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Baseline Forsmark – Digital elevation model

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Abstract

This report describes the work to produce a new digital elevation model (DEM) for the Forsmark area. A DEM describes the terrain relief. An accurate DEM is important for further modelling of the Forsmark area. The aim of this project was to improve the DEM for the Forsmark area using new airborne laser scanned data, new depth data, and to further develop the method used for the construction of the previous DEM.

The data used in the previous DEM have been replaced by airborne laser scanned data in most of the terrestrial area. In the sea, new depth data has been obtained and most of the data used for the construction of the previous DEM has been reprocessed. All data used for the interpolation were combined into a data set of approximately 154 million elevation points unevenly spread over an area of about 900 km^2. The software ArcGIS 10.3 Geostatistical Analysis extension was used for the interpolation of data points. The interpolation was done in two domains demarcated by the sea shoreline. The interpolation method used was ordinary kriging. Finally, a validation of unused or removed data was performed in order to verify that the model fits unmeasured areas.

The map projections used in the elevation model are RT 90 2.5 gon V and SWEREF 99 18 00, with associated height systems RHB 70 and RH 2000, respectively. The model is produced and delivered in four different cell sizes: 1 × 1 m, 5 × 5 m, 10 × 10 m and 20 × 20 m. The higher-resolution models do not include sea bathymetry. An analysis of the elevation model confirms the existing knowledge that the area is very flat. The range in elevation is approximately 101.5 metres with the highest point at 43.9 metres above sea level in the south-western part of the DEM, and the lowest point at –57.5 metres in the sea in the northern part of Gräsörännan (the trench running parallel to the Gräsö island).

The highest accuracy of the DEM is reached in the land areas described by data from the airborne laser scanning and in the 10 km^2 large area where the Geological Survey of Sweden (SGU) has performed a detailed bathymetric survey. The accuracy is lowest in the parts of the sea for which there are only data from the digital nautical chart and in areas below 20 m depth. Errors in modelled elevations of a few metres appear not to be uncommon in these parts of the DEM and errors larger than 10 m can also be expected there.

Sammanfattning

Den här rapporten beskriver arbetet med att framställa en ny höjdmodell över Forsmarksområdet. En digital höjdmodell (DEM) beskriver terrängens relief. En bra DEM är viktig för fortsatt modellering av Forsmarksområdet. Syftet med detta projekt var att förbättra den digitala höjdmodellen över Forsmarksområdet genom att använda nya laserskannade data, nya djupdata och att utveckla metoden som användes vid framställningen av tidigare DEM.

Den data som användes i tidigare DEM har ersatts med laserskannade data i största delen av den terrestra delen av modellområdet. I havet har nya djupdata mätts in och största delen av de data som användes vid framställandet av tidigare DEM har omarbetats. All data som användes vid interpoleringen slogs samman till ett dataset med sammanlagt cirka 154 miljoner punkter ojämnt spridda över ett cirka 900 km^2 stort område. Interpolering mellan olika datapunkter utfördes i programmet ArcGis 10.3 Geostatistical Analysis extension. Interpoleringen utfördes i två domäner, avgränsade av kustlinjen. Metoden ”ordinary kriging” användes vid interpoleringen. Avslutningsvis gjordes en validering med data som inte använts eller som tagits bort vid modelleringen för att verifiera att modellen är bra även i områden där mätdata saknas.

I höjdmodellen används båda kartprojektionerna RT 90 2.5 gon V och SWEREF 99 18 00 med de tillhörande höjdsystemen RHB 70 respektive RH 2000. Modellen har tagits fram och levererats i fyra olika cellstorlekar; 1 × 1 m, 5 × 5 m, 10 × 10 m och 20 × 20 m. I modellerna med högre upplösning inkluderas inte batymetrin för havet. En analys av höjdmodellen bekräftar att området är mycket flackt. Det totala höjdintervallet är ungefär 101,5 m med den högsta punkten 43,9 meter över havsnivån i den sydvästra delen av modellområdet och den lägsta punkten –57,5 m under havsnivån i norra delen av Gräsörännan.

Den högsta noggrannheten finns i den terrestra delen av höjdmodellen där enbart laserskannade data har använts och i det 10 km^2 stora havsområde där Sveriges geologiska undersökning (SGU) har gjort en detaljerad batymetrisk undersökning. Noggrannheten är lägst i de delar av havet där det enbart finns data från det digitala sjökortet och i områden där det är djupare än 20 m. I dessa delar av höjdmodellen är fel på några meter inte ovanliga och fel större än 10 m kan också förväntas förekomma där.

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) has conducted site characterisation at two different locations, the Forsmark and Laxemar-Simpevarp areas, with the objective of siting a final repository for spent nuclear fuel. In 2009, Forsmark was selected by SKB as repository site, and in 2011 SKB applied for a license to build the final repository for spent nuclear fuel in Forsmark. In 2014, SKB submitted an application to expand the existing final repository for low- and intermediate-level waste (SFR) in Forsmark.

An integrating component in the characterisation work within these repository projects was the development of a site descriptive model (SDM) that constitutes a description of the Forsmark site and its regional setting. The model addresses the current state of the geosphere and the biosphere as well as the ongoing natural processes that affect their long-term evolution; see SKB (2008, 2013) for SDMs associated with the two repository projects mentioned above.

The shoreline displacement rate in Forsmark is high, resulting in a young landscape where new land areas form and change relatively quickly. This aspect is important for the assessments of the long-term radiological safety of existing and planned repositories in Forsmark, and areas presently covered by the Baltic Sea will form new land areas within the time frames that need to be considered in the safety assessments. Thus, a high-quality digital elevation model (DEM) describing both present and future land areas and bathymetries is of great importance for SKB.

The surface system part of the site descriptive model (e.g. Lindborg 2008) includes descriptions of surface and near-surface systems concerning disciplines and sub-systems such as hydrology, Quaternary deposits, hydrogeochemistry, vegetation, animals, and human population and land use. Access to a proper DEM, describing the terrain relief, is important for many of the different models constructed for the Forsmark area.

As a part of the development of an updated site descriptive model of Forsmark, it is relevant to construct a new, improved DEM. Three earlier digital elevation models were produced in connection with the site investigations for localisation of the deep repository for spent nuclear fuel and extension of the existing repository for low- and intermediate-level radioactive waste at Forsmark. These models are reported in Brydsten and Strömgren (2004a) and Strömgren and Brydsten (2008, 2013).

Since the previous DEM was produced, new elevation data have become available and some measurements and adjustments are performed to obtain a DEM with higher accuracy. Airborne laser scanning data, i.e. LiDAR (light detection and ranging) data, are now available for the whole terrestrial part of the Forsmark area. Complementary depth soundings have been performed in the sea and new depth data have become available for Lake Eckarfjärden. In addition, parts of the sea shoreline are adjusted based on LiDAR data, and the levels of some lakes are adjusted to fit with the LiDAR data. In some lakes for which bathymetry was not modelled in the previous DEM, bathymetry is now modelled or estimated in this DEM and measurements of the bottom levels of road culverts have been performed to enable more correct hydrological modelling using the new DEM.

The extent of the DEM presented in this report is smaller and somewhat shifted compared to the previous one (Figure 1-1). The previous DEM extends a few kilometres further to the south and the east. The model area of the updated DEM is changed so that it extends at least 2 km beyond present and future watersheds used in the safety assessment for a repository for spent nuclear fuel at Forsmark (SR-Site, see SKB 2010). Therefore, the DEM presented in this report extends almost 2 km further in the western direction and 1 km further in the northern direction.

The DEM resolution is the size of gridded cells. A DEM is constructed by an interpolation of irregularly spaced elevation data. In this model, kriging interpolation was used. Kriging is a geostatistical interpolation method based on statistical models that include autocorrelation (a statistical relationship). Kriging weighs the surrounding measured values to predict an unmeasured location. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points. Normally, a DEM has a constant value for the sea surface and constant values for lake surfaces. For the Forsmark area, the DEM has negative values in the sea to represent water depth, but constant positive values for land or varying positive and negative values to represent lake bottom elevations.

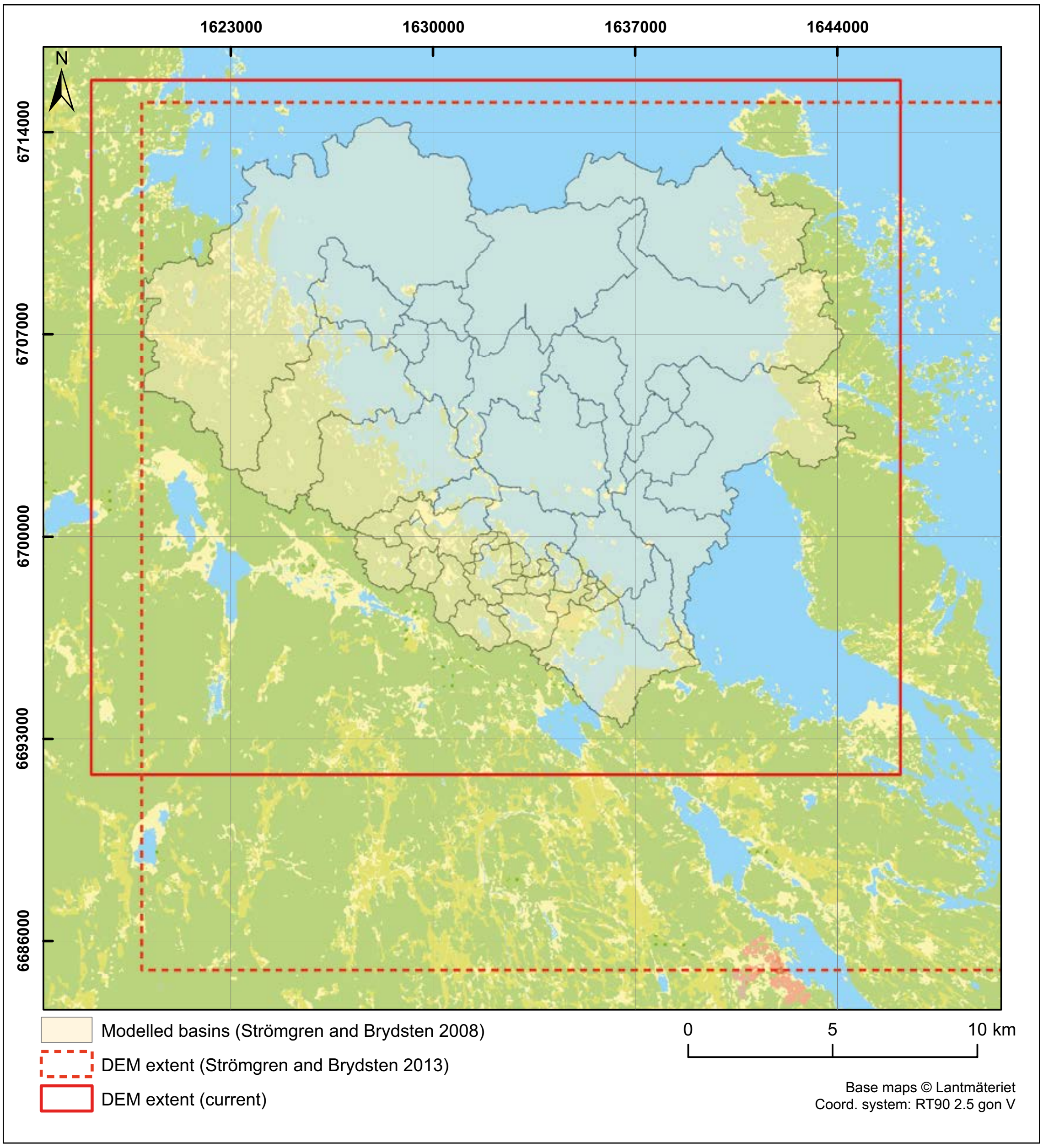

Figure 1-1. *Map showing the difference in extent between the current DEM and the previous one, as well as the basins modelled using the DEM in Strömgren and Brydsten (2013).*

Input data for the interpolation have many different sources, such as airborne laser scanning measurements, digital nautical charts, and depth soundings in both lakes and the sea. The quality of these data sources varies. The density and spatial distribution of input data are different for the terrestrial and marine areas. The elevation data available for the terrestrial area have a higher density and they are also more evenly distributed throughout the landscape. In the marine area, on the other hand, most depth measurements are distributed along survey lines and there are no depth measurements at all in large areas between the survey lines. As a result of the big difference in the density and spatial distribution of elevation data and depth data, the interpolation was performed separately for the marine and terrestrial areas.

The kriging interpolation was performed using the ArcGIS 10.3 Geostatistical Analysis extension. Digital elevation models are produced with 1 and 5 m resolutions in models covering the terrestrial area only and with 10 and 20 m resolutions in models covering both the terrestrial and the marine areas. The DEM is constructed in both 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, for the model area shown in Figure 1-1.

Recently, SKB migrated all geographical data to SWEREF 99 18 00 and RH 2000. However, during the work with this elevation model RT 90 2.5 gon V was still the map projection used by SKB and the figures and data in the present report are mostly displayed in this map projection and the RHB 70 height system. This facilitates easy comparisons between new and earlier models that are based on the same projection. The primary differences between the previous DEM and the DEM presented in this report are summarised in Table 1-1.

Table 1-1. Differences between the previous and the current digital elevation models produced for the Forsmark site.

	Current DEM	**Previous DEM (Strömgren and Brydsten 2013)**
Model area	Smaller and further to the west and north.	Larger and further to the east and south.
Number of input data	154 075 561	2 348 588
Spatial resolution	1, 5, 10 and 20 m for the terrestrial area, 10 and 20 m for the marine area.	20 m for the terrestrial and marine areas.
Model projections (xy / z)	RT 90 2.5 gon V / RHB 70 SWEREF 99 18 00 / RH 2000	RT 90 2.5 gon V / RHB 70
Culverts	Adjustment layer for culverts in all spatial resolutions.	No adjustment layers for culverts.
Sea shoreline	Partly adjusted from LiDAR data.	No adjustment from LiDAR data.
Lake bathymetry	Lake bathymetry digitised from depth maps and estimated depths of lakes not previously processed.	No lake bathymetry digitised from depth maps and no estimated depths of lakes outside the site investigation area.
Kriging interpolation	Exact interpolation performed in both the marine and terrestrial areas.	Exact interpolation performed in the terrestrial area and smooth interpolation performed in the marine area.
Nuclear power plant inlet canal	Re-digitised and increased number of points.	
Brook measurements	Significantly increased number of points.	

2 Methodology

2.1 Overview of methodology and data

The process of developing the new DEM can be generalised as follows. First, elevation data was collected, sorted and processed. Different domains were used to match density and spatial distribution of input data. Finally, the data was interpolated separately in each domain and merged into the final model. The general workflow can be seen in Figure 2-1 and is further explained below.

The various data sets used in the modelling are described in Table 2-1 and Table 2-2. They have either been collected during the production of earlier model versions or are newly acquired data used for the first time in the current modelling. In each case, the general collection methods are described first and then the processing steps taken to adjust the data density and/or distance to data of other origin. In some cases, the quality and accuracy of data differ between data sets, which implies that there must be a prioritisation to allow higher quality data to govern the model in the best possible way.

The data processing is a dynamic process aiming to provide a suitable data set to be used in the interpolation resulting in the final model. The data sets have in many cases undergone several iterations in the data processing. The tables with the different data sets (Table 2-1 and Table 2-2) also include a qualitative classification of the accuracy of each data set. For more detailed descriptions of the data used, see the individual sub-sections in Section 2.2 and 2.3.

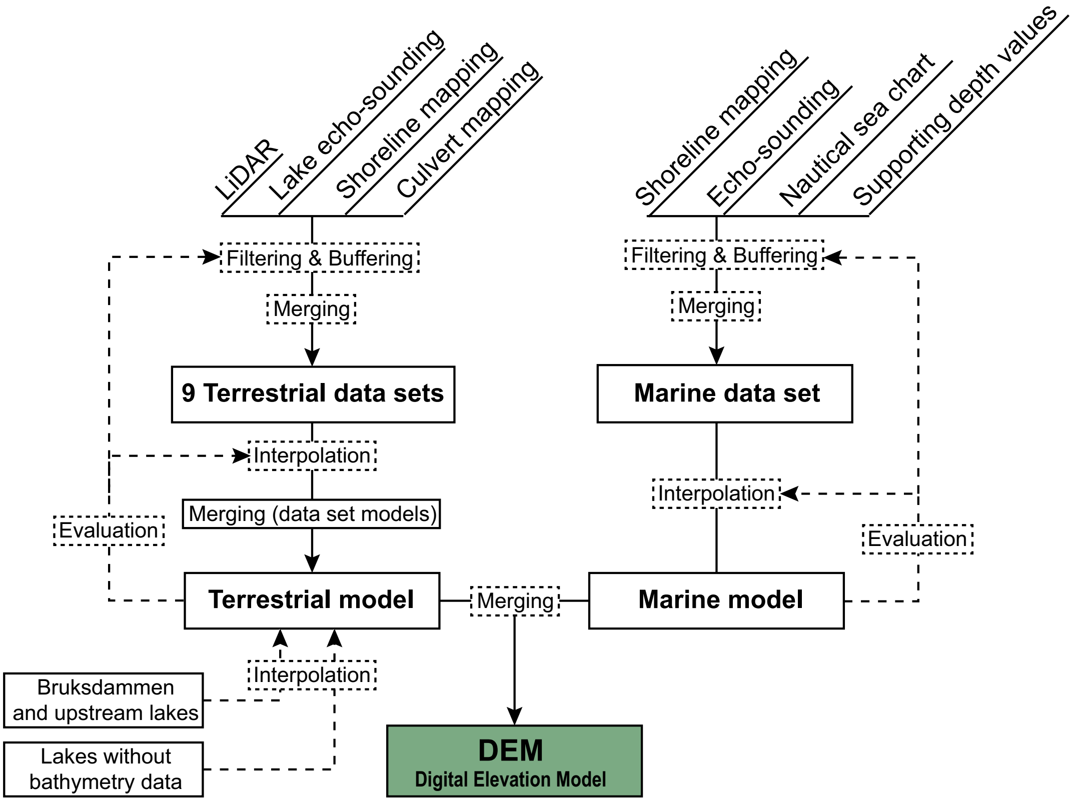

Figure 2-1. General workflow for the construction of the digital elevation model.

Table 2-1. Terrestrial data sets used in the modelling.

Data set	Year of acquisition	Reference	Original number of data points	Processed number of data points	Relative accuracy
LiDAR	2010–2011	Present work	152 940 608	152 940 608	Very high
Lakes, depth sounding	2003–2014	Present work Brunberg et al. 2004	24 266	24 266	Very high
Wetland objects	2009	Sohlenius and Hedenström 2009	6	6	High
Wetland objects other data	2015	Present work	1 406	1 406	Medium
Brook measurements	2004–2005	Brydsten and Strömgren 2005	614	2 436	Very high
Culverts	2015	Present work	5 949	5 949	High
Bruksdammen depth sounding	2003	Present work	4 344	4 344	High
Lakes upstream Bruksdammen, digitised	2015	Present work	5 623	5 623	Medium
Lakes upstream Bruksdammen, estimated depths	2015	Present work	30 847	30 847	Medium

Table 2-2. Marine data sets used in the model.

Data set name	Year of acquisition	Reference	Original number of data points	Processed number of data points	Relative accuracy
Regional survey area	2011	Nyberg et al. 2011	155 301	7 013	Very high
Detailed survey area	2011	Nyberg et al. 2011	174 937	127 739	Very high
Detailed survey area, 10 km^2	2011	Nyberg et al. 2011	430 558	430 558	Very high
Detailed survey area, interpreted data	2005	Elhammer and Sandkvist 2005	27 480	19 179	High
Shallow bays	2004	Brydsten and Strömgren 2004b	84 122	78 358	Very high
Mapping of reed	2011	Strömgren and Lindgren 2011	12 639	12 639	Very high
Depth chart for Lake Biotestsjön from 1976	1976	Personal communication with Peter Karås SLU⁽¹⁾	3 874	3 874	High
Supporting depth values	2008 and 2015	Present work Strömgren and Brydsten 2008	5 857	2 406	Medium
Digital depth chart	2015	Sjöfartsverket 2015	85 692	26 845	Medium
SKB sounding 2015	2015	Present work	80 486	6 953	Very high
Constructional drawings for the inlet canal to the nuclear power plant	1977	Internal documents	441	10 438	Medium
Söderviken depth sounding 2015	2015	Present work	7 936	2 017	High
Sea shoreline	2004 and 2015	Present work Brydsten and Strömgren 2004a	186 778	186 778	High
Sea shoreline buffered points	2015	Present work	192 139	192 139	High

1) Data set also stored at SKB_SVN\SFR\SR-PSU\Landscape\Indata

2.2 Terrestrial data and processing of data

2.2.1 LiDAR data

Airborne laser data covering the terrestrial part of the model area was delivered to SKB by Lantmäteriet in the coordinate system SWEREF 99 18 00 and the height system RH 2000. The data are divided into grids, each covering 2.5 × 2.5 km. The average point spacing within the grids ranges from around 0.7 to a little more than 1.5 points per m^2. Point counts per delivered grid vary between 2 and 12 million points, mainly depending on proportion of land and water within the grid. Each point has been classified as either ground or water, or where no classification has been determined, as unassigned. In several grids the classification has been enhanced by Lantmäteriet using the software TerraScan.

The data was collected on the 23rd, 27th and 29th of September 2010 and on the 6th and 7th of November 2010. 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). The different grids and their properties are presented in Appendix 1.

Figure 2-2. The two domains and the sub-areas dividing the data used for the construction of the terrestrial part of the DEM. Green colour shows the terrestrial part and blue colour the marine part of the DEM.

The LiDAR data was split into 9 different sub-areas (Figure 2-2) due to size limitations in the shape file format. The sub-areas have 20-m overlaps to allow for a smooth transition between areas in the final model. Points within the terrestrial part of the model area were kept and points outside of the defined shoreline (i.e. within the marine part) were removed. As noted above, LiDAR data classifies particularly thick vegetation (e.g. reed) as ground which would lead to incorrect elevation values of up to several metres depending on the height of the reed. Large areas around Lake Bruksdammen were processed and worked on extensively to obtain a satisfactory topography within these wetland and submerged areas. LiDAR-data at the outlets of certain lakes, particularly where thick reed was present, was also processed to correct the modelled topography so that water would exit the lakes at the proper locations in models built on the DEM.

2.2.2 Shoreline

A new shoreline was created for this model to separate the marine and terrestrial domains. The new shoreline has four main data sources:

- Measured shoreline using differential GPS (Brydsten and Strömgren 2004a).
- Manual digitising of shoreline using aerial photos.
- Base maps from Lantmäteriet.
- The raw LiDAR data that differentiates between land and water.

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 in reality 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. Figure 2-3 shows an example where the reed has been filtered out to produce a more accurate shoreline.

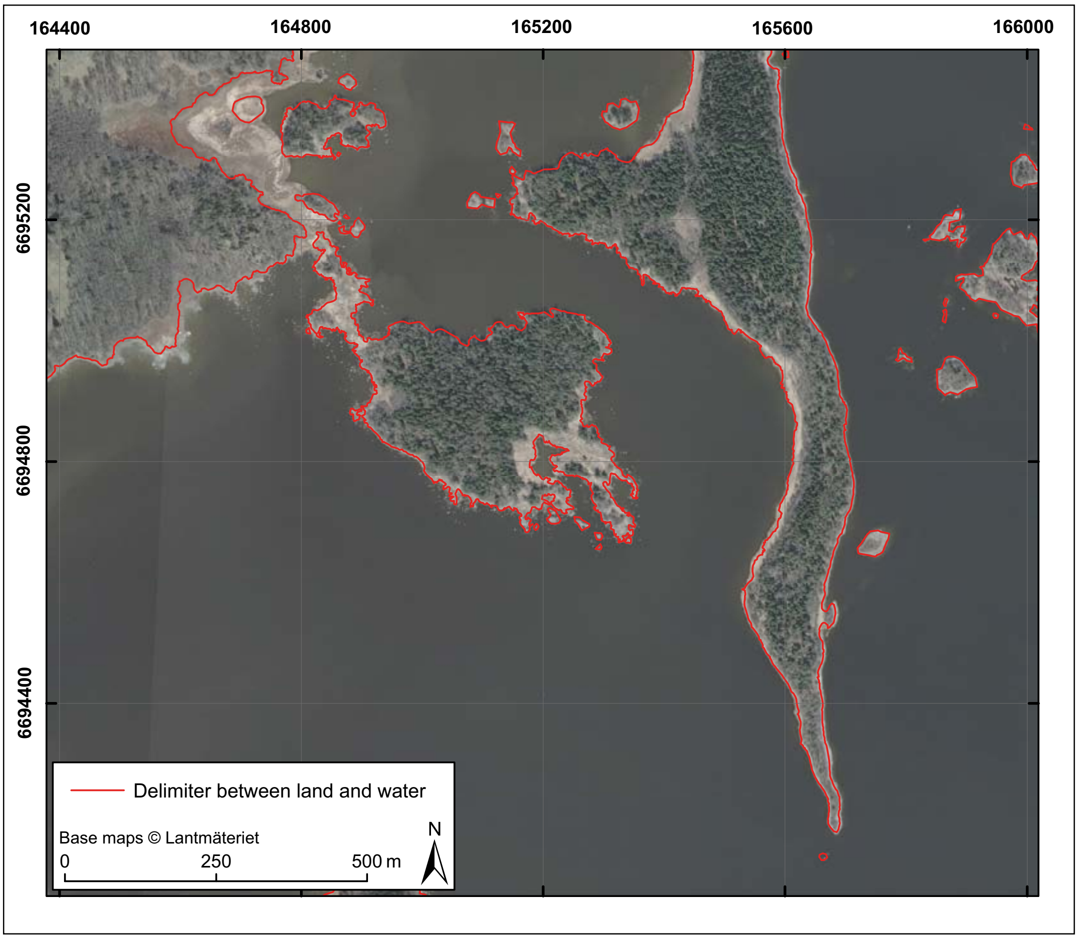

Figure 2-3. Illustration of the shoreline acquired from LiDAR data over a sample area. Red outlines the shoreline. The esker Börstilsåsen runs in a north-south direction in the eastern part of the area.

2.2.3 Lakes, depth sounding

Depth values for lakes within the site investigation area (Figure 2-4), described in Brunberg et al. (2004) and used in the previous DEM (Strömgren and Brydsten 2013), were also used in this DEM. However, a lot of depth data was collected in 2014 in Lake Eckarfjärden during a project (not reported) the main purpose of which was to characterise the bottom type with an echo sounder. With this depth data almost 25 000 depth values are used for Lake Eckarfjärden in this DEM compared to less than 4 000 in the previous DEM (Figure 2-5).

The lake extents have been kept the same as in the previous DEM, but the levels are adjusted based on LiDAR data from the lake boundaries. Table 2-3 shows lake surface levels used in the previous and the present elevation models. For some of the lakes, especially Lake Bolundsfjärden and Lake Norra Bassängen, differences between lake levels in the two models are relatively large (0.25 m). This is mainly due to differences in how the lake levels were obtained. As explained above, lake levels in the present DEM are based on LiDAR data. In the previous DEM, the mean level of the lake surface for one year was used for six of the lakes, including Lake Bolundsfjärden and Lake Norra Bassängen, whereas for all other lakes the levels were obtained from a single measurement.

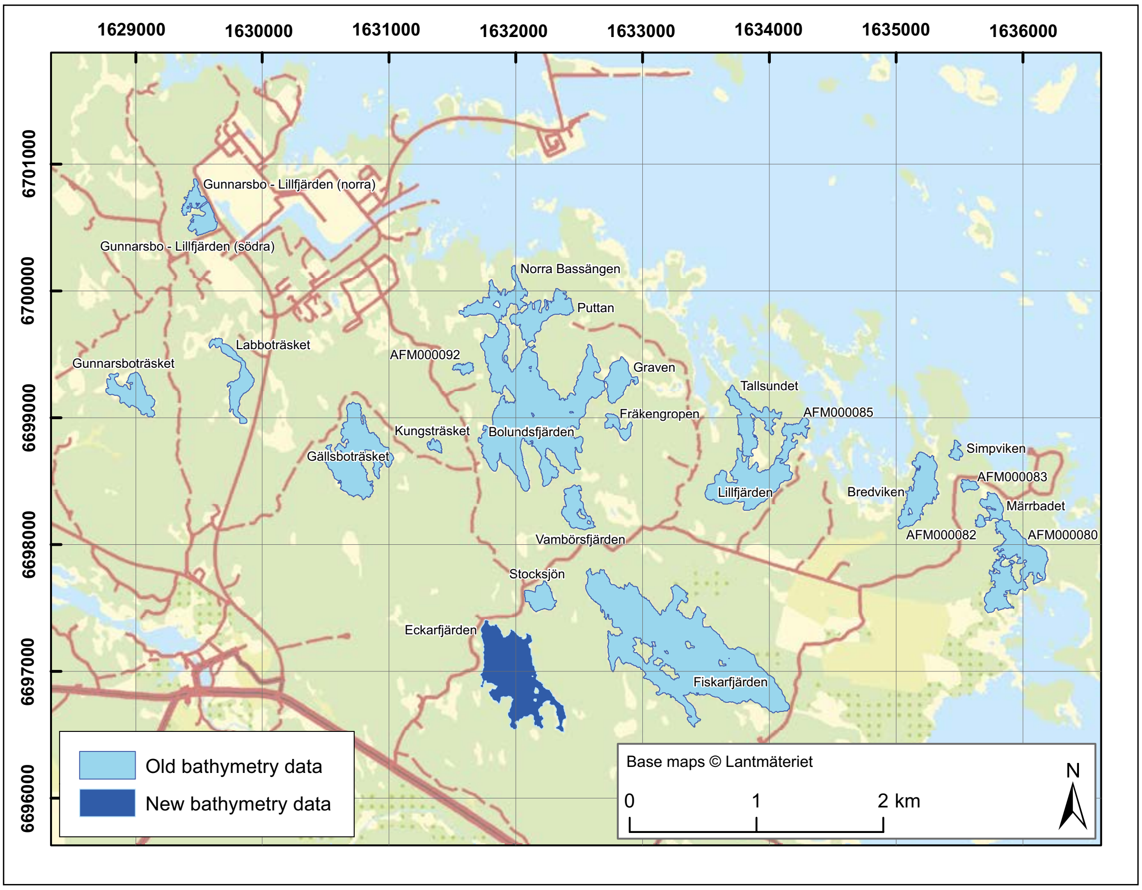

Figure 2-4. *Map over the site investigation area showing the lakes with older bathymetry as well as the location of Lake Eckarfjärden for which new bathymetry data is available.*

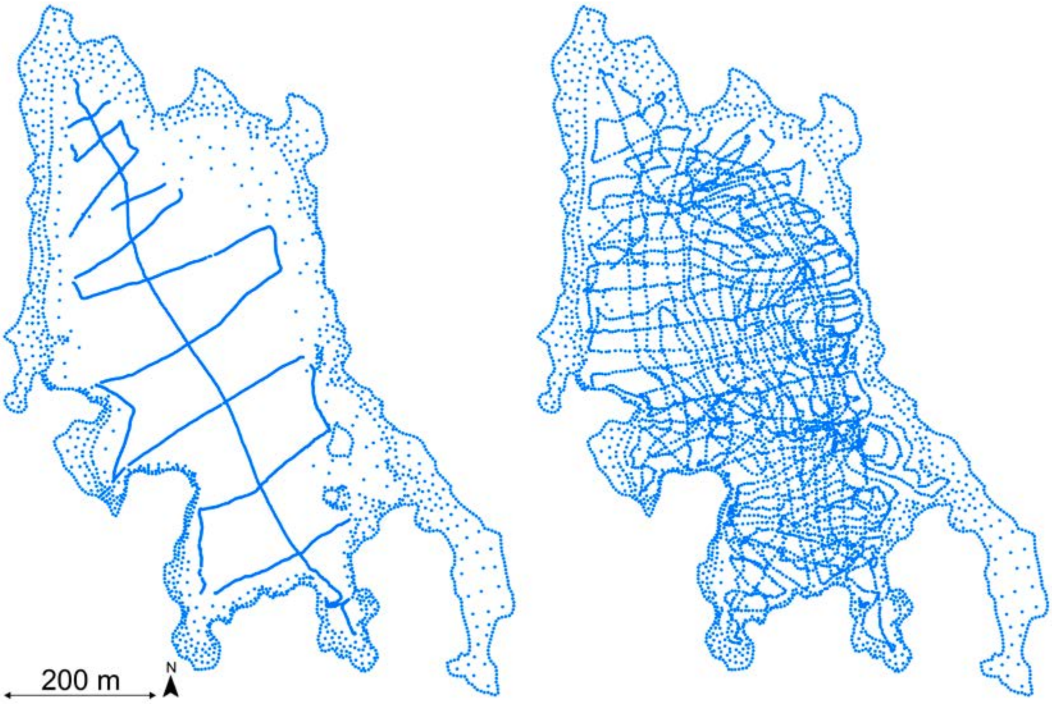

Figure 2-5. *Lake Eckarfjärden bathymetry data used in the previous DEM (Strömgren and Brydsten 2013) to the left and bathymetry used in the present DEM to the right.*

Table 2-3. Lakes in the site investigation area with levels used in the previous DEM and levels adjusted from surrounding LiDAR data and used in the current DEM. In the previous DEM, mean lake surface levels for one year were used for six lakes and levels measured on a single occasion for the others. For more information on lake levels in the previous DEM, see Strömgren and Brydsten (2008, 2013).

Lake name / ID	Old level (m in RH 2000)	New level (m in RH 2000)
AFM000080	0.08	0.12
AFM000082	0.41	0.27
AFM000083	0.57	0.41
AFM000085	0.11	0.17
AFM000092	2.01	1.77
Bolundsfjärden¹⁾	0.83	0.58
Bredviken	0.07	0.10
Eckarfjärden¹⁾	5.56	5.49
Fiskarfjärden¹⁾	0.73	0.59
Fräkengropen	1.54	1.39
Graven	0.84	0.59
Gunnarsbo – Lillfjärden (norra)	1.83	1.86
Gunnarsbo – Lillfjärden (södra)	1.79	1.91
Gunnarsboträsket	6.00	6.02
Gällsboträsket¹⁾	2.10	2.04
Kungsträsket	2.79	2.42
Labboträsket	3.75	3.58
Lillfjärden¹⁾	0.12	0.27
Märrbadet	0.19	0.33
Norra Bassängen¹⁾	0.75	0.50
Puttan	0.82	0.58
Simpviken	0.11	0.10
Stocksjön	3.11	3.01
Tallsundet	0.32	0.28
Vambörsfjärden	1.33	1.12

¹⁾ Lake for which the mean surface level for one year was used in the previous DEM.

2.2.4 Bruksdammen and upstream lakes

Four relatively large lakes, i.e. Skälsjön, Norra Åsjön, Södra Åsjön and Bruksdammen, are situated in the central-western part of the model area. These lakes are located just outside the water divide formed by previously modelled basins (Figure 1-1). Since depth data were available for these lakes and could be processed and included in the model with limited effort, it was decided to improve the description of this lake system in the DEM. Three named streams connect the four lakes: Årböleån, Nyböleån and Svarvarån. Furthermore, large areas surrounding the lakes are classified as "wetlands" and "open wetlands" (Figure 2-6).

Depth charts from Skälsjön, Norra Åsjön and Södra Åsjön were digitised based on maps found in Brunberg and Blomqvist (1998). Images were scanned from the book and rectified based on orthophotos. Depth contours were extracted from the maps. The result can be seen in Figure 2-7. No elevation information could be found regarding the surface levels of these lakes. LiDAR data from surrounding areas were used to estimate a minimum elevation and it was found that all three lakes share a similar lake level (Table 2-4).

Table 2-4. Lakes where depth contours have been digitised from depth maps in Brunberg and Blomqvist (1998).

Lake name	Lake level (RH 2000)
Norra Åsjön	12.2
Södra Åsjön	12.2
Skälsjön	12.2

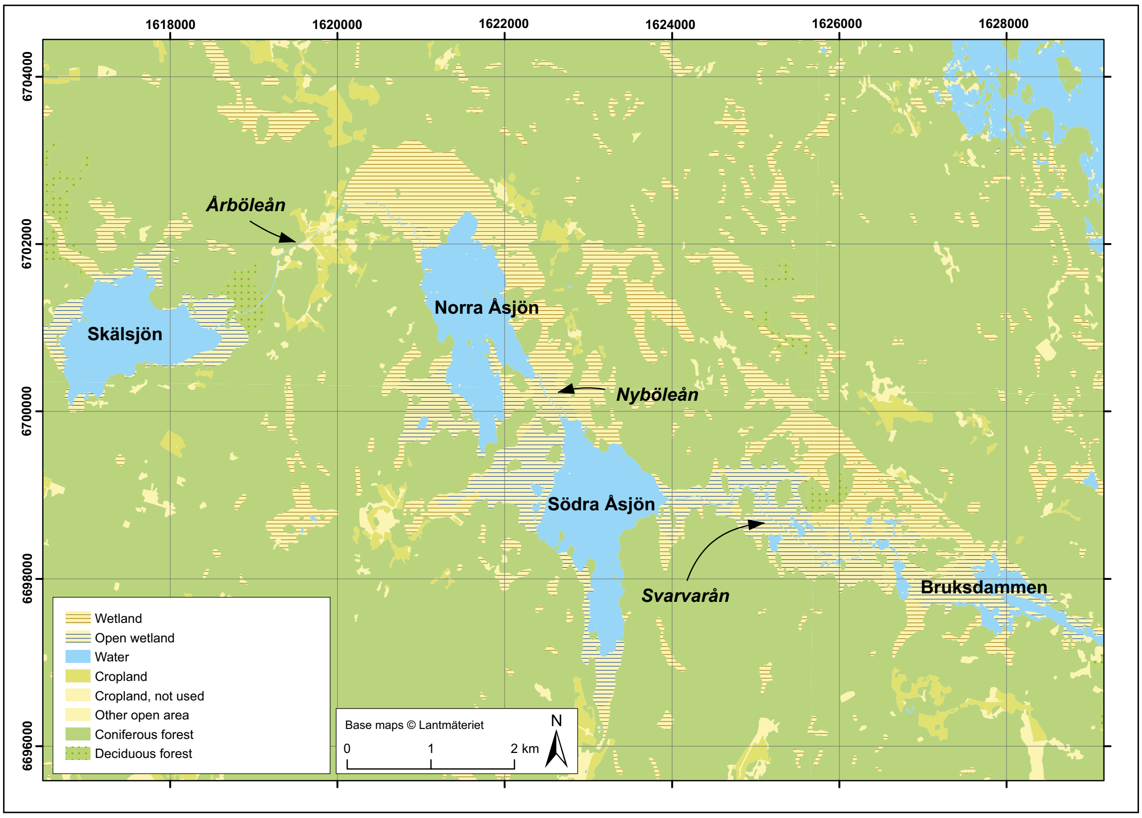

Figure 2-6. Overview of the different lakes and wetland areas for which bathymetries have been calculated for the new DEM.

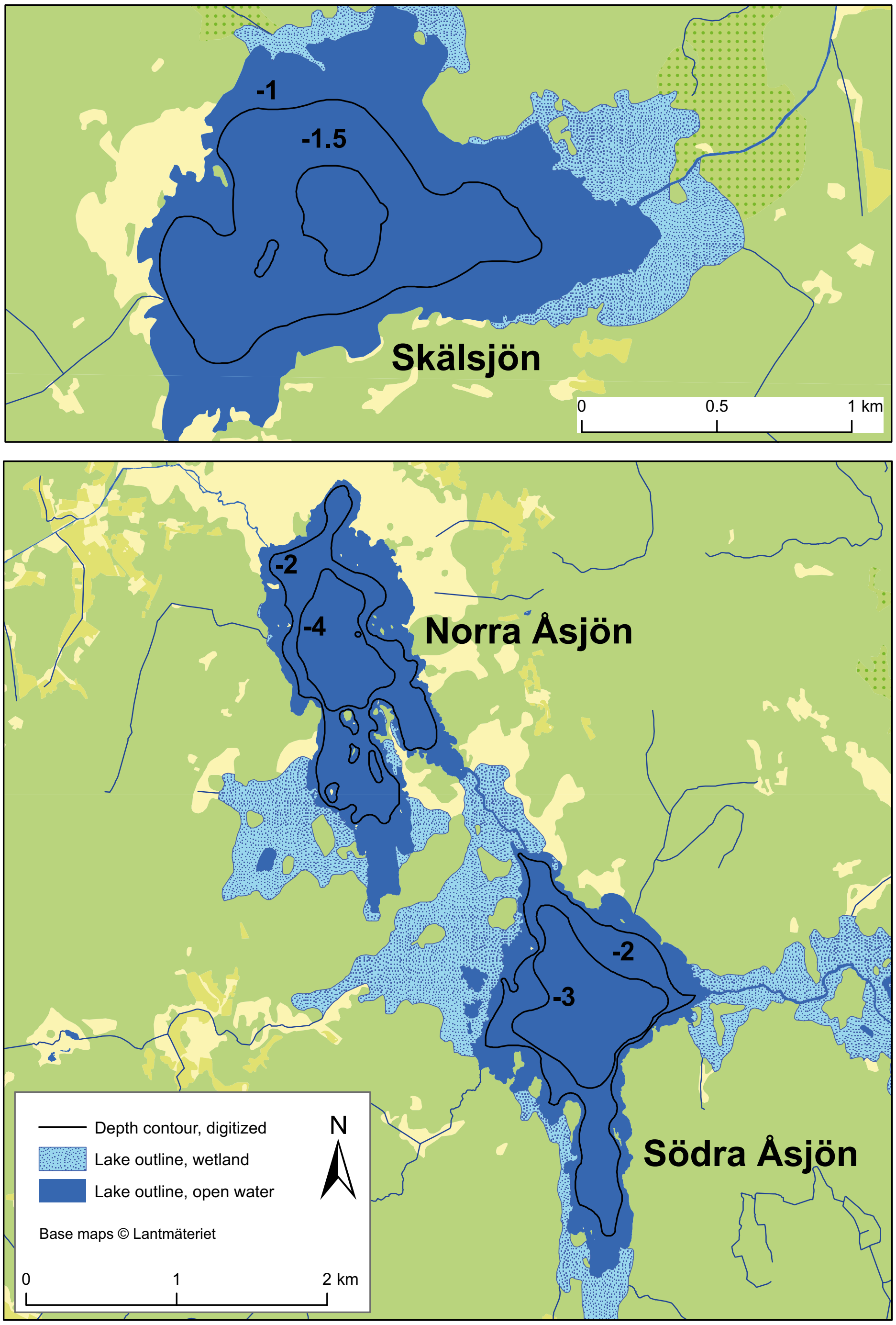

Figure 2-7. *Digitised depth contours for Skälsjön, Södra Åsjön and Norra Åsjön based on depth maps in Brunberg and Blomqvist (1998).*

To produce a bathymetry for this lake complex, as well as for Lake Bruksdammen, several different data sources were used:

- The digitised depth contours for Skälsjön, Norra Åsjön and Södra Åsjön.
- Older echo sounding data from Bruksdammen (not reported).
- The layer "Sankmark – Svårframkomlig" (Open wetland in Figure 2-6).
- LiDAR data near lake or wetland.
- Estimated depth values where no other information could be gathered.

The wetland areas pose the biggest challenge. No depth data can be acquired there since it is not possible to use a boat and these areas cannot be crossed on foot either. It was concluded that these areas must be at a higher elevation than the bottom level in the nearby lakes but at a lower elevation than the level of the lake surfaces. The lake levels were estimated to be at ~12.2 m.a.s.l. in the RH 2000 height system and the shallowest depth values found with the echo sounder were ~11.5 m.a.s.l. Based on these elevations, the bottom of the wetlands was estimated to be between 11.7 and 11.5 m.a.s.l. However, there are also small ponds with open water surfaces not directly connected to the lakes shown in Figure 2-7 or Bruksdammen. The outline of these water bodies was estimated to be 11.7 m.a.s.l.

To enable a smooth transition to the terrestrial part, all LiDAR data that was closer than 5 m from the border of either open water or wetlands was kept. In certain areas where data points were scarce, manual entries with estimated depth values were placed to ensure proper interpolation. For Svarvarån there was only echo sounding data halfway up from Bruksdammen to Södra Åsjön. Depth values were estimated based on the echo sounding data collected at different parts of this stream. A section of the final data set used to interpolate this lake complex can be seen in Figure 2-8.

2.2.5 Lakes with estimated depths

There are other lakes within the model area but outside the main site investigation area where no bathymetric surveys have been performed. There are many very small lakes and for practical reasons depth estimations were performed only for lakes with areas larger than 29 000 m^2. These 12 lakes have been assigned generic depth values based on mean depths in lakes with similar areas within the PLU area. A depth value of 0.59 m was used for lakes with areas less than 50 000 m^2 and 0.96 m was used for larger lakes. The lake shoreline levels for these lakes were estimated from LiDAR data.

2.2.6 Wetland objects

Some wetland objects have been probed and the water depth values at the time were used in the model to assign water depth to a number of smaller wetlands objects in the area (Sohlenius and Hedenström 2009).

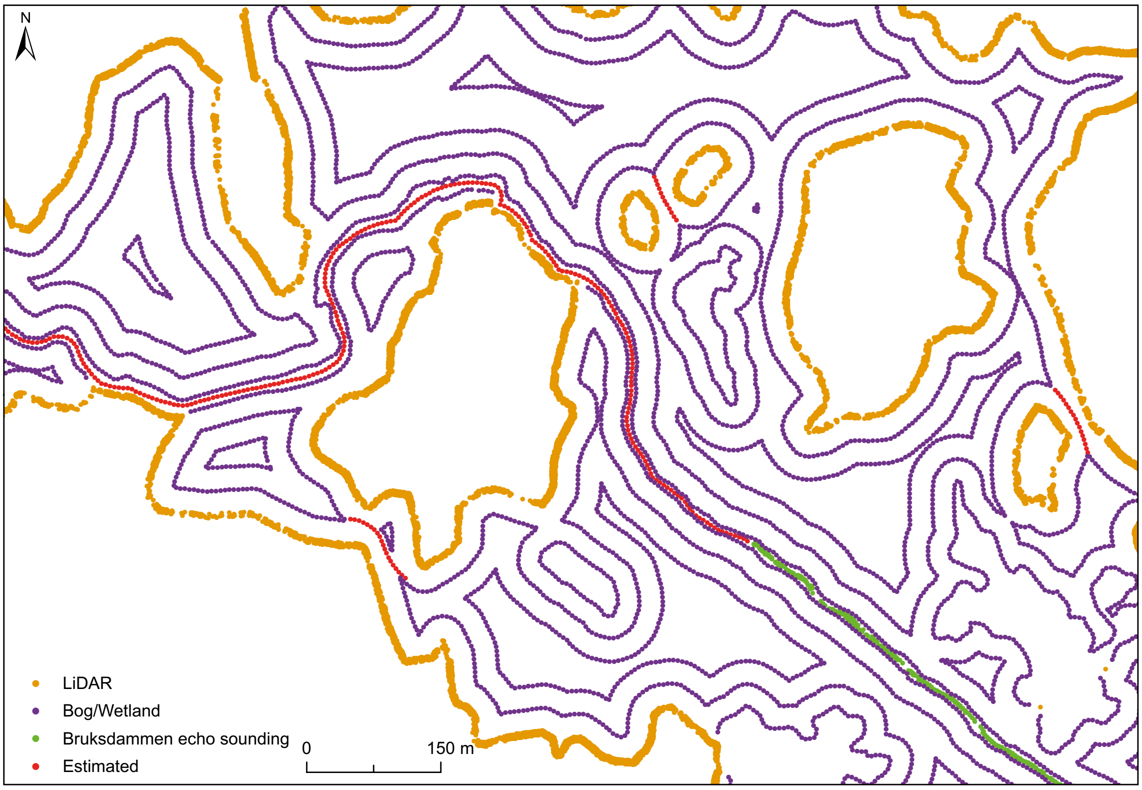

Figure 2-8. Point distribution from a sample location in the northern part of Lake Bruksdammen to visualise the different points that were used to calculate the final bathymetry of the lake system.

2.2.7 Brook measurements

When reviewing LiDAR data in and around the measured brooks it was evident that the laser sometimes fails to register the stream bed due to vegetation and/or water. The stream bed was not evident in the model when only using LiDAR data and original brook measurements. Original brook measurement data were too scarce (up to 10 m distance between points) to leave an imprint of the bed in the model (red dots in Figure 2-9). The brooks and their gradients were thus modelled separately using only the manual measurement points (i.e. without LiDAR data) to extract points every metre along the gradient (blue dots in Figure 2-9). Additional points related to the stream bed in the terrain were thus included to better match the high density of surrounding LiDAR points. As an example, a section of a brook can be seen in Figure 2-9.

2.2.8 Culverts

In and around the site investigation area the location of culverts was measured using a handheld GPS device. Adjustment layers to be used with the final DEM, representing the bottom levels of the culverts, were created to ensure a proper hydrological description of this area and the right prerequisites for topographically driven hydrological models. The bottom levels were obtained from nearby LiDAR data. However, these adjustment layers are separate raster layers and not part of the final DEM.

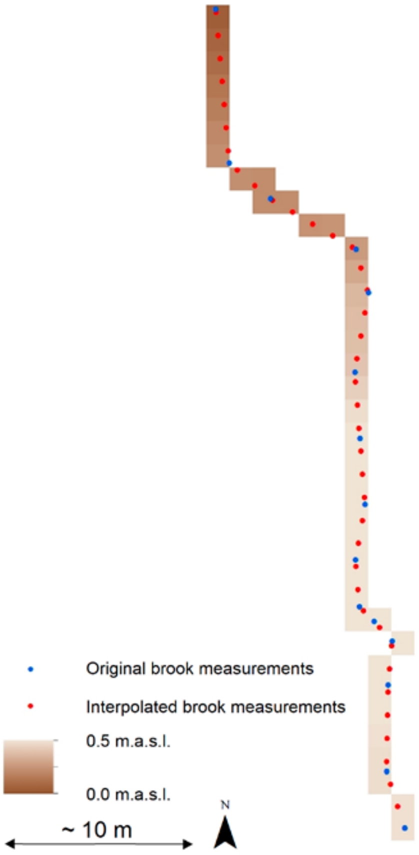

***Figure 2-9.** Original brook points and processed brook points extracted from an interpolated raster model. The gradient can be seen in the cell values.*

2.3 Marine bathymetry data and processing

The areas represented by the different data sets used in the marine model are shown in Figure 2-10. The processing of these data sets is described below. Origin and information regarding the sources of the data are described in Table 2-2.

2.3.1 Regional survey area

The distance between survey lines in the original data within the regional survey area is sometimes more than 1 000 m with depth values at about 3 m distance between them along these survey lines. During June and July 2015, SKB carried out additional echo sounding in the regional survey area to improve the quality of the bathymetry data set. A Trimble Sonarmite BT echosounder was used with a 200 kHz echosounder transducer to collect depth values every 5 m along survey lines. The positions and levels were collected with a high precision GPS, Trimble R10 GNSS (Global Navigation Satellite Systems), in the map projection SWEREF 99 TM and the height system RH 2000. A Trimble TSC3 field computer with the software Trimble Access was used to store the data.

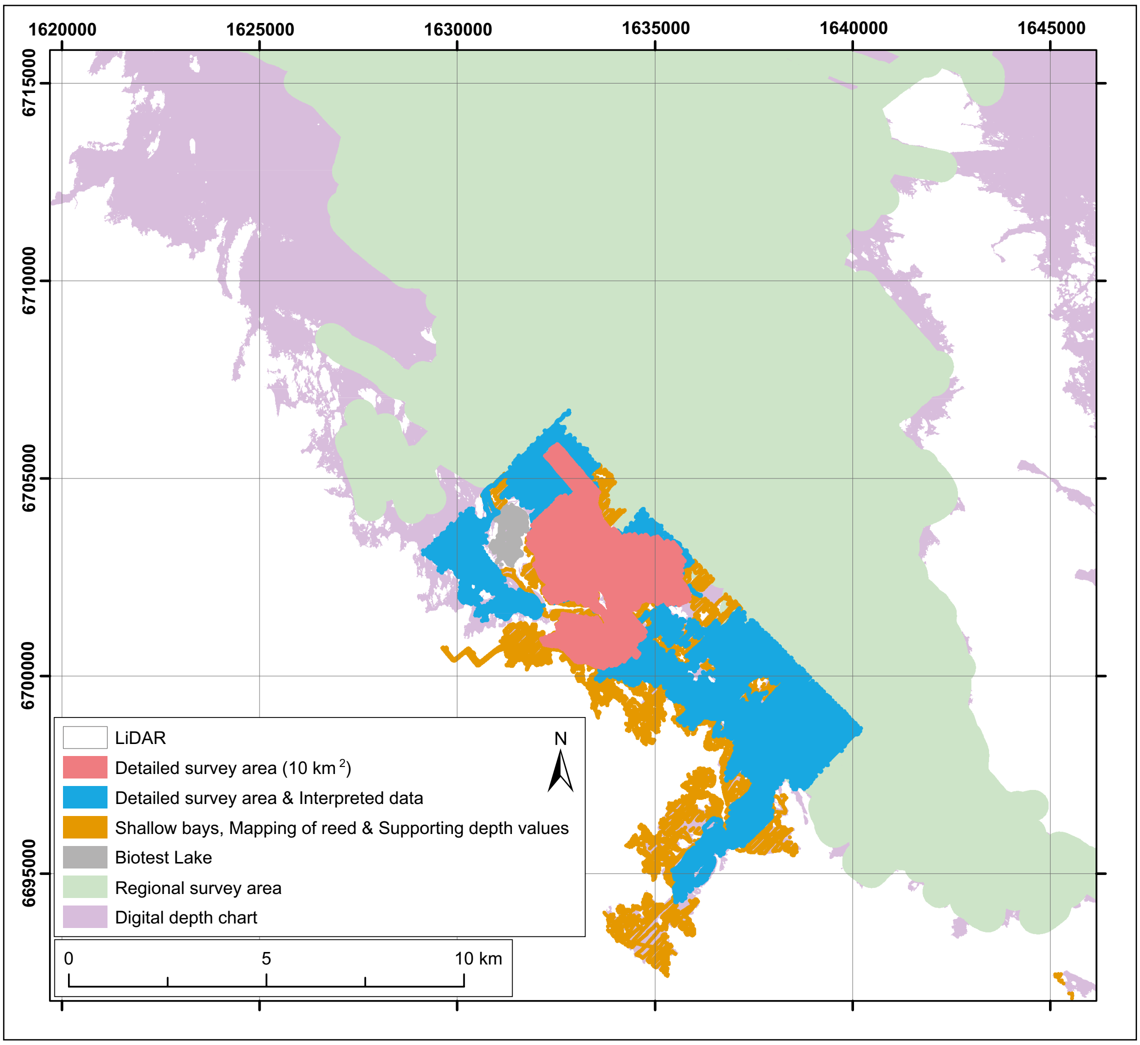

Figure 2-10. Different data sets used in the interpolation of the marine bathymetry.

During the bathymetric survey, the distance between survey lines in the area was halved, but the distance between survey lines is still long compared to the distance between measured depth values along the survey lines. Due to the uneven distribution of depth data, depth values were thinned out so that only depth values with about 50 m distance between them were used in the final elevation model. This processing was necessary to get a smoother model surface. The result would otherwise have been clear imprints in the model surface along the survey lines. Parts of the depth data that were not used in the modelling were instead used in the validation of the final model. This is further described in Section 4.2.

2.3.2 Detailed survey area (10 km^2)

Depth values were extracted from the processed side-scan sonar image of the sea bottom. The image had 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.

2.3.3 Detailed survey area and interpreted data

No additional processing was done, with the exception of removal of all depth data within the area corresponding to the detailed survey area, 10 km^2. The interpreted data set consists of depth values extracted from interpreted depth contours based on the bathymetric measurements of the detailed survey area. Depth values from this data set are removed within 10 m of measured depth values from the detailed survey area.

2.3.4 Shallow bays, mapping of reed and supporting depth values

The only processing step made in the shallow bays was to remove all data points within the detailed survey area, 10 km^2. As for the supporting depth values, a buffer of 1 m outside the shoreline with a depth of −0.2 m (RH 2000) has been made to simulate the transition from land to sea bottom at the shoreline. In certain shallow bays, depth values have been estimated where no depth 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. Any supporting depth values within 8 m of the new modelled shoreline have been removed. Furthermore, depth values related to the mapping of reed have been used in the model. No additional processing was made of these data.

To increase the quality of the bathymetry data set for Asphällsfjärden and Söderviken, a complementary bathymetric survey was performed in late June 2015. A combined echo sounder and GPS (Humminbird 798ci HD SI) was used. Positions and water depths were stored every other second during the measurements. Incorrect measurements were subsequently removed. It was concluded that the shallow bays data set was of higher accuracy and quality than the depth data collected during this bathymetric survey. Points within 5 m of shallow bay points were thus removed to ensure that no conflicting depths were present. Finally, data points related to the nuclear power plant inlet canal were increased, compared to the number of points used in the previous DEM, by increasing the number of points extracted from previous digitised elevation lines.

2.3.5 Biotest lake

A previously rectified and digitised depth chart map was used. No additional measurements or processing were made.

2.3.6 Digital depth chart

A newly acquired digital depth chart was used in the construction of the new DEM. 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.

- Every depth point with a specific depth of −1, 0 and 1 m above sea level was kept.
- Any depth point values extracted from the depth contours within 100 m of all depth data from the detailed survey area, the regional survey area, shallow bays and depth data from the SKB sounding in 2015 were removed.
- Any depth points that extend more than 500 m from the model area boundary were removed.
- Any depth points outside the marine area and within 2 m of the shoreline used in this DEM were removed.
- Any depth points extracted from the 15, 20 and 30 m depth contours within a distance of 300 m from depth data from the SKB sounding 2015 and the regional survey area were removed. The exception was points from the 10 and 15 m depth contour lines that do not cross survey lines from SKB sounding 2015 and the regional survey area, which were included in the modelling.
- Points with specific depth values have been shifted in weight by increasing the number of points from one to four.

Figure 2-11 shows all data point locations used for the final marine data set. The distance between points ranges from several metres to several hundred metres. This variation in data point density is evident in the map.

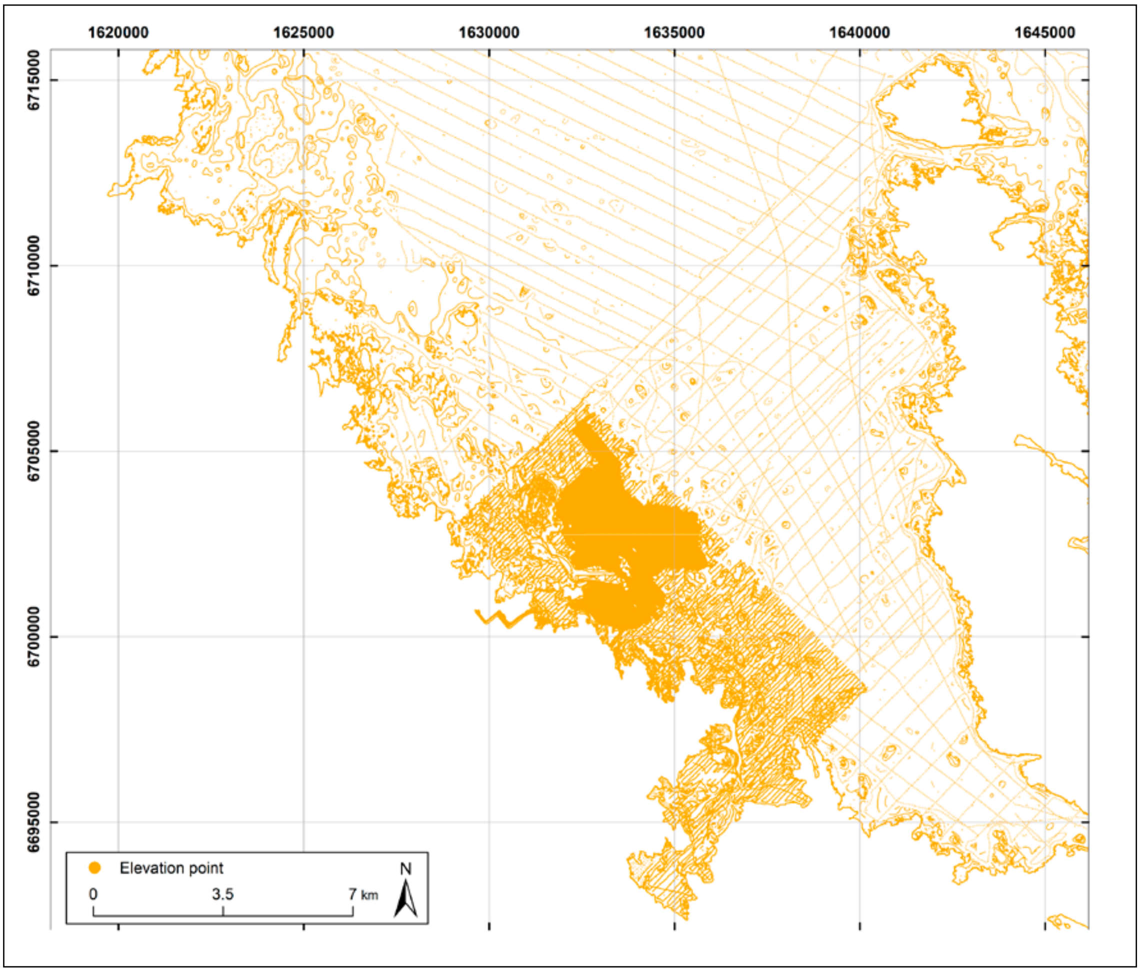

***Figure 2-11.** Data points used in the interpolation of the marine model.*

2.4 Construction of the digital elevation model

When the previous DEM (Strömgren and Brydsten 2013) was produced, LiDAR data was only available for a small part of the terrestrial area and the maximum distance between some of the survey lines in the marine area could be as large as 1 000 m. The accuracy of the previous DEM in these parts is considerably lower compared to the area covered by LiDAR data and the marine part where survey lines are now separated by shorter distances. In this work, LiDAR data were available for the whole terrestrial part of the DEM, and new bathymetric measurements have reduced the maximum distance between survey lines in the marine part of the model area to approximately 500 m. Altogether, this makes it possible to produce a new DEM with considerably higher accuracy.

The processing of data used in the construction of the DEM is described earlier in this chapter. Several test interpolations were performed to obtain the final data sets used for the interpolation of the DEM (Table 2-5). The aim of these tests was of course 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.

The interpolation was done in two domains, land and sea, due to the big difference in density and spatial distribution of elevation data. A natural border between these two domains is the sea shoreline, since LiDAR data with very high density covers most of the terrestrial area and most data in the sea are arranged along survey lines with little data in between.

Different data sets for the land and sea domains were created. All elevation point values for land (including lakes) and the sea shoreline were used for the interpolation of the land domain. All elevation point values from the sea and the sea shoreline were used for the interpolation of the sea domain. It was necessary to use the sea shoreline in both the terrestrial and marine data bases to generate a smoother transition on the border between the marine and terrestrial parts of the DEM. The terrestrial area was further divided into 9 sub-areas (see Section 2.2, Figure 2-2) depending on the large quantity of LiDAR data (more than 150 million elevation data points) and the size limitation of the ESRI shape format (2 GB) used for the interpolation. 20-m overlaps of LiDAR data were used in the 9 data sets for the terrestrial area to generate smooth transitions on the borders between sub-areas.

Table 2-5. Number of points used for interpolation of nine terrestrial sub-areas and the marine part of the DEM (see Figure 2-2).

Area	Number of points
1	12 955 733
2	27 942 031
3	25 303 301
4	9 507 506
5	18 749 400
6	14 731 922
7	18 913 430
8	11 017 124
9	15 732 084
Marine area	1 106 839

Kriging (Davis 1986, pp 383–404, Isaaks and Srivastava 1989) was chosen as interpolation method. 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. Different models, different combinations of lag size and number of lags and different parameter values in the searching neighbourhood were used until appropriate models were found for the terrestrial and the marine areas in the DEM. Instead of describing all tests performed here, only the models, lag size/number of lags and the searching neighbourhood used for the construction of the digital elevation models are summarised in Appendix 2. An exact interpolation of the point elevation data in the 9 terrestrial areas and the marine area was performed. The extent of the final DEM was used for the marine part and the extents of the 9 terrestrial sub-areas were used for the terrestrial part (Table 2-6).

The resolution was chosen to 1, 5, 10 and 20 m cell sizes in the different models produced for the terrestrial area. For the marine area, digital elevation models with 10 and 20 m cell sizes were produced.

Table 2-6. Corner coordinates of the nine terrestrial sub-areas and the marine part in the construction of the DEM. The coordinates are specified in both map projections used in the modelling, as RT 90 2.5 gon V/SWEREF 99 18 00.

Area	West	East	North	South
1	1618170/146910	1646170/175710	6715830/6714550	6710930/6709550
2	1618170/146910	1646170/175710	6710930/6709550	6706030/6704550
3	1618170/146910	1628170/156910	6706030/6704550	6701130/6699550
4	1618170/146910	1624170/152910	6701130/6699550	6696130/6694550
5	1618170/146910	1628170/156910	6696130/6694550	6691770/6689550
6	1618170/156910	1638170/166910	6696130/6694550	6691770/6689550
7	1624170/152910	1638170/166910	6701130/6699550	6696130/6694550
8	1628170/156910	1646170/175710	6706030/6704550	6701130/6699550
9	1638170/166910	1646170/175710	6701130/6699550	6691770/6689550
Marine area	1618170/146910	1646170/175710	6715830/6714550	6691770/6689550

The models for the land and sea domains were merged into one DEM, representing the Forsmark area. In a postprocessing procedure raster layers for the bathymetry representing Lake Bruksdammen and upstream lakes (described in Section 2.2.4) were produced in 1, 5, 10 and 20 m cell sizes. The kriging model used for this interpolation is described in Appendix 2. These layers were used to adjust the digital elevation models for all cells within the area representing Bruksdammen and upstream lakes. Finally, the models were adjusted to elevations representing the 12 lakes outside the site investigation area for which bathymetry data were not available (described in Section 2.2.5).

Digital elevation models including both the terrestrial and marine parts of the Forsmark area were produced in 10 and 20 m cell sizes and models for the terrestrial part only were produced in 1 and 5 m cell sizes. The RT 90 2.5 gon V map projection and the height system RHB 70 are used in these elevation models. The data sets for all terrestrial sub-areas and the marine area were transformed to the SWEREF 99 18 00 map projection and the RH 2000 height system. In Table 2-6, the extents of the terrestrial sub-areas and the marine area are specified in both map projections. Elevation models in SWEREF 99 18 00 and RH 2000 were developed with the same cell sizes and according to the same method as already described for the models produced in the RT 90 2.5 gon V map projection and RHB 70 height system.

3 Results

Digital elevation models with 1 and 5 m cell sizes have been produced for the terrestrial area in Forsmark and models with 10 and 20 m cell sizes for both the terrestrial and the marine areas. Most of the results presented in this section are from the 20-m model with both terrestrial and marine areas; this model was selected primarily to enable comparisons between the model presented in this report and the previous one. The 1-m model of the terrestrial area is also displayed, in order to illustrate the capabilities of this high-resolution model. All models produced are listed and described in Table 3-1.

SKB has developed a model data base (SKBmod) where the DEM and other types of models will be stored. However, at the time of finalising the present report (February 2020), only the 1-m and 5-m models in the SWEREF 99 / RH 2000 coordinates are available there; the SKBmod ID numbers of these models are 1859072 (the 1-m model) and 1859070 (the 5-m model).

Table 3-1. Names and properties of models.

Name	Cell size [m]	Terrestrial [yes/no]	Marine [yes/no]	Projection [x,y]	Height system [z]
FM_REG_1m_99	1	Yes	No	SWEREF 99 18 00	RH 2000
FM_REG_5m_99	5	Yes	No	SWEREF 99 18 00	RH 2000
FM_REG_10m_99	10	Yes	Yes	SWEREF 99 18 00	RH 2000
FM_REG_20m_99	20	Yes	Yes	SWEREF 99 18 00	RH 2000
FM_REG_1m_90	1	Yes	No	RT 90 2.5 gon V	RHB 70
FM_REG_5m_90	5	Yes	No	RT 90 2.5 gon V	RHB 70
FM_REG_10m_90	10	Yes	Yes	RT 90 2.5 gon V	RHB 70
FM_REG_10m_90	20	Yes	Yes	RT 90 2.5 gon V	RHB 70

The previous DEM extends almost 7 km further in the southern direction and almost 4 km further in the eastern direction (see Figure 1-1). The size of the current DEM is modified to exceed the present and future watershed boundaries in the previous DEM by a margin of at least 2 km and therefore extends almost 2 km further in the western direction and almost 1 km further in the northern direction.

The 20-m digital elevation model describing land surface, sediment level at lake bottoms, and sea bottom is shown in Figure 3-1. A zoomed-in version of the 1-m DEM is shown in Figure 3-2. The 20-m digital elevation model has a size of approximately 24 × 28 km, a cell size of 20 m, 1 203 rows, and 1 400 columns, a total number of DEM cells of 2 684 200 and a file size of approximately 7.1 MB (ESRI Grid format). The corner coordinates of the model area are 1618170 (146910) west, 1646170 (175710) east, 6715830 (6714550) north, and 6691770 (6689550) south in the RT 90 2.5 gon V coordinate system with the corresponding SWEREF 99 18 00 coordinates within brackets. The height systems used for the RT 90 and SWEREF projections are RHB 70 and RH 2000, respectively. The area is very flat; the range in elevation is only approximately 101 m with the highest point at 44 m above sea level at the south-western part of the DEM, and the deepest sea point at –57.3 m in the northern part of the Gräsörännan trench.

The mean elevation in the DEM is 1.8 m. The mean elevation in the terrestrial area is around 10.7 m and the mean depth in the sea is around 13.8 m. The model area is covered by 52 % land and 48 % sea. The flat landscape is also shown in the statistics of the slope, where the mean slope is 1.39 degrees, and 97.7 % of the cells have slopes lower than 5 degrees and 2.2 % have slopes between 5 and 10 degrees. Almost all of the cells with slopes steeper than 10 degrees (0.09 %) are man-made such as the inlet canal to the nuclear power plant and the SFR pier and Forsmark harbour close to SFR.

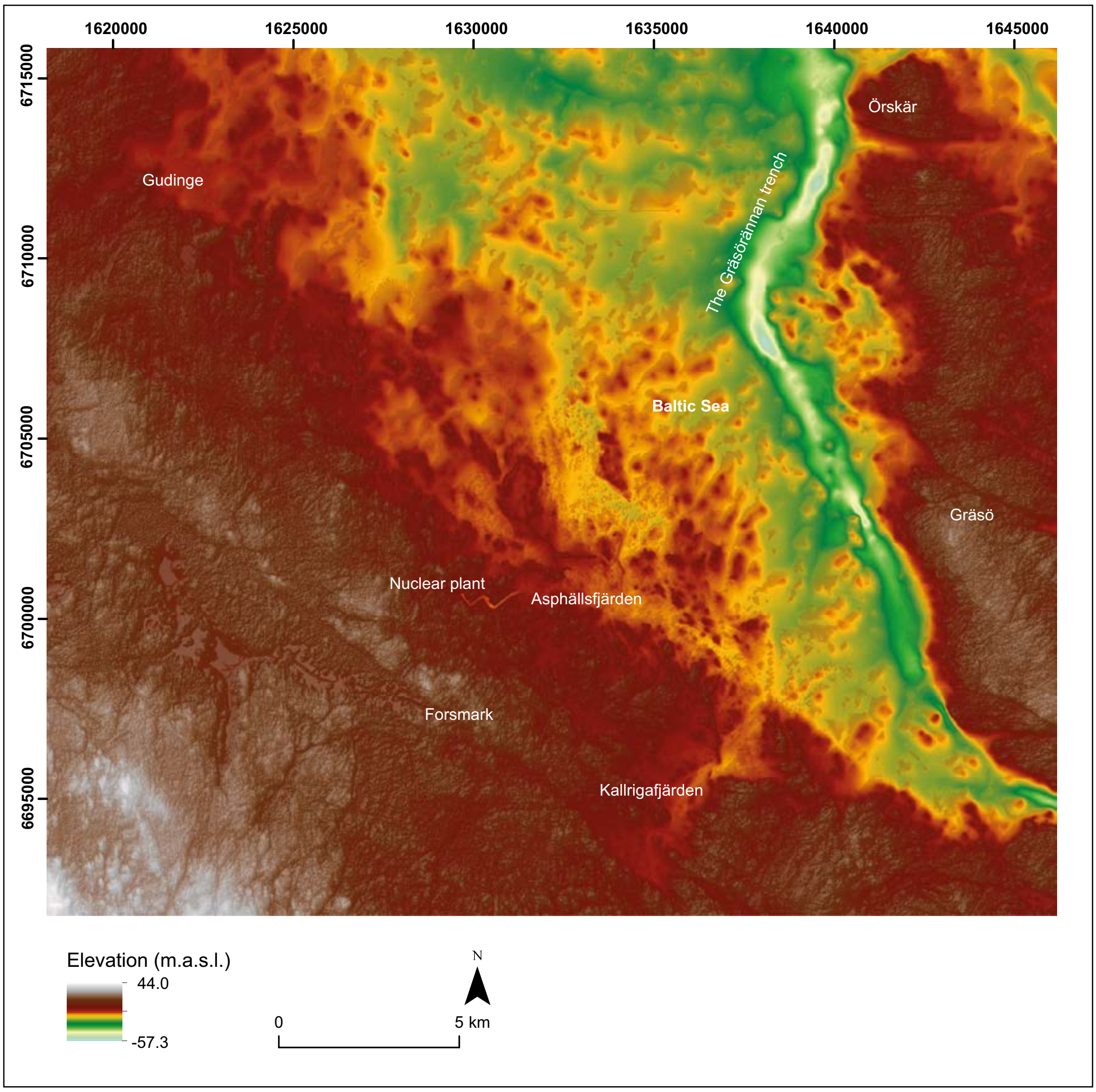

Figure 3-1. *The 20-m digital elevation model describing land surface, lake bottoms, and lake sediment surfaces. The DEM is displayed in the projected coordinate system RT 90 2.5 gon V and the height system RHB 70.*

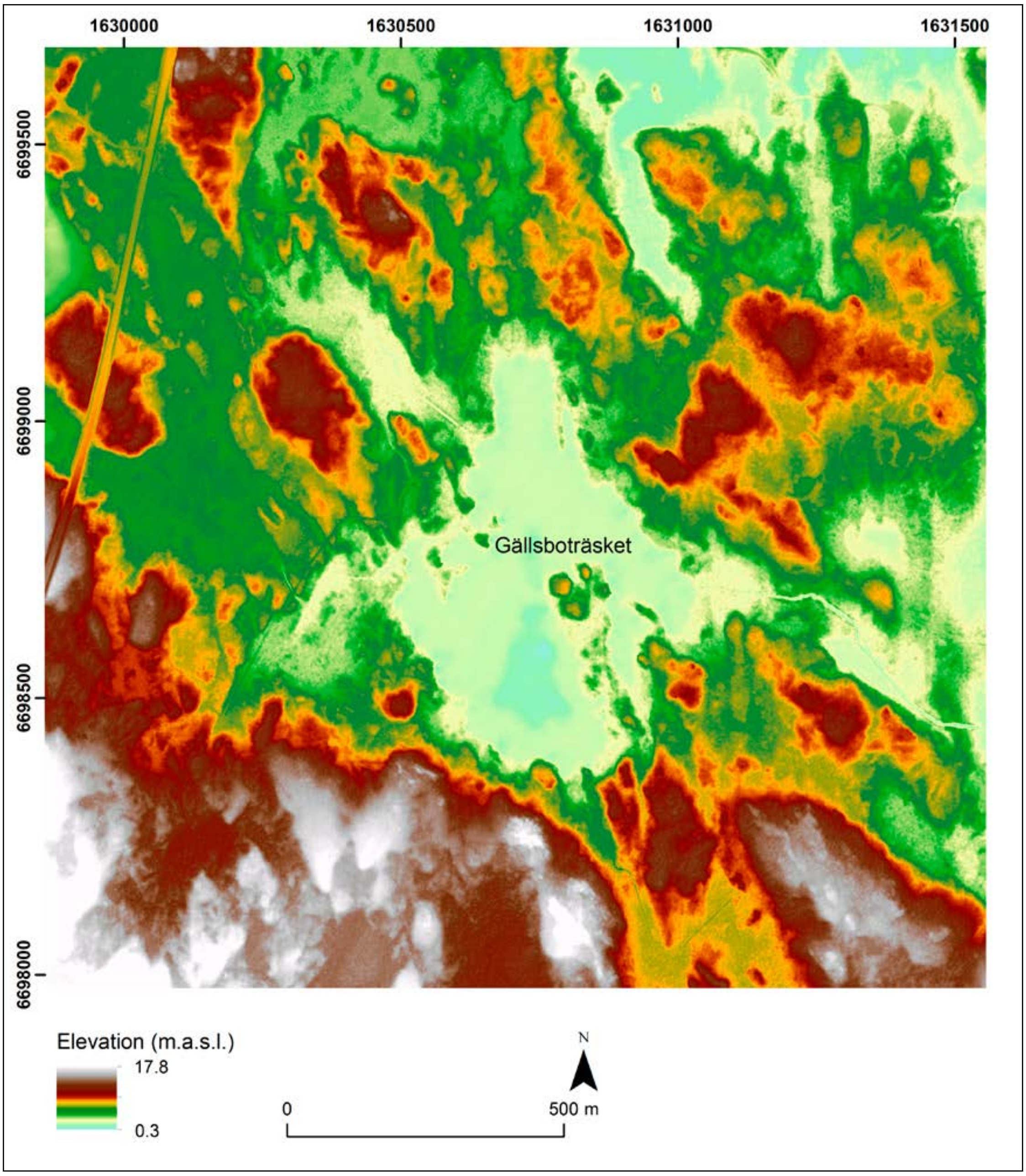

***Figure 3-2.** A zoomed-in area on the high resolution (1 m) DEM showcasing the high level of detail achieved using LiDAR data over the terrestrial areas. The DEM is displayed in the projected coordinate system RT 90 2.5 gon V and the height system RHB 70.*

Figure 3-3 and Figure 3-4 show comparisons between the current DEM and the previous DEM (20 m resolution in both cases). Both models are stretched and hillshade effect is used. Lighter parts in the models are areas where the elevation is higher and darker parts areas where the elevation is lower. The terrestrial part of the current DEM (Figure 3-3a) shows a finer structure than in the previous DEM (Figure 3-3b) and the marine part of the current DEM (Figure 3-4a) is smoother than the corresponding part of the previous DEM (Figure 3-4b).

The mean elevation difference in the overlapping model area (1 521 058 raster cells) between the previous and current 20-m models is 0.38 m, the standard deviation is 1.71 m and the maximum and minimum elevation difference is 32.09 and −13.65 m, respectively. The absolute mean elevation difference between the two models is 1.14 m. Figure 3-5 shows areas where the elevation of the current DEM is higher compared to the previous DEM and Figure 3-6 shows areas where the elevation of the current DEM is lower compared to the previous DEM, in the area covered by both models. The elevation of the current DEM is more than 10 m higher than in the previous DEM in 0.12 % of the area and the elevation is more than 10 m lower in the current DEM in only 0.002 % of the area (red colour in Figure 3-5 and Figure 3-6.). The areas with a difference of more than 10 m between the two models are situated in the deeper part of the marine area.

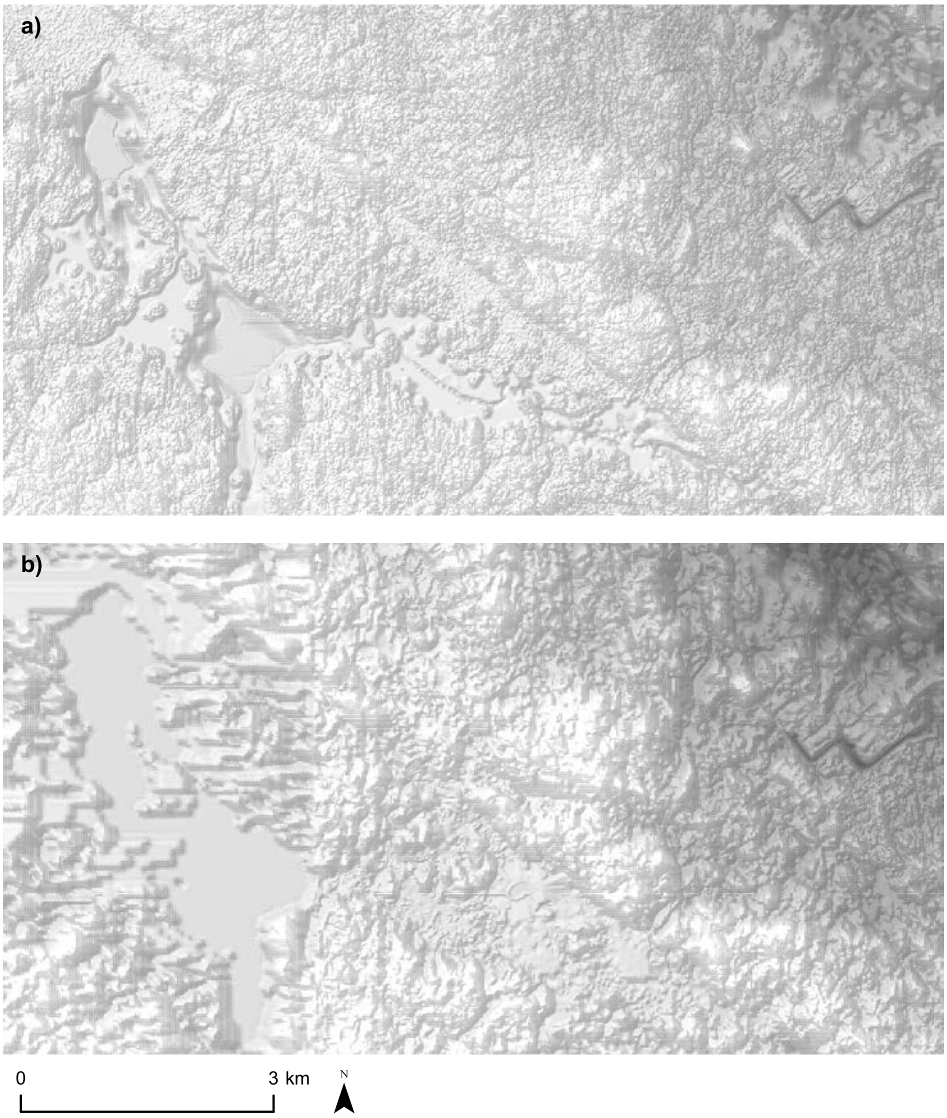

Figure 3-3. *Comparison of the same terrestrial area in the current DEM (a) and the previous DEM (b) (Strömgren and Brydsten 2013). Both models are stretched and hillshade effect is used. The lighter parts represent high elevation areas and the darker parts represent low elevation areas. The terrestrial part of the current DEM has a finer structure than in the previous DEM. The resolution is 20 m in both models shown in the figure.*

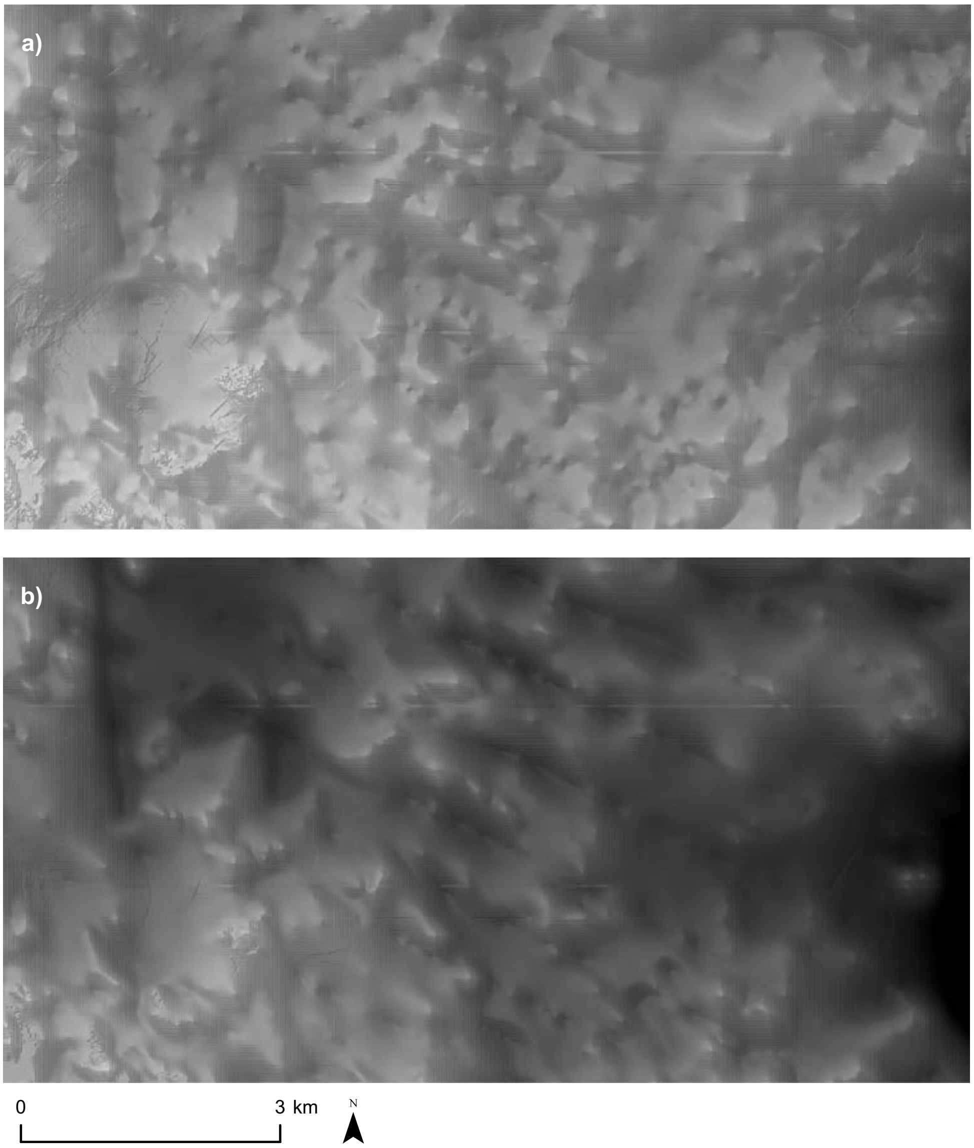

Figure 3-4. *Comparison of the same marine area in the current DEM (a) and the previous DEM (b) (Strömgren and Brydsten 2013). Both models are stretched and hillshade effect is used. The lighter parts represent high elevation areas and the darker parts represent low elevation areas. The marine part of the current DEM is smoother than the corresponding part of the previous DEM. The resolution is 20 m in both models shown in the figure.*

The corresponding values for areas with a difference of 5 to 10 m between the two models are 1.07 % and 0.52 % for areas with higher or lower elevation, respectively, in the current DEM compared to the previous one (blue colour in Figure 3-5 and Figure 3-6). Most of the areas with 5–10 m higher elevation in the current DEM are situated in the terrestrial area and areas with 5–10 m lower elevation in the marine area. The elevation of the current DEM is 1–5 m higher than in the previous DEM in 24.9 % of the area and 1–5 m lower in 12.6 % of the area, as indicated by orange colour in Figure 3-5 and Figure 3-6. The majority of areas with 1–5 m higher elevation in the current DEM are situated in the terrestrial area and areas with 1–5 m lower elevation in the marine area.

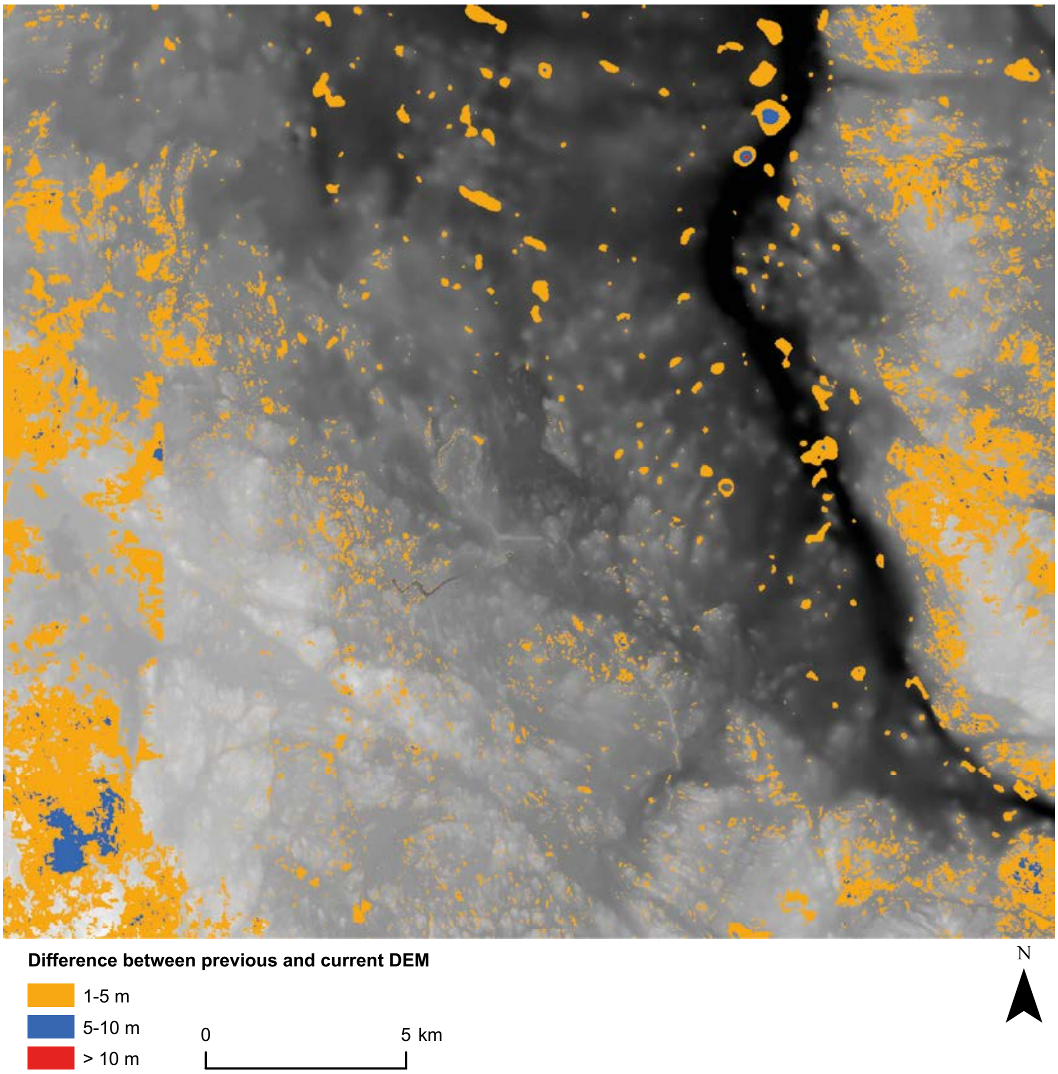

Figure 3-5. *Difference between the previous DEM and the current DEM in the overlapping model area. Orange colour shows areas where the elevation of the current DEM is 1-5 m higher than in the previous DEM. Blue colour shows areas where the elevation of the current DEM is 5-10 m higher than in the previous DEM and red colour shows areas where the elevation of the current DEM is more than 10 m higher than in the previous DEM. The 20-m version of the current DEM is displayed in the background.*

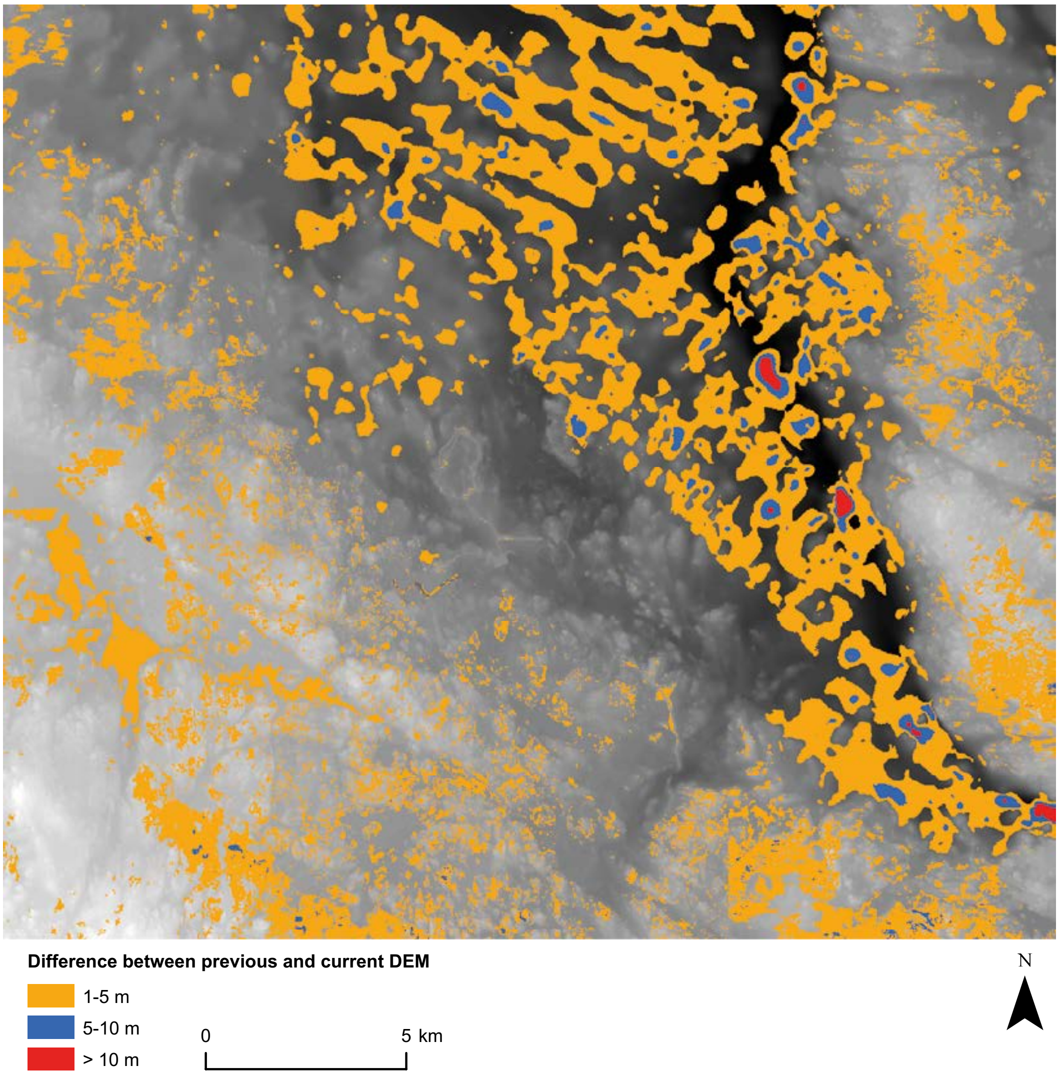

Figure 3-6. *Difference between the previous DEM and the current DEM in the overlapping model area. Orange colour shows areas where the elevation of the current DEM is 1–5 m lower than in the previous DEM. Blue colour shows areas where the elevation of the current DEM is 5–10 m lower than in the previous DEM and red colour shows areas where the elevation of the current DEM is more than 10 m lower than in the previous DEM. The 20-m version of the current DEM is displayed in the background.*

4 Model validation

4.1 Validation of the terrestrial part of the model

To evaluate the accuracy of the terrestrial part of the digital elevation model, measured elevations were collected from 264 locations in the central part of the model area. The goal was to measure points in different parts of the landscape, including coastal areas, forests and fields. The positions and levels were collected with a high precision GPS, Trimble R10 GNSS (Global Navigation Satellite Systems) and a Trimble S7 total station. A Trimble TSC3 field computer and the software Trimble Access were used to store the data. The vertical accuracy of the measured points is approximately 1 cm.

The points were not included in the terrestrial data set but instead used to compare measured and modelled elevations. A statistical analysis of the differences between the measured elevations and modelled elevations is shown in Table 4-1.

Table 4-1. Statistical analysis of differences between measured and modelled elevations at selected locations within the terrestrial part of the model area. No test of normal distribution was performed. Figure 4-1 shows the locations of points used in the comparison. The unit is metres (where applicable).

Model	N	RMS	Mean	STDV	Min	Max	5 %	95 %
1 m	264	0.19	−0.08	0.18	−0.56	0.64	−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.

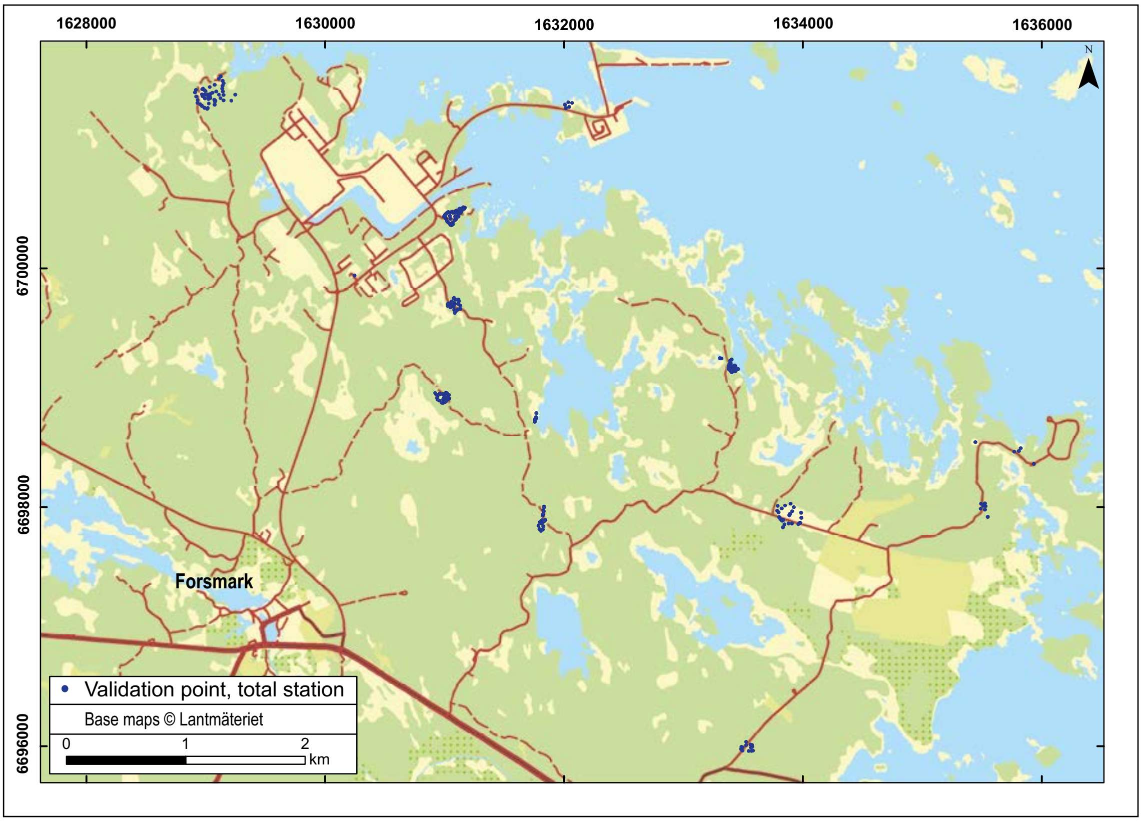

Figure 4-1. *Data points used in the validation of the terrestrial part of the models.*

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.

4.2 Validