, 2004a, b), Sohlenius and Hedenström (2009)
Area 8 (Lakes and shallow bays)	59.33	Interpreted from DEM and surrounding regolith.	Interpreted from distribution of surrounding regolith (Hedenström and Sohlenius 2008)

The regolith types shown on the map and in stratigraphical descriptions are defined based on properties such as grain size and organic content. But the nomenclature is also based on the environment and processes that caused the formation of the regolith types. The nomenclature used by SKB is equivalent with the one used by SGU and is described in several reports (e.g. Hedenström and Sohlenius 2008, Karlsson et al. 2021).

3.1.1 Terrestrial

The regolith map representing the terrestrial area is a compilation om maps from SKB's investigations and maps that have been produced within SGU's regular mapping program (Karlsson et al. 2021) that currently is updating and producing new maps all over Sweden. All these maps demonstrate the distribution of Quaternary deposits (QD) at a depth of 50 cm below ground surfaces. Surface layers thinner than 50 cm have also been marked in the map (e.g. peat overlying other deposits). In areas with till the surficial frequency of boulders and effects of wave-washed surface layers were also determined in the field. The map also includes objects marked as points or line, e.g large boulders and end moraines respectively.

The most detailed map (Sohlenius et al. 2004, 2019) covers the terrestrial area in the central part of the model area (Area 1a and b in Figure 3-1). It includes all observed bedrock exposures and regolith with areas larger than 10×10 m². The detailed geological map was initially presented at the scale 1:10 000.

Area 2 is represented by data from the Geological survey of Sweden (SGU) database for regolith in terrestrial areas and is adapted for presentation at the scale 1:50 000. That map also covers areas beyond the areas investigated by SKB and were originally published by Persson (1985, 1986).

In Area 1a and b the older SGU map represented in Area 2 was replaced by more detailed map (Sohlenius et al. 2004) that largely was produced during the site investigation (SR-Site). However, Area 1b (the drainage area of Gunnarsboträsket) was mapped later (Sohlenius et al. 2019).

The methods for studies and classification of QD used during the site investigation (SR-Site) are described in detail in SKB MD 131.001 (Table 3-2). That is the same method as used during SGU's regular mapping, except that the aim SKB's investigation was to produce a map with much higher geographical resolution. Before the fieldwork in Area 1a started, aerial infrared photos, taken from a height of 2 300 m, were interpreted by using a computer. Areas with exposed bedrock were marked. This information was checked during the fieldwork. In the field, the distribution of QD was marked directly on high resolution aerial photos and a GPS was used for positioning. All Quaternary deposits, which can be delimited from other deposits, and have an area larger than 100 m^2, were marked on the aerial photo as surfaces. The QDs were classified in the field using samples taken with a spade or a hand driven probe. Certain samples were analyses for grain size distribution to verify the field interpretations. In addition, the direction of glacial striae found on outcrops was determined using a mirror compass.

The methodology for mapping QD has however changed slightly since the studies of QD that took place during SKB's site investigation more than 15 years ago. During mapping of the drainage area of Gunnarsboträsket (Area 1b) Sohlenius et al. (2019) used methods that nowadays are used within SGU's regular mapping (Karlsson et al. 2021). The mapping of QD is now to a large extent supported by Lantmäteriets digital elevation model that is based on laser scanning (LiDAR). Since topography and QD correlates the digital elevation model is used to delineate different types of QD, making it possible to produce maps with a high geographical precision. As an example, areas with water deposited clay or silt are characterised by flat surfaces whereas till has a much rougher surface, and it is therefore possible to delineate these types of deposits with high precision using LiDAR. Today more interpretations can consequently be made using GIS-software and less field work is needed. Aerial photos are still used for interpreting the distribution of QD but are of less importance due to the use of LiDAR data. Before the fieldwork in Area 1b started the old QD map (Persson 1985, 1986) was reinterpreted by using LiDAR data and aerial orthophotos. The reinterpreted QD map was exported to a field computer. Other geographical data such as topographical maps, aerial photos and the height model was also stored in the field computer. In the field, the mapping of QD was done using the field computer with GPS. It was then possible to use the computer for delineating different types of QD in the field. The geographical distributions of the different QD were marked directly in the field computer. Delineations between different types of QD were, as mentioned above, interpreted before the fieldwork started. Many of these delineations were correctly interpreted already in the office when preparing for the fieldwork. In the field new delineations were only made when misinterpretations were discovered or where deposits not recognized in the office were discovered. In Area 1b small outcrops were marked with a point symbol. Several classes of thin surface layers (< 50 cm) are demonstrated in the map for Area 1. These thin layers, except thin peat layers, are not shown on the earlier SGU maps from the area (Persson 1985, 1986).

Before the use of field computers, the field map had to be redrawn by hand and thereafter digitised. That method was used for the map representing Area 1a as well as for the area mapped during SGU's regular mapping (Area 2). Since all interpretations, today, are made in the computer fewer steps are required during the transformation of field data into the final map. That makes it less probable for errors to occur during the transformation. Furthermore, Area 2 was mapped before the use of GPS and the delineation of different QD types were therefore highly dependent on the skill of the field geologist. The development of new mapping methods has, however, not changed the classification system used for describing different types of regolith.

In addition to the maps described above a detailed map for the of the access area for the planned spent nuclear fuel repository was produced (Follin 2019). That map differs from the other maps since it shows the distribution of the uppermost regolith whereas the other maps show the distribution at a depth of 0.5 m below ground surface.

3.1.2 Marine areas and lakes

The distribution of regolith in the marine area was mapped during SR-Site and SR-PSU (Elhammer and Sandkvist 2005 and Nyberg et al. 2011 respectively). Additional data was collected in 2008 during SGU's regular mapping programme. Data for the DEM was collected simultaneously as the geological surveys.

In the shallow coastal bays, Area 3 (Figures 3-1 and 3-2), the survey vessel used for the regular mapping could not enter. Therefore, the distribution of regolith was investigated as point observations by sampling regolith from the sea ice or using a small boat (Ising 2005). Many of the studied points include determinations of the thickness of regolith layers (Figure 3-3). It was, however, not possible to determine the total thickness of regolith with that method. The investigations were performed along lines, approximately 200 meters apart. This method makes the precision of the map adapted to the presentation scale 1:50 000 and regolith areas smaller than 50 × 50 m^2 are not displayed.

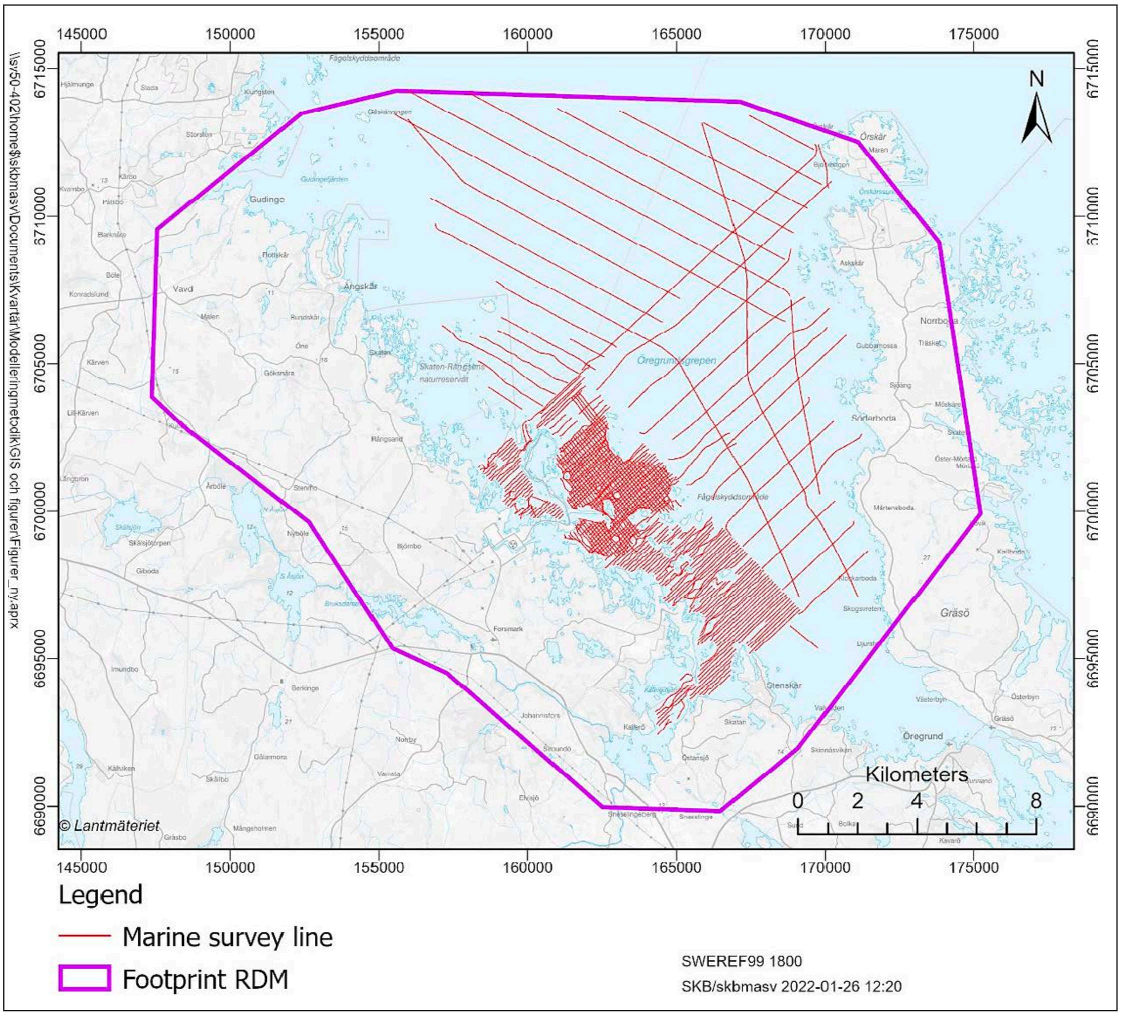

__Figure 3-2.__ Lines in the marine area along which hydroacoustic data from side-scan sonar or swathsonar, single beam echosounder, seismics and sediment profiler were collected. The results were used for modelling both total regolith thicknesses and the thicknesses of the individual regolith layers. Depth data that was used for the DEM was collected contemporaneously.

Regolith data, including stratigraphical information and surficial distribution if the deposits, from Area 4, Area 5 and Area 6 were collected from boat by SGU (Figure 3-1), simultaneously as depth data was collected. The distribution of regolith map types therefore coincide with the areas with different types of depth data (Figure 2-2). Data from these areas were used to determine the geographical distribution of regolith as well as the thickness of the regolith layers. In Area 4 geological data were collected along lines with a distance of 100 m (Elhammer and Sandkvist 2005). For Area 5 there are data along lines with a spacing of c 1 000 m, collected during the SKB site investigation (Elhammer and Sandkvist 2005) and during 2008 within SGU's mapping programme. It was possible to improve the map by Elhammer and Sandkvist (2005) since additional data was collected in Area 5 during 2008. A new more detailed map representing Area 5 was therefore produced by Nyberg et al. (2011). The data obtained by SGU in 2008 was used for that reinterpretation. Data from both Area 4 and 5 was originally presented by Elhammer and Sandkvist (2005) at the scale 1:100 000.

Area 6 represents the area above the present SFR and comprises data obtained from network of lines with a spacing of 100 m, which was interpreted by Nyberg et al. (2011). Data from some of these lines were collected and originally interpreted by Elhammer and Sandkvist (2005).

Area 7 comprises lakes and ponds in the central part of the model area and were investigated by the same method as used in shallow bays (Area 3, Ising 2005). The thicknesses of the regolith layers have been determined in almost all lakes and ponds (Hedenström 2003, 2004a, b, Sohlenius and Hedenström 2009). This was done using a hand driven corer and it was therefore not possible to determine the thickness of the till. The horizontal distribution of regolith in Area 7, as well as in Area 3, was interpreted using the point data from the stratigraphical investigations. To obtain a complete map showing the distribution of regolith, the remaining areas located under shallow water in the marine area and under the lakes and streams were interpreted as well. The resulting map (Area 8) is based on interpretations from the general knowledge of regolith in lakes and bays (e.g. Hedenström 2003; Ising 2005), bathymetry from the DEM and the distribution of regolith in surrounding terrestrial areas. The regolith map in Area 8 has consequently larger uncertainties than in other areas.

Different types of instruments were used for mapping the distribution of regolith at the sea floor (Areas 4, 5 and 6). The surveying was performed along pre-planned survey lines using different types of hydroacoustic equipment. A single beam echo sounder, a sediment profiler and seismics were used to map the vertical distribution of regolith along the lines (Elhammer and Sandkvist 2005, Nyberg et al. 2011). These three instruments emit sound with different frequencies and energy that to different extent penetrate the water and sea floor. The sound from the emitters is reflected at the seafloor and at the depth transitions between different types of regolith. By measuring the reflected sound, it is possible to calculate properties such as water depth and thickness of regolith layers. The depth profiles are used to interpret the regolith types and their vertical distribution. The echo sounder emits sound with high frequency, the sediment profiler has a lower frequency and the seismics the lowest. Instrumentation for reflection profiling in the range above c 10 kHz are mostly referred to as echo sounders, whereas those in the range 3–10 kHz are called sediment profilers. Technically they are very similar, using ceramic transmitters which usually also serve as receivers. Below c 3 kHz it becomes necessary to use other types of transmitters; air guns, water guns and various types of high voltage transmitters. These low frequency instruments, referred to as seismic profilers, also require separate receivers in the form of hydrophone arrays. The instruments with high frequency are not able to penetrate all regolith layers but have on the other hand a higher resolution, whereas the seismic profiler with low frequency can penetrate all regolith overlying the bedrock but have a lower resolution. The sediment profiler (sub bottom profilers) can produce sound penetrating fine grained sediments and sand, under favourable conditions down to more than 50 m below the seafloor. It is however rarely possible to penetrate till with this method. A high-resolution reflection seismic system was therefore used to acquire information about the subsurface geology down to the bedrock. The till and bedrock surfaces are usually derived from these seismic soundings when the soundings from the sediment profiler are attenuated.

Side-scan sonar (SSS) or Swath sonar equipment was used to obtain information about the seabed surface. That method is used to survey the properties of the sea floor and was done along the same lines as used for the investigations described above. The ship tows the SSS transducer, while the Swath sonar is hullmounted, and the survey coverage is normally from a few tens to hundred meters across the survey line depending on water depths and wanted resolution. The intensity of the reflecting sound corresponds to different sediments and seabed textures. Data from SSS are converted into images, which in turn are used by the geologist for interpreting the surficial geology of the seabed.

Sampling was done to verify the geological interpretation of the acoustic data and to solve interpretation problems. Different types of sampling methods were applied: In soft sediments 1 and 6 m corer were used. The 6 m corer was used at one site and gives a stratigraphical model of the sampling point. Coarser sediments were sampled with a grab sampler. Before sampling the sea bed, the sampling site was filmed with an under-water video camera and notations were made in a protocol.

Nyberg et al. (2011) used a Swath sonar also for water depth measurements, which gave a full cover bathymetric dataset for the sea floor in Area 6 (Figure 3-1).

3.1.3 Stratigraphy and total depth

Several methods have been used to obtain data representing depth and stratigraphy of regolith. The stratigraphical information was used as input to the regolith depth model (see Section 3.4 below).

These methods are only shortly described here but are thoroughly described in the reports cited below. The data includes both direct observations from e.g. drillings and interpretations from different types of geophysical measurements (Figures 3-3 and 3-4). Results from direct observations are generally more reliable than interpretations from geophysics, even though such result in many cases have a high quality.

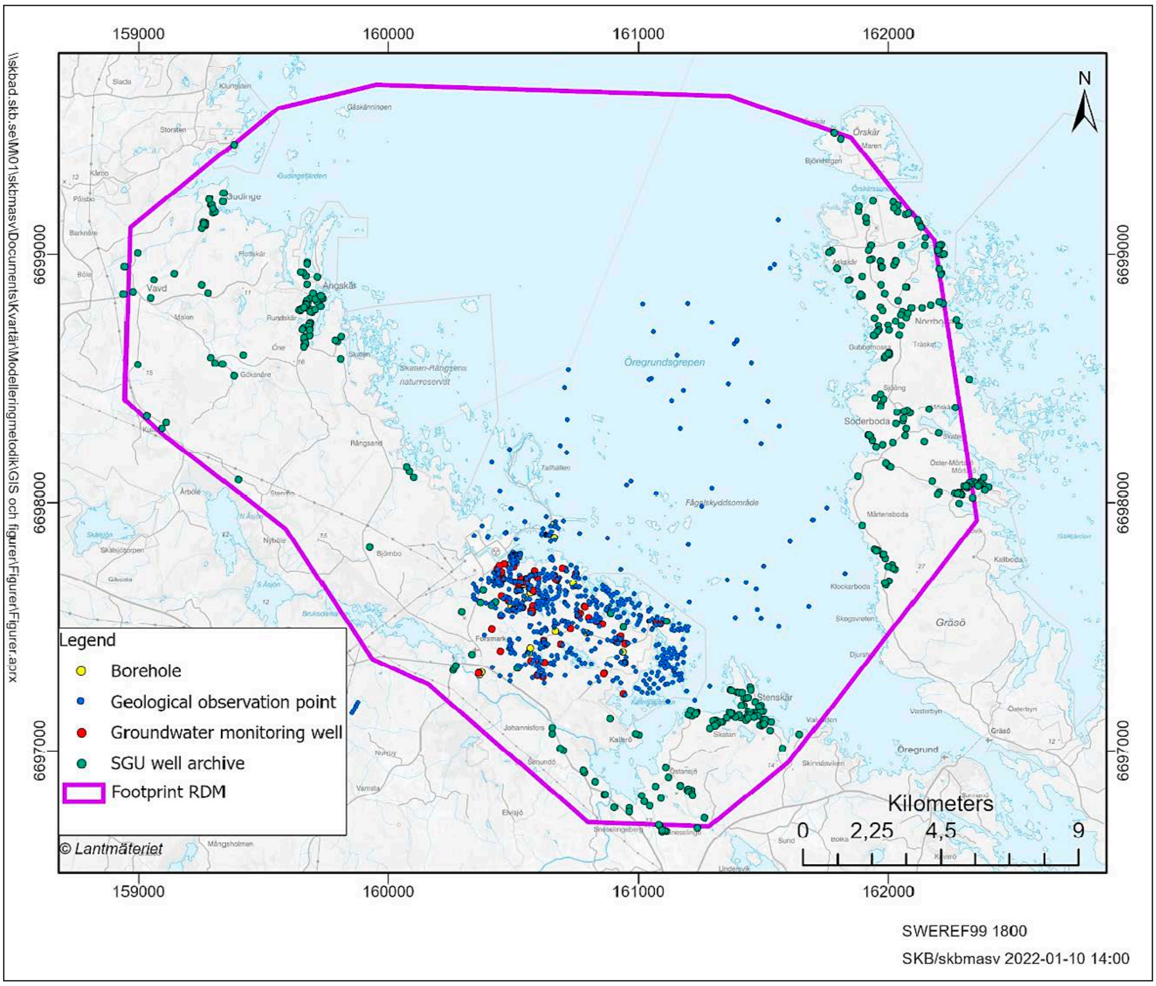

Figure 3-3. Distribution of stratigraphical data that were used for modelling the total regolith depth and the thickness of the different regolith layers.

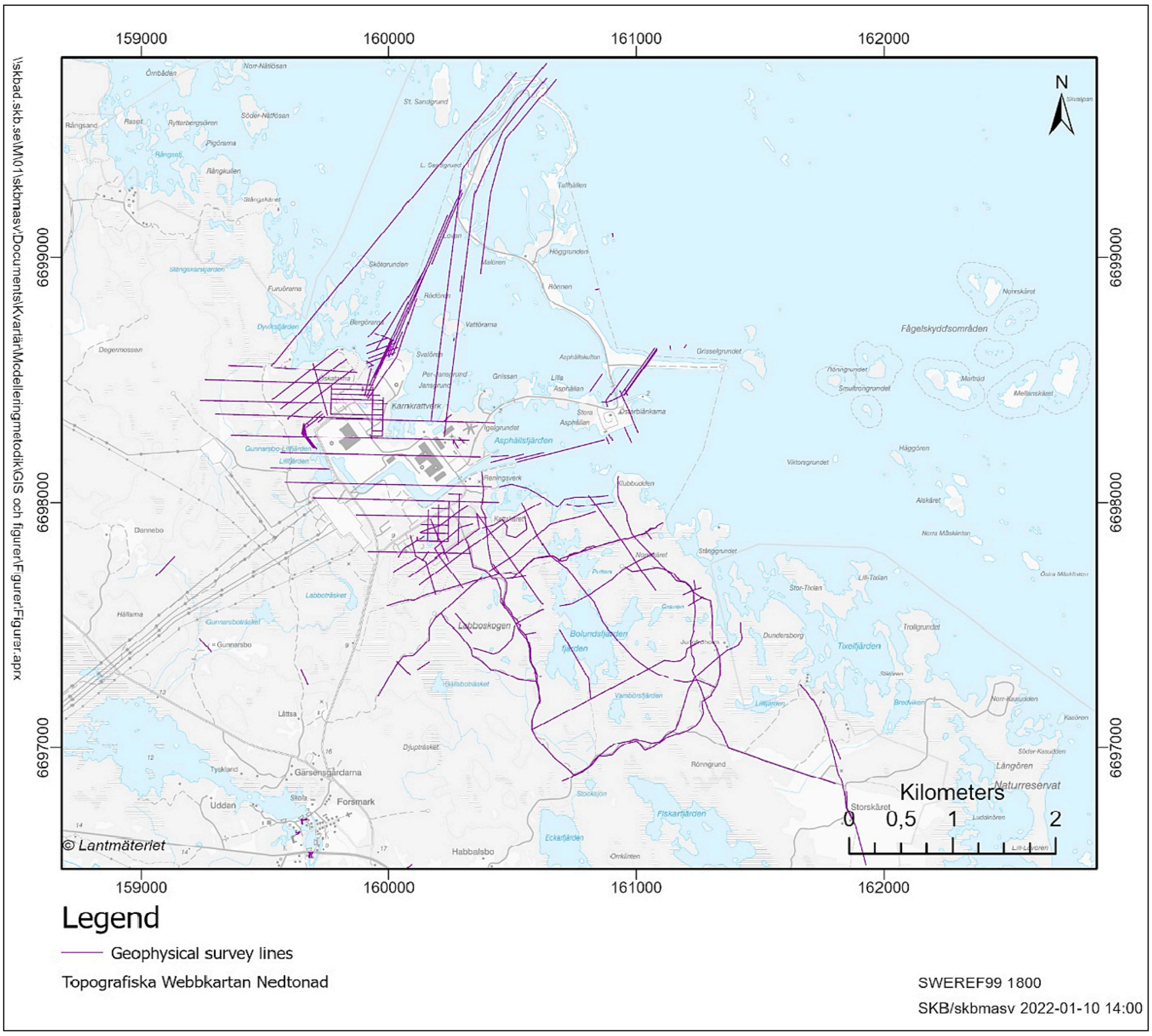

Figure 3-4. *The distribution of data from refraction seismics and continuous vertical electrical soundings (CVES) that were used for modelling the total thickness of regolith.*

In lakes, wetlands and shallow bays, the stratigraphy of clay and gyttja was determined by characterisation of cores (Area 7) obtained by hand coring (Ising 2005, Hedenström 2003, 2004a, b, Sohlenius and Hedenström 2009). This method makes it possible to sample soft sediment but not coarse grained regolith layers (e.g. till). Large efforts have been put on investigating stratigraphy and regolith properties in some of the wetlands having high nature values (e.g. Sohlenius et al. 2020).

Additional stratigraphical information was obtained from the mapping of regolith in the terrestrial areas (Sohlenius et al. 2004) and by stratigraphical studies in machine dug trenches (Albrecht 2005, Sundh et al. 2004). Most of these observations did not reach the bedrock surface. To evaluate development and possible future land use of wetlands two peatlands were investigated by Fredriksson (2004).

Numerous drillings were performed for installing groundwater-monitoring wells and data from these drillings provides information on stratigraphy and total depths of regolith in the terrestrial areas (Figure 3-3) and in certain lakes (Johansson 2003, Hedenström et al. 2004, Werner and Johansson 2003, Albrecht 2007). Furthermore, in the terrestrial area geophysical measurements from the site investigation give information about the total depth of regolith (e.g. Bergman et al. 2004). In addition, geophysical data from the building of the nuclear power plant is available and give the same type of information (Keisu and Isaksson 2004). In the marine area sediment profiler and seismic data acquired along survey lines give information on the total thickness of all the regolith layers (Figure 3-2) overlying the bedrock surface (Elhammer and Sandkvist 2005, Nyberg et al. 2011). The distance between the surveyed and investigated lines varies between the mapped areas (Figures 3-1 and 3-2).

3.2 Analyses of regolith properties

The different types of regolith have been analysed for numerous chemical and physical properties within several studies with different purposes. The methods for most of these analyses are not described here but only shortly summarised and referred to. The most used methods are, however, described.

Samples from the different types of regolith have been analysed for grain size composition. The results from these analyses are used to confirm interpretations done during the mapping and stratigraphical studies of regolith but are also useful when interpreting results from physical and chemical analyses. Furthermore, the grain size composition gives information regarding hydrological properties of the different regolith types. These analyses were made on grain sizes smaller than 20 mm, and coarser material was consequently omitted. The grain size distribution of coarse material (20–0.063 mm) was determined by sieving (SIS 1992a) and finer material (< 0.063 mm) with a hydrometer (SIS 1992b). The nomenclature from SGF (2016) was used for classifying the different grain sizes (Table 3-4). The different types of regolith were, however, classified, based on several additional parameters such as organic content and genesis (see Karlsson et al. 2021, Hedenström and Sohlenius 2008).

Table. 3-4. The mineral grains in regolith were classified according to the diameters of the grains.

Boulder	Stone		Gravel			Sand			Silt			Clay
Coarse boulder	Coarse Stone	Medium sand	Coarse gravel	Medium gravel	Fine gravel	Coarse sand	Medium sand	Fine sand	Coarse silt	Medium silt	Fine silt	
Grain 2000 Size (mm)	600	200	60	20	6	2	0.6	0.2	0.06	0.02	0.006	0.002

The content of $CaCO_3$ was determined on grain sizes < 0.063 mm using Passons apparatus (Talme and Almén 1975), which measures the pressure of gas (CO_2) emitting after pouring HCl on the samples.

Different methods have been used for determining the content of organic material. The total content of organic material (e.g. Ising 2005, Hannu and Karlsson 2006) was determined by weighting samples before and after burning samples at 550 °C. That method is referred to as Loss on ignition (LOI). The clay content is used to recalculate the LOI values since clay contain some water that give LOI-values too high. Analyses of elemental C, N and S were carried out on a LECO element analyser according to SIS (1996), measuring gases emitted during combustion of samples (e.g. Hedenström 2004b, Lundin et al. 2004). The organic content was thereafter calculated as 1.7 times the carbon (C) content, based on the van Bemmelen factor (Jackson 1958). The content of organic material is one of the parameters used to classify fine grained sediments and peat (Karlsson et al. 2021, Hedenström and Sohlenius 2008).

Water content of peat and sediments was analysed and is expressed as water loss after drying at 105 °C as weight percentage of wet sample (Borgiel 2004, Hannu and Karlsson 2006, Sternbeck et al. 2006, Nordén 2007). The water content was used to determine the porosity and bulk density of the deposits (Grolander 2013). For these calculations, the average mineral grain density of 2.65 g/cm^3 and a density for the organic matter of 1 g/cm^3 were used (Talme and Almén 1975). These two parameters are used within the safety assessment for modelling transport of radionuclides (Grolander 2013).

Several methods, not described in detail here, have been used for determining the chemical and physical properties of the different types of regolith. These methods are described in the reports that are referred to below.

The chemistry and mineralogy of a few samples have been analysed by Sohlenius and Rudmark (2003). Chemistry was of till was determined with ICP-MS after leaching the samples with 7M HNO_3 whereas the mineralogy of till was determined using X-ray diffraction (XRD). The clay fraction (material < 2 μm) was analysed using qualitative XRD-analyses to determine the clay mineralogy composition in oriented samples (Drever 1973). The distribution of elements in till was used to determine if there are indications of mineralisations of economic value in the area (Nilsson 2003). The samples were analysed with ICP-MS for 35 elements after digestion with aqua regia.

To determine how long the material in till has been transported (Bergman and Hedenström 2006) studied the composition of bedrock and minerals in the till. That was done by visually studying the composition of gravel and boulders. To characterise both deposits and biota with respect to the chemical composition, several samples were analysed for more than 60 elements (Hannu and Karlsson 2006). Most regolith samples were analysed after digestion with HNO_3 and were there after analysed with ICP.

The Solid/liquid partition coefficients (K_d) can be used to estimate the mobility of elements in different types of regolith and have been determined within two investigations (Sheppard et al. 2009, 2011). The K_d-values are used within SKB's safety assessment to indicate the relative mobility of radionuclides that in the future might reach the surface system from the storages of nuclear waste.

The uppermost 0.6 m of the regolith, the soil, has been thoroughly investigated by Lundin et al. (2004, 2005). These studies include chemical and physical characterisation of the soils in the Forsmark area. Results from studies of soils at selected sites were used to produce a soil map of the Forsmark area (Lundin et al. 2004). That map was produced by using GIS for combining results from the soil investigations with the geographical distribution of Quaternary deposits, hydrological index and vegetation. The report by Lundin et al. (2005) also includes different hydrological properties of the soils.

Sediment and peat from wetlands with high nature values were studied to determine if acid condition could develop because of a groundwater lowering (Sohlenius et al. 2020, Sohlenius and Svensson 2021). Measurements of pH before and after oxidation of regolith samples were used as the main tool.

Sternbeck et al. (2006) determined mass accumulation rates of organic carbon, nitrogen and phosphorus in sediments from two coastal sites and in peat from one wetland. Accumulation rates were determined using ^{210}Pb and ^{14}C dating of sediments and peat.

The bio- and lithostratigraphy in a sediment core sampled at the sea floor in the area between the mainland and the Island of Gräsö, Öregrundsgrepen, was investigated by Risberg (2005). The purpose was to use the sediment record to study how the environment, e.g. salinity, has changed through time. AMS radiocarbon dating of bulk sediment was applied to establish the age of the sediment sequence. Determinations of organic carbon content, grain size distributions and carbonate contents were used to describe the sediment composition. The environmental changes were verified using the sediment composition of siliceous microfossils.

Robertsson (2004) studied the composition of pollen in some till samples. The aim was to determine if some of the till layers were deposited during glaciations older than the last.

3.3 Uncertainties in regolith models

3.3.1 Terrestrial areas

There distributions of QD shown om SGU's regular map (Area 2 in Figure 3-1) have generally much larger uncertainties compared to the maps from SKB's investigations. Figure 3-5 compares SGU's regular map (Persson 1985) with the map from SKB's site investigation (Sohlenius et al. 2004). The main reason for the differences is that more field time was used for producing the latter maps. Furthermore, the areas mapped within SGU's regular mapping program (Persson 1985, 1986) were produces before the use of GIS and GPS. These maps were consequently produced for visualisation on printed maps and generalisations were therefore made. As an example, small outcrops are often representing as too large areas on the map by Persson (1985, 1986). Furthermore, since GPS was not available there are uncertainties in the positioning of the transitions between different regolith types That is especially true in forested areas lacking roads. In such areas the geologists used compass and counted the number of footsteps to determine positions. As mentioned earlier Lantmäteriet's digital height model (LiDAR data) nowadays can be used to delineate different types of regolith. The LiDAR data has a high geographical resolution and since topography and regolith distribution often is correlated LiDAR can be used for high precision geographical delineation. A comparison between LiDAR data and a regular SGU's map (Figure 3-6) shows that the error in some cases is larger than 100 m. LiDAR data is nowadays used to update old regolith maps to increase the accuracy of the maps.

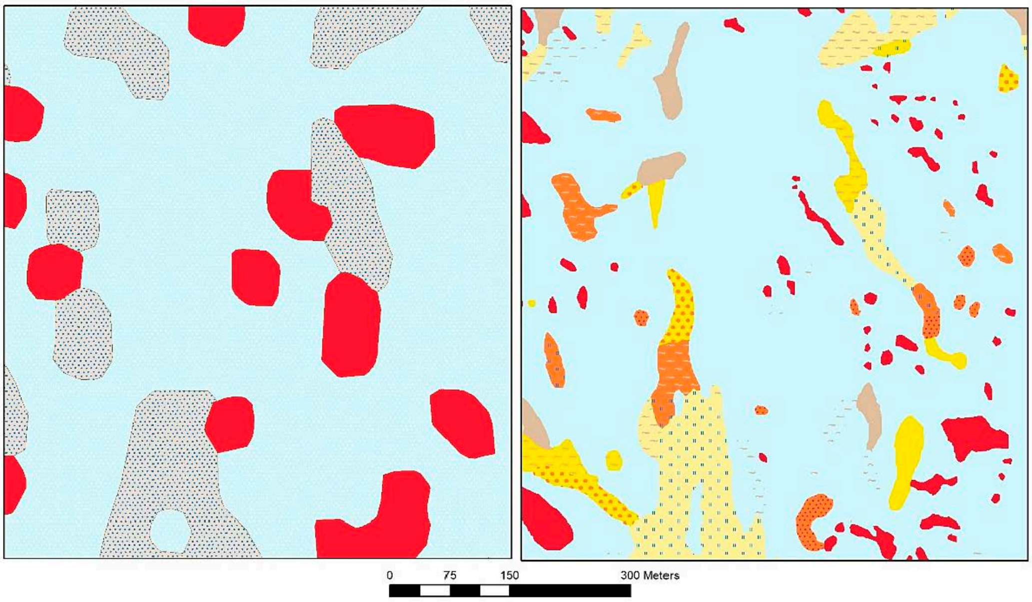

Figure 3-5. A comparison between two maps from Area 1a (see Figure 3-1). The map from SGU's regular mapping program (Persson 1985) is shown tot to the left, and the map to the right was produced during SKB's site investigation (Sohlenius et al. 2004). There are several differences between the two maps showing the higher accuracy of the newest map. 1) Areas with peat (light brown with blue dots) were overrepresented on the old map, 2) areas with clay and sand were underrepresented (different shades of yellow and orange, respectively), 3) the distribution of bedrock outcrops (red) is shown in a much more detailed way on the new map.

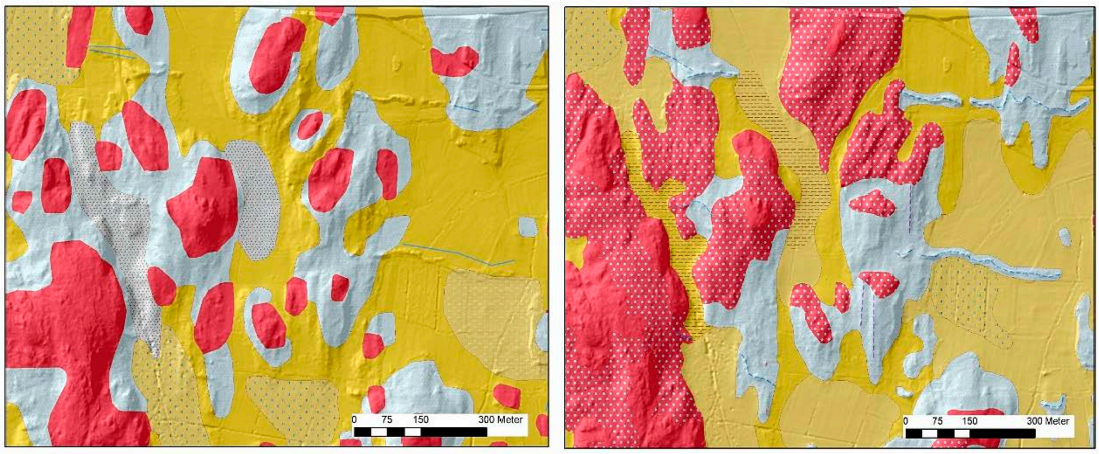

Figure 3-6. A comparison between LiDAR data and two regolith maps from SGU's regular mapping program. The left map was produced before LiDAR was available and it is obvious that the transitions between different regolith types don't follow topography. LiDAR data implies that the transitions between different types of regolith has errors of up to more than 100 m. The right map has been produced to improve the quality of the left map using LiDAR data. It is obvious that the accuracy of the newest regolith map has improved and that e.g. transitions between clays (different shades of yellow) and till (blue) is displayed in a much more precise manner.

During SR-site (Sohlenius et al. 2004) GPS in combination with printed aerial photos with a high resolution was used during the mapping. LiDAR was, however, not available during that time but a comparison between LiDAR data and the map of QD shows that the errors generally are small (less than 10 m).

LiDAR data was available during the mapping of the drainage area of Gunnarsboträsket (Sohlenius et al. 2019) and some of the regolith types could therefore be geographically delineated in the GIS environment at the office. Another advantage with that method is that less time for field work is needed. However, the Forsmark area is to a large part very flat and transitions between different types of regolith are therefore not always mirrored in the height data. Some deposits are therefore difficult to delineate both in the field and by use of aerial photos or LiDAR.

A comparison between the SGU map (Area 2 in Figure 3-1, Persson 1985, 1986) and the map produced within SR-Site (Area 1a in Figure 3-1, Sohlenius et al. 2004) show that numerous outcrops are lacking on the SGU map (Figure 3-5). Furthermore, small occurrences of water laid deposits such as sand and clay are missing on the SGU map. The SGU map also implied that there is a peat coverage in wetlands close to the sea level. The mapping during SR-Site showed, however, that the peat coverage is thin in these recently formed wetlands.

Regolith depth data from both the terrestrial and water covered areas was used for the RDM (see below). In most of the terrestrial area there are relatively few drillings or geophysical observations, e.g. seismic, showing the depth to bedrock. The bedrock surface is generally more undulating compared to the topography. In many areas it is therefore difficult to interpret the altitude of the bedrock surface with a high degree of certainty. The bedrock surface at a certain point can generally be interpreted with a high certainty using results from drillings, whereas geophysical observations have a lower reliability. However, at some site sediment filled cracks have been observe in the uppermost bedrock. The depth to bedrock interpreted from drillings can then be overestimated since the bedrock overlying the sediment filled cracks can be interpreted as large boulders underlain by a thin layer of till.

Most stratigraphical data used for the RDM comes from SKB's investigation in the area but, there are also data from external sources that have been used in that model. Data from the SGU's archive of wells gives information about the total depth of regolith. However, some of these observations have a low reliability concerning the coordinates of the observation points. In the peripheral parts of the model area data from the archive of wells is the only available data showing the total depth of regolith (see Figure 3-3). Data from the archive of wells used in the latest RDM (Petrone et al. 2020) is from 2015. The archive of wells is, however, continuously updated with new data and can be used as an input for improving future RDMs.

3.3.2 Areas covered by water

In the marine areas regolith data was collected along survey lines by using geophysical, hydroacoustic methods (Figure 3-2). In the area close to the mainland and above SFR (Elhammer and Sandkvist 2005, Nyberg et al. 2011) the density of data is high compared to Area 5 (Figure 3-1), with a 100 m spacing between the lines. It was, however, not possible to collect data from boat in the shallowest areas. In some marine areas there is a 1 km separation between these survey lines (Figure 3-2) and the distribution of QD between the lines is because of this at many places uncertain. The regolith thicknesses in the marine area was interpreted from seismic- and sediment profiles obtained from geophysical measurements and could only in rare cases be confirmed by drillings. It is therefore difficult to evaluate the exact uncertainty of these interpretations. The reliability of these interpretations also varies with the quality of the profiles. In certain areas, gas in the postglacial sediments obstructed the interpretations of underlying deposits through attenuating the hydroacoustic pulses. The interpreted thicknesses of water laid sediments generally have a higher reliability compared to the interpreted thickness of till (cf Novak and Krarup Pedersen 2000). Furthermore, the interpretations from the shallow areas (Area 4) obtained by Elhammer and Sandkvist (2005) have lower reliability than interpretations from deeper marine areas. This is due to problems with double multiple echoes that are common when using seismic and sediment echo profiler soundings in shallow areas. The hydroacoustic pulses are also reflected by the sea surface and returned down into the sea floor giving multiple echoes. Most data from the marine areas were collected during SKB's two site investigations. As mentioned above, data from SGU's regular marine geological mapping was also used (Area 6) (Nyberg et al. 2011).

3.4 Regolith depth models

3.4.1 Introduction

A regolith depth model (RDM) is a geometrical model and the models used by SKB presents the total regolith depth thickness and bedrock topography in relation to sea level. Furthermore, the models demonstrate depth and thickness of the most commonly occurring regolith types. SKB have today two active RDMs (see Table 3-1). The regional RDM covers the area of Forsmark (Figure 1-1) in a resolution of 20 × 20 m (Petrone et al. 2020). The more detailed one covers the area of Söderviken (Figure 1-1) in a resolution of 1 × 1 m (Follin 2019). The two models are produces following the same methodology.

The two active RDMs show the distribution of the nine most commonly occurring regolith layers and was produced by using the software SubsurfaceViewer MX®. For future modelling a corresponding software that in the same way makes it possible to apply general knowledge and understanding of the vertical and horizontal distribution of regolith layers will be used for producing new RDMs.

The data used for the RDMs includes the DEM (see Chapter 2), maps of regolith, as well as data from drillings and geophysical surveys. For the last regional RDM 20 000 data points were used to model the total regolith depths. A clear majority of these data originates from the marine geological surveys. The output from the 3D software was post-processed using ArcGIS spatial functions.

3.4.2 Methodology

The workflow of producing the RDM is summarized in Figure 3-7. For producing an RDM all stratigraphical data is first evaluated and a conceptual model for the stratigraphical and horizontal distribution of regolith in the Forsmark area is constructed (Figure 3-7). This model serves as a rule for the modelling. All available data regarded as reliable, is used for modelling the thickness and altitude of the nine most commonly occurring regolith types. The process for determining reliability of data is described below. Then regolith maps, DEM and stratigraphical data are imported to the 3D software. The data is used for interpreting the stratigraphical distribution and thicknesses of regolith along profiles. The profiles are thereafter used together with the regolith map to calculate the thicknesses and elevation of the different regolith layers. The experiences from the work with earlier RDMs (Sohlenius et al. 2013, Hedenström et al. 2008, Vikström 2005) were used to improve the methodologies used in the RDM described by Petrone et al. (2020) and the former conceptual models were partly used in the latest RDM. However, the latest model (Petrone et al. 2020) includes more regolith layers compared to former models and the conceptual model was therefore slightly modified.

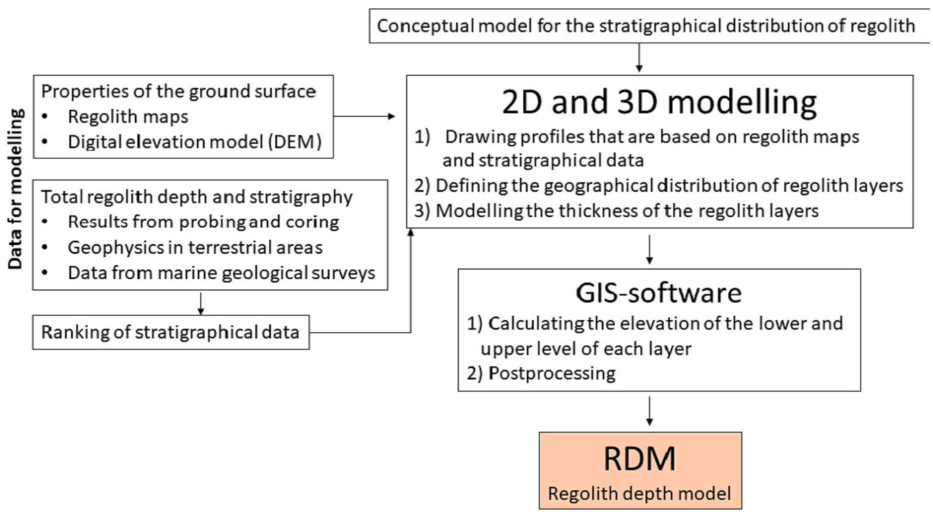

Figure 3-7. *The workflow of producing the RDM.*

3.4.3 Conceptual model

Before the modelling is initiated, a conceptual model is constructed, showing the general distribution of the regolith layers (Figure 3-8). The conceptual model shows the surficial and horizontal distribution of regolith layers in the landscape and is used as a precondition for constructing the RDM. This conceptual model becomes especially important when modelling areas with few or none stratigraphically observations. The vertical, or stratigraphical, distribution of regolith shows the relative age of the layers, i e younger deposits overlay older deposits. Properties, such as grain size distribution, of the layers reflect the environments in which they were deposited. As an example, sediments deposited in water are generally more well sorted with respect to grain-size compared to till that was deposited directly by the inland ice. One important input to the conceptual model is therefore the knowledge of the different environments that have prevailed during and after the latest ice age (e.g. Söderbäck 2008). Another important input for the conceptual model is the results from the numerous stratigraphical studies conducted during the site investigations for the repository for spent nuclear fuel (Hedenström and Sohlenius 2008) and for the extension of the existing SFR facility (e.g. Nyberg et al. 2011). The conceptual model does not only describe the stratigraphical distribution of regolith but also how the regolith is distributed in the landscape (e.g. in topographically low areas the till is often overlain by different types of clay). That distribution was observed when regolith was mapped during SKB's site investigations (e.g. Sohlenius et al. 2004) but have also been observed during several other studies in the region (e.g. Persson 1985, 1986). For future RDMs additional data will be available. The methods for surveying the stratigraphical and horizontal distribution of regolith are described in Section 3.1 above. The conceptual model might be updated in the future even though there is no such need according to the present knowledge.

Nine regolith layers and the bedrock are included in the present conceptual model (Petrone et al. 2020) in the following order: bedrock (Z6), till deposited by the ice during the ice age (Z5_I), glaciofluvial material deposited by the meltwater from the ice (Z3b), glacial clay deposited close to the ice margin at the floor of the Baltic (Z4b), gyttja clay deposited at deep water (Z4a_I), postglacial sand and gravel deposited by currents and waves at the floor of the Baltic (Z3a), gyttja clay deposited I shallow bays close to the coast (Z4a), gyttja deposited in lakes (Z4c), peat formed in fens and bogs, and finally artificial fill that is a manmade deposit (Z3c).The conceptual model is illustrated in Figure 3-7 and Table 3-5. This model is stored in SKB's database (a word-file with model-ID: 1712500). Note that the layer thicknesses are shown in a schematic way in Figure 3-7. The model shows the typical stratigraphical distribution of regolith in different environments, e.g. wetlands. Results from stratigraphical investigations show that some of these layers are absent at some sites representing these environments. The order in which the layers are distributed is, however, always the same as in the conceptual model. Furthermore, it should be noted that all these nine layers are present in the regional model area but Z3b and Z4a_I are lacking in the detailed model representing the access area (Follin 2019). Former models (Sohlenius et al. 2013, Hedenström et al. 2008) have an additional layer (Z1) that has a fixed thickness and represents the uppermost regolith, which is affected by, weathering, bioturbation, and soil processes. That layer was, however, excluded from the last model (Petrone et al. 2020). Since Z1 has a fixed thickness, any user can produce this layer in GIS.

Table 3-5. General stratigraphical distribution of Quaternary deposits (i.e. the regolith) in the Forsmark area. The Z-layers associated with the different deposits are shown in the RDM produced by Petrone et al. (2020). Note that all these layers are not always present at the same location, i.e. an area covered by peat is not necessarily underlain by all the regolith layers shown in the table. Artificial fill (Z3c) is the youngest deposit but is not shown in the table.

Regolith type	Relative age	Layer in the RDM
Peat	Youngest	Z2_I
Gyttja	↓	Z4c
Clay gyttja		Z4a
Postglacial sand and gravel		Z3a
Clay gyttja		Z4a_I
Glacial clay	↓	Z4b
Glaciofluvial sediments		Z3b
Till	Oldest	Z5_I
Bedrock		Z6

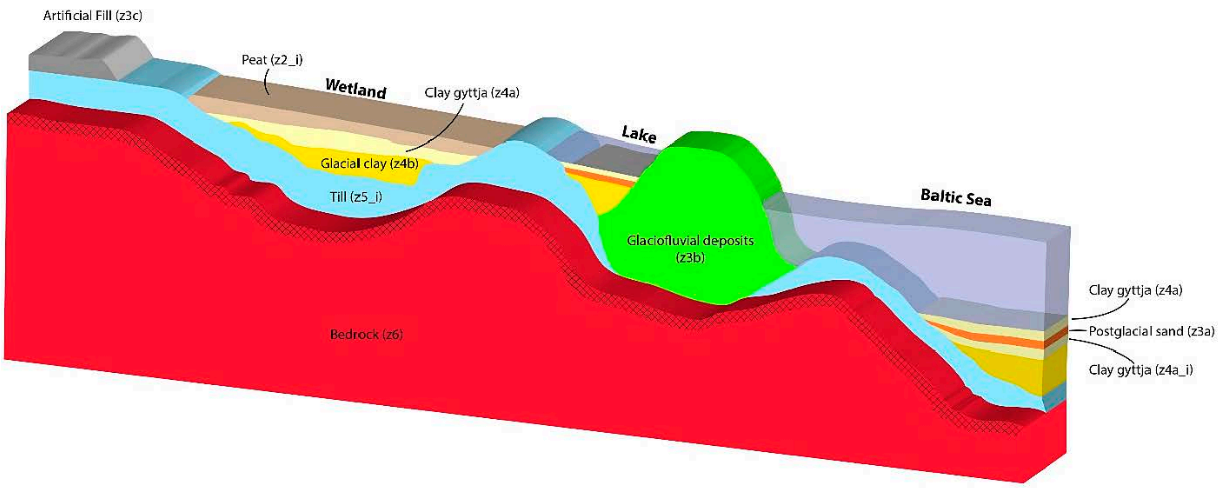

Figure 3-8. *The general distribution of the regolith layers (Z-layers) used in the present RDM (Petrone et al. 2020). The stratigraphy is further explained in Table 3-5. This conceptual model is stored in the SKB model database SKBmod as a word-file with SKBmod ID 1712500. Note that gyttja (Z4c) is missing in the figure. Gyttja should be the uppermost layer in the lake.*

Ranking of stratigraphical data used in the RDM

The different types of regolith depth data used in the RDM have different accuracy. In certain cases, overlaps occur and data with lower accuracy are then not used in the model. Data used in the present model (Petrone et al. 2020) is shortly described in Section 3.4 above. The datasets used were classified and ranked according to their accuracy in the estimation of the total regolith depth as listed below in order of decreasing accuracy. The direct observations from drillings excavations and outcrop observations have the highest reliability. These observations were used to rank the reliability of geophysical interpretations. The ranking of marine geological observations was done after discussions with the geologists that made the surveys (Elhammer and Sandkvist 2005, Nyberg et al. 2011).

1. Direct observations of bedrock outcrops and coring or probing and drilling that reach the bedrock and have GPS-measured coordinates.
2. Data from marine geological measurements in Area 5 and 6 in Figure 3-1.
3. Data from marine geological measurements in Area 4 in Figure 3-1.
4. Data from the SGU archive of wells has a relatively low ranking since such data often have a low accuracy in positioning.
5. Stratigraphical observations from the site investigations that did not reach the bedrock surface. These observations have, however, GPS-measured coordinates and the highest ranking for estimating the thickness of individual regolith layers.
6. Ground geophysical measurements (refraction seismics and electrical soundings) in terrestrial areas performed with the purpose of investigating regolith thickness.
7. Data from refraction seismic sounding that was carried out with other purposes than determining regolith depth.

The order of the ranking is based on information from the reports describing the data, as well as discussions with some of the persons involved in the measurements. In addition, there is a general assumption that the direct observations from the field are more reliable than the interpretations from geophysical data.

Modelling with the 3D software

The latest RDMs was produced using the software SubsurfaceViewer MX® (© INSIGHT Geologische Softwaresysteme GmbH) for interpreting and modelling the elevation and thicknesses of the regolith layers (Petrone et al. 2020). SubsurfaceViewer and a proceeding software (GSI3D) has earlier been used by SGU to model the thicknesses and elevation of different regolith layers (Peterson et al. 2014, Jirner et al. 2016). Today SGU use another software, Groundhog (developed by British Geological Survey), for corresponding modelling of regolith (e.g. Nolin Nyström 2021). Even though Groundhog might be used by SKB for future modelling of RDMs other more suitable software's might be available in the future. The same modelling concept as described here and used by Petrone et al. (2020) will, however, be used also in the future. The 3D software makes it possible to use the general knowledge of the stratigraphical distribution of regolith layers to construct a model based on available data. A conceptual model (Figure 3-8) is used for that purpose.

The final RDM constitute several raster files, that can be used in GIS, representing different types of regolith. In the latest version all these files have the coordinate system SWEREF99 and Swedish national elevation system RH2000. One set of files show the geometry of the upper level for each layer as elevation above sea level in meters. A second set of files show the thickness of each layer in meters. The model produced by Petrone et al. (2020) has a spatial resolution of 20 × 20 m. However, the RDM for the access area (Follin 2019) has a much higher resolution 1 × 1 m.

In the model by Petrone et al. (2020) the lower level for Z5_I (till) was produced from data showing the total regolith depth, and from the distribution of bedrock outcrops. Thus, the lower level of Z5_I represent the bedrock surface, regardless of whether it is covered by regolith or not.

Compared to the regional model area a more detailed regolith map was used for the RDM representing the access area (Follin 2019). The DEM in the access area was modelled with a resolution of 1 × 1 m whereas the DEM used for the regional model area has as mentioned above a 20 × 20 m resolution. The map of regolith used for the access area shows the distribution of thin surficial regolith layers in a much more detailed manner (see Table 3-1 above) compared to the regolith map for the regional model area. Furthermore, numerous drillings have been conducted in the access area and since that data generally has a high reliability whereas results from geophysical investigations having a lower reliability were not used in that area.

For producing an RDM several files must be constructed. One that describes the stratigraphy of the regolith in the model area (Z-layers in Table 3-5). This file is based on the conceptual model (Figure 3-8) and determines in what stratigraphical order the different regolith (Z) layers can occur in the model. The regolith layers are displayed according to a file where the colours of all layers are defined. The same colours as used on the regolith map is used for symbolising regolith in the RDM (Figure 3-9). When using SubsurfaceViewer stratigraphical data from the different surveys, (e.g. results from drillings and geophysical studies) are imported in two separate files, one with id-numbers, coordinates, and altitudes and one that contains id-number and the lower level of each regolith layer. Furthermore, the DEM (see above) and regolith map are imported as a raster and shape files, respectively. For the model presented by Petrone et al. (2020) most data were imported as point data but geophysical data from the terrestrial area and some of the marine data were imported as 3D shapes, showing thicknesses of regolith along lines. In the marine area data was obtained from geophysical data collected along lines. Most of this data were imported as point data, showing the interpreted stratigraphical distributions at points with separations of 25–50 m along the lines. The original dataset from the marine are contains, however, information with a much denser separation, but concerning the much larger distance between the investigated lines this separation was regarded as acceptable.

In SubsurfaceViewer three windows are displayed (Figure 3-9), which illustrates how the work producing an RDM is proceeded. In one window, all points with stratigraphical information are shown together with the map of regolith (Figure 3-9). In that window sections can be drawn between the points with stratigraphical data. The section and the points with stratigraphical data are thereafter displayed in a second window, where the distribution of regolith layers along the line is interpreted by using the stratigraphical information and the map of regolith. The different regolith types were delineated by drawing lines along the sections. A third window can be used to visualise the sections in 3D (Figure 3-9). The imported 3D-shapes are shown directly as lines. Most of the sections from the terrestrial area needed to be modified since they only show the total regolith depths. Regolith layers were therefore added by using the regolith map and the conceptual model showing the stratigraphical distribution of regolith. Many of the sections based on geophysical data and cross areas shown as outcrops on the regolith map. In such areas the regolith depths have been interpreted to be zero.

For the RDM produced by Petrone et al. (2020) the sections from the marine area were as mentioned above imported as points and were thereafter completed by drawing lines delineating the regolith types. Regolith depth zero was interpreted in areas where the sections cross areas shown as outcrops on the regolith map. In the marine areas, there are some discrepancies between the map of regolith and geophysical data. As an example, there are places where the regolith map shows that the sea floor consists of till whereas geophysical data suggest that the till is covered by glacial clay and postglacial sand. In most cases the data from the geophysical investigation was then used when drawing the sections. However, along some sections the geophysical data suggests the occurrence of water deposited clays in topographically high areas and till in the topographically low areas. This is a highly unlikely distribution of regolith (i.e. not in line with the conceptual model), and in such cases geophysical data was consequently not used when interpreting sections.

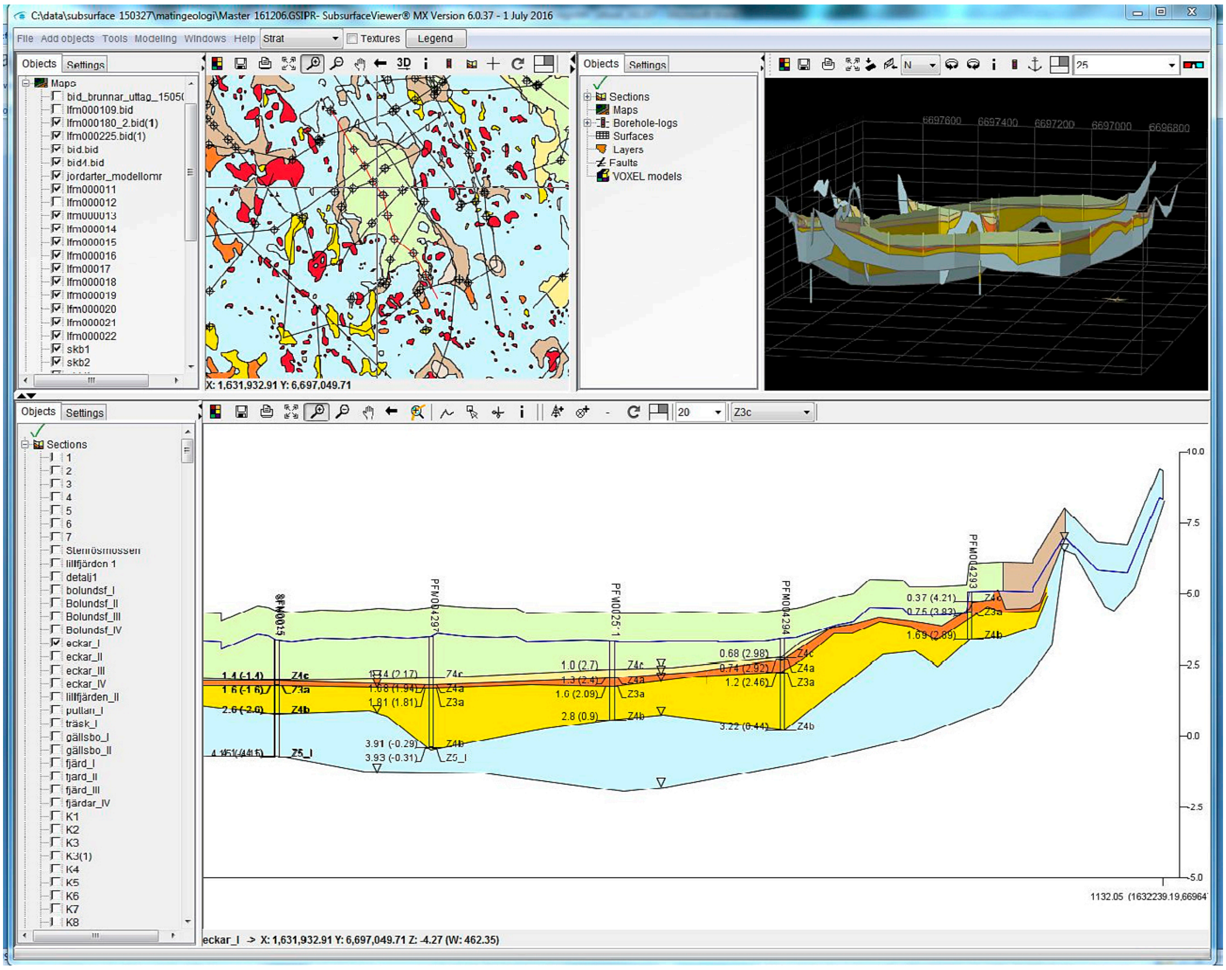

Figure 3-9. *Three windows are available when working with the software SubsurfaceViewer. The map of regolith and location of stratigraphical observations are shown in the upper left window, which also displays the positions of the sections. The distributions of regolith layers along the sections were interpreted in the lower window, by using the map of regolith together with the stratigraphical observation. The regolith map is shown in the upper part of the sections and the stratigraphical observations are displayed as stacks. The triangles show where sections cross. The regolith is displayed with the same colours in the sections and on the regolith map. All sections can be displayed and studied from different directions in the upper right window. A corresponding approach is used by other 3D software's.*

Some areas in the vicinity of the model area lack stratigraphical data and there the sections were interpreted by Petrone et al. (2020) using the map of regolith and the general stratigraphical knowledge (Table 3-5) that was obtained from stratigraphical studies in other parts of the model area. As an example, areas shown as gyttja clay on the map were interpreted as underlain by glacial clay, followed by till that rests directly upon the bedrock. The stratigraphical studies have, however, shown, that some of the layers shown in Table 3-5 may be lacking at certain sites, and it can therefore be assumed that there are too many layers at some locations situated in the vicinity of the model area.

When all sections have been interpreted, the crossings between sections are checked to make sure that the distribution and thicknesses of regolith layers are the same in both sections where they cross. If there is a discrepancy between a section based on geophysical data and a section based on drillings the results from the drillings are regarded as more reliable, and the section based on geophysical data is consequently reinterpreted. In the sections situated closest to the border of the model area a bedrock layer is entered. This layer reaches below the level of the deepest recorded regolith layer to secure that all regolith in the final model is underlaid by bedrock. The geographical density of sections mirrors the density of data and varies consequently within the model area (Figure 3-9). Lines are also drawn in areas lacking data to secure that all areas were realistically modelled. In this way Petrone et al. (2020) interpreted more than 700 sections (Figure 3-10).

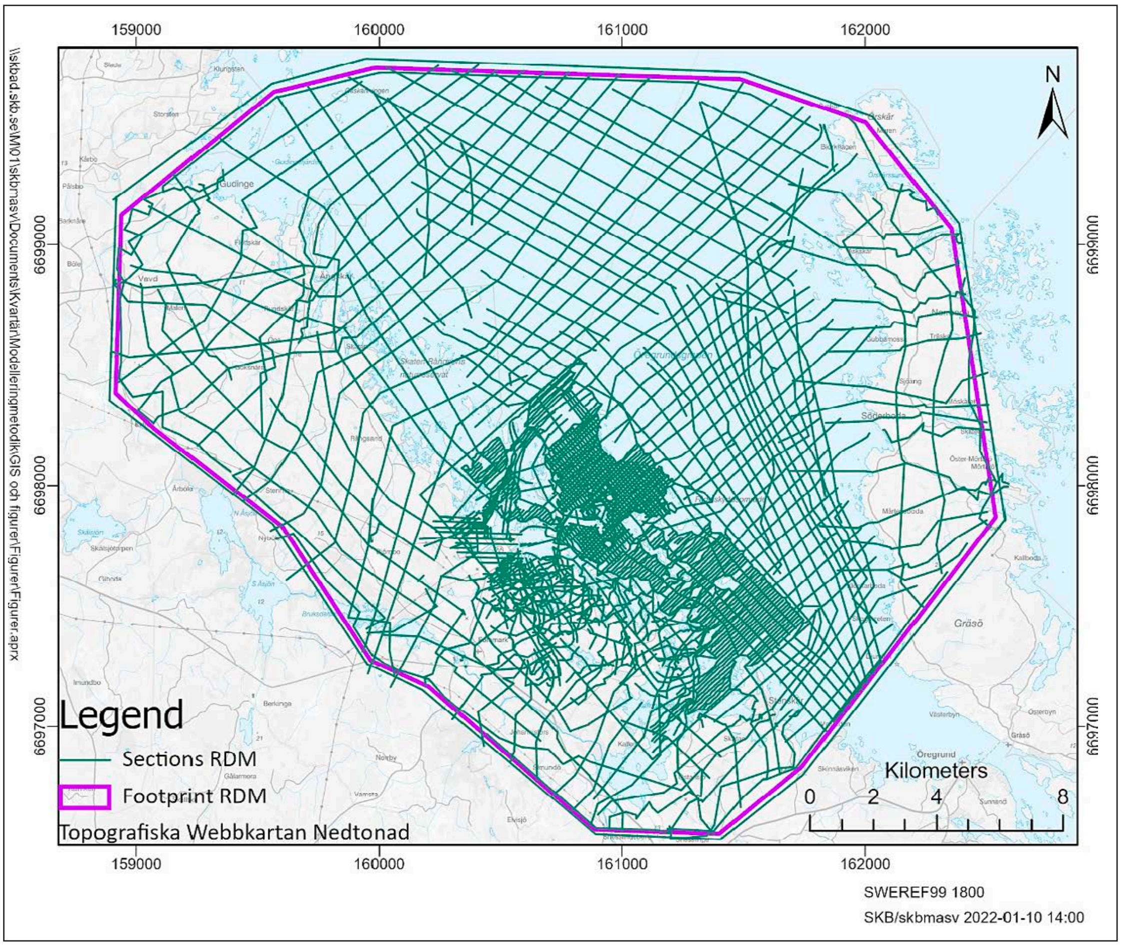

Figure 3-10. *The geographical distribution of the more than 700 sections that were drawn by hand in SubsurfaceViewer (Petrone et al. 2020). The sections are based om information from different type of stratigraphical studies. The density of sections reflects the density of available data.*

3.4.4 Areal distribution of regolith layers used for interpolation

The map of regolith contains numerous surfaces representing different types of regolith. Most of these surfaces lack stratigraphical observations. Based on the regolith map and the sections the areal distribution of each regolith type (layer) used for modelling is determined. Since several types of regolith may occur at one location, several layers can be present at that location. The stratigraphical distribution of the regolith layers is shown in the conceptual model (Figure 3-8). These layers are equivalent to the regolith layers shown in Table 3-5. One additional layer, Z6, represents the bedrock and is present in the whole model area.

In some areas, observations confirm that some of the layers in the conceptual model are lacking. In areas where observations contradict the conceptual model, the results from the observations are always used for delineating the layers. The order in which the layers are distributed is, however, never changed. In some areas, especially in the marine area, data used for the sections contradict the map of regolith, e.g., there are marine data implying that the seafloor is covered with postglacial sand whereas the regolith map implies glacial clay in the same are. The interpretation from the sections is then used for constructing the layers.

In the terrestrial areas, there are numerous small surfaces with water laid deposits and peat. Stratigraphical observations (e.g. Sohlenius and Hedenström 2009) have shown that these deposits often are situated directly upon the till and lack the complete stratigraphy illustrated in Figure 3-8. If the peat according to the map of regolith is not surrounded by water laid sediment, it is assumed that the peat rests directly on the top of the till. Accordingly, based on field observations it is assumed that the deposits in small areas with water laid sediments rests directly upon till. There are of course places where different types of water laid deposits occur between the peat and the till, and where this assumption consequently is wrong.

3.4.5 Calculations of layer elevation

The upper and lower elevation of each layer are calculated in the 3D program. The thicknesses are thereafter determined as the differences between the upper and lower elevation of each regolith layer. To avoid unrealistically thin or thick layers in the areas between the interpreted sections, minimum allowed thicknesses for each regolith layer are used for the calculation. These values constitute the average values of the recorded thicknesses of each layer (see Petrone et al. 2020 for further explanation). The average values are calculated from observed thicknesses. However, thicker, and thinner layers occur along the interpreted sections and at places with observations showing the actual layer thicknesses.

In SubsurfaceViewer Delaunay triangulation (Delaunay 1934) was used to calculate the upper and lower elevations of each of the nine regolith layers. Other methods, such as Kriging, may, however, be used for calculations of layer elevations in upcoming RDMs.

The peat (Z2_I) layers in areas at low altitudes (below 5 m) are thinner than peat at higher altitudes. A lower minimum thickness (0.4 m) was therefore used by Petrone et al. (2020) for calculating the peat thickness in these low laying areas. This was, however, done during the post-processing (see below).

The calculated layers are exported to a GIS software, e.g. ArcGIS, (see below) as layers representing the upper and lower elevations for the layers in the whole area. The first version of the model is reviewed, and some unrealistic model results are identified, e.g. thick or thin regolith layers that were interpreted as artefacts caused by geographically uneven distribution of input data. Extra sections are drawn to eliminate these unrealistic results and a final model was thereafter produced. Petrone et al. (2020) observed some unrealistic features, e.g. places with regolith depth zero, that were impossible to correct in SubsurfaceViewer. These features were corrected in ArcGIS during the post-processing (see the section below).

3.4.6 Post-processing of interpolated surfaces

For producing the final model, it is necessary to make some additional work called post-processing. That final work can be performed in ArcGIS, and the most important parts of that work is described below.

- The layers produced in the 3D program show the thicknesses of each modelled regolith layer. Layers showing the altitudes (m a.s.l.) of the lowest limit of each layer can be produced in ArcGIS by using the DEM.
- Petrone et al. (2020) observed places where there unrealistically sharp differences within small distances in the regolith thicknesses occurred within the layers interpolated in SubsurfaceViewer. These sharp transitions can be smoothed using a filter function in ArcGIS.
- Since the map of Quaternary deposits in some area has a high resolution, the raster may indicate thick layers of regolith within areas that are represented by small outcrops on the map of Quaternary deposits. The regolith thicknesses at these sites must therefore be set to 0 in a GIS programme.
- Some of the layers may have interpolation errors and interpolation artefacts present, such as lines of null cells (cells with no value) in areas where a thickness of that layer has been interpreted. Such errors can be corrected in ArcGIS.
- The peat layer (Z2_I) produced in SubsurfaceViewer was too thick in recently uplifted areas, i.e. was too thick close to sea level where thinner peat layers occur. A layer representing peat at low altitudes was therefore produced in ArcGIS.

3.4.7 Uncertainties in the RDM

The quality of the RDM varies with the density and quality of the input data. The quality of data was evaluated for the ranking of data (Section 3.4.3). It is, however, difficult to quantify the uncertainty of especially the geophysical interpretations, since drillings that could be used to check these interpretations are lacking in large areas.

Important uncertainties that can be identified are listed below.

- The thicknesses of the regolith layers in the marine area are modelled from interpretations of seismic and sediment echo soundings only. There are only results from a few drillings available to confirm the thickness of the regolith cover.
- Large parts of the terrestrial areas, including many lakes, lack both stratigraphical data and regolith depth data.
- The interpreted till thicknesses in Area 4 (in the marine area) are probably too large. The thickness of till (Z5_I) is therefore probably too large in Area 4 (Table 3-3). This is shown by larger regolith depths than in surrounding areas.
- The modelled thickness of artificial fill (Z3c) is too small at some places. That is obvious since the distribution of artificial fill, at some places, is reflected as positive landforms in the layer showing the elevation of the uppermost till (Z5_I). One reason for this is that the artificial fill to a large extent occurs as narrow elongated layers along roads.
- The cell size is too large to visualise all recorded variations in regolith depths. One example is that many of the outcrops mapped in Area 1 (Table 3-3) are much smaller than the cell size. Many of these outcrops are not shown as regolith depth zero in the model, but as the average regolith depth within the cell.
- A few of the drillings used in the model have and non-vertical inclination. That was not observed during the modelling work and certain of the regolith depths used for the model are therefore too large.

Some of the issues described above could probably be improved by using a smaller cell size in the modelling. In some cases, additional data is needed to improve the model.

For the future it would be of great value to quantify the uncertainty of the RDM more precisely. That is further discussed in Section 3.5.

3.5 Future improvements of existing models

The need of improvements and updates of the current models will arise for several reasons. New methods have been developed since the SDM-site investigation, allow for development and improvement of the existing models. Furthermore, both the safety assessment and environmental impact assessment (EIA) have and will identify new issues that have to be addressed and require model updates. In some cases, there is also a need to correct or adjust the models as the understanding of the site and collected data increases.

3.5.1 Digital elevation model (DEM)

The resolution of the DEM could be improved in several ways. Much of the low-resolution areas are situated in the marine area, which need to be in focus for an update with better resolution. Regarding data there is not yet included data from Swedish Maritime Administration (Sjöfartsverket) which could be used to improve the DEM in the marine areas. For the terrestrial parts, there are more LiDAR data available at Lantmäteriet. These could be used to enhance the resolution of the DEM. This, however, might not give that much more understanding of the model area since the present model resolution is already high. Regarding measuring methods in water covered areas, the methods of acquiring data has improved considerably since SKB's site investigations. In marine areas situated close to the two repositories and where the DEM has large uncertainties new depth data would have to be collected to increase resolution. Todays improved LIDAR equipment can be used to improve the DEM in sallow marine areas and in areas with lakes and wetlands. These instruments, mounted on airplanes, give detailed and qualitative seamless topographic and bathymetric data down to 3–4 meter of water depth along the coast. At deeper location these datasets can be combined with new high-resolution water depth data measured with multibeam from boat. Backscatter data, simultaneously collected from the multibeam, gives information on regolith-distribution. Regolith-distribution can also be retrieved from the LiDAR-data by studying reflected waveforms, amplitudes etc. Investigation of the QD distribution at the sea floor should be done simultaneously (see below) with the bathymetric measurements. That data can then be used in combination with the DEM to update the QD map and RDM.

When the topography of the model area has been altered to such extent that the present DEM is no longer representative, an update will be necessary. This can for example be after construction of the over ground facilities related to the repository for spent nuclear fuel work has started. Such update should also use the new methods available for of acquiring topographical data.

3.5.2 Maps of Quaternary deposits

The map of Quaternary deposits (QD) has, as mentioned above, been constructed by using several methods. A map showing the distribution of regolith in the whole model area is presently available in SKB's database and can be displayed using GIS. There are, however, some discrepancies in that database and the different deposits are not consequently classified in the whole area. Furthermore, the QD maps from areas representing different mapping methods have not been merged in a proper manner. At the transition between the different areas there are consequently both overlaps between the maps but also small holes lacking regolith information. The QD map will therefore be adjusted in the nearest future, and a map that represents the regolith types in a consequent manner for the whole area will thereafter be available. That work will entirely be made in a GIS environment.

In terrestrial areas that were mapped during the site investigation the map of QD has generally a high accuracy. Remaining terrestrial areas were mapped almost 40 years ago before the use of GPS and LiDAR. These areas have consequently much larger uncertainties. Some of these areas with older QD maps have been identified as of importance for the safety assessment. For upcoming safety assessments where these areas are of importance there is a need to improve the maps of QD in theses certain terrestrial areas. Since the topographical properties and QD distribution are strongly correlated, LiDAR data makes it possible to improve the QD maps in the terrestrial areas (Figure 3-6). That can be done by reinterpreting the distribution of QD using GIS. The old map is then used in combination with LiDAR data to interpret the geographical distribution of different QD. These interpretations should later be verified in the field.

Large parts of the marine area in Forsmark were mapped during SDM-Site almost twenty years ago (Elhammer and Sandkvist 2005). Some of these areas have been identified as of importance for the safety assessment and the QD map in these selected areas should therefore be updated to meet these needs. The equipment used for mapping the bathymetry of the sea floor using multibeam echo sounders has together with hydroacoustic instruments, computers, software, and positioning systems developed significantly during the last decades. Even though the hydroacoustic instruments used to retrieve the regolith data then are similar as the one used today, consisting of sidescan sonar, sediment profiler and seismics, the acquisition and processing software's, computers etc are significantly developed yielding better results. In addition, a multibeam echo sounder that give bathymetric data for the whole sea floor can be used together with backscatter for producing a more accurate regolith map. Also, additional sampling and photo data that is used to verify interpreted regolith from hydroacoustic data should be retrieved. This data can be used for interpreting both horizontal and vertical distribution of regolith. For shallow marine areas new data from LiDAR with green laser can be used for mapping regolith distribution. These updates should be done simultaneously as the bathymetry of the sea floor is updated (see above). In the marine areas, as in the terrestrial areas, there is a correlation between topography and regolith distribution. The new depth data from the Swedish Maritime Administration (see above) that covers part of the model area and can therefore be used to improve parts of the QD map. That data set may also include backscatter data that can be used to improve the regolith map further.

3.5.3 Stratigraphy of regolith

The marine geological surveys described above will obtain additional stratigraphical information showing the thicknesses of the individual regolith layers. Further stratigraphical investigation will also take place in the terrestrial area. As construction begins within the central area for the repository for spent nuclear fuel it is important to collect detailed stratigraphical data. This data will be analysed, interpreted and included in the models. The construction work will include the excavation of a shaft that will make it possible to get detailed stratigraphical from wetlands which are of special interest both for EIA and safety assessment (Follin 2019). Stratigraphical data will also needs to be continually collected as new core samples are taken in Forsmark.

3.5.4 Regolith depth models (RDM)

Both the RDM in the regional model area (Petrone et al. 2020) and the more detailed RDM for the access area (Follin 2019) should be updated when new stratigraphical data is available. Stratigraphical data, together with updated version of the DEM and the QD map will make it possible to improve the quality of the models. Furthermore, additional regolith data that can improve the RDM has been obtained since the last model (Petrone et al. 2020) was finished. The QD map representing Lake Gunnarsboträskets drainage area (Sohlenius et al. 2019) has not been used for the present RDM. Additional stratigraphical data has been collected from wetlands with high nature values (Sohlenius et al. 2020) as well as during the installation of groundwater wells (Johansson and Werner 2019).

The last RDMs were, as mentioned earlier, produced using SubsurfaceViewer but other software's have developed since the RDMs were produced. The present RDMs will be updated using other software. The concept for producing future RDMs will, however, be the same as the one described here. SGU is today using another software, Groundhog, that has been developed by the British geological survey (BGS). The same concept for modelling is used in Groundhog as in SubsurfaceViewer. There are, however, several advantages in using Groundhog compared to SubsurfaceViewer, e. g. better support, easier to visualise 3D data, faster modelling, more modelling options. Data and interpreted profiles from SubsurfaceViewer can be used in Groundhog and the profiles made for the latest RDM's can therefore be used for updating the RDMs. New software will be available in the future, and it is therefore possible that new RDMs will be produced using a software presently not available. The same modelling concept as described in this report will, however, be used.

A development of the present RDM (Petrone et al. 2020) should include a proper quantification of uncertainties. Since the quantity and quality of data varies within the modelled area the area must be divided into subareas that will be validated separately. A method for validation could be to use results from coring and drilling, that haven't been used for the present model. Since the last model was produced, SKB have collected around 100 new data points which could be used for this purpose. That data can be used for validating the model and determine the differences between observed and modelled regolith depths. This would be done by extracting total regolith depths from the RDM and compare with the measured data. The results can be analysed looking at general trends in error distribution. Since the amount of data used for producing the RDM varies spatially the difference between model and new results will probably vary geographically. Some initial validation tests have already been performed and the results show that the total regolith depths shown in the RDM has uncertainties of several metres. The accuracy of some of the data used for that validation needs, however, to be verified and the result from the validation is therefore not shown here.

For future RDMs, a more thorough validation is necessary. That can be done by omitting some data during the modelling and use that data for validation of the model. The validation can include data from both marine and terrestrial areas, and validations should be done separately in areas with different type and density of data. The areal distribution of different types of regolith maps (Figure 3-1) could be used as a tool to delineate areas for separate validation. A thoroughly described method for determining uncertainties must, however, be determined before starting the work with a new RDM.

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SKBdoc documents will be submitted upon request to document@skb.se.

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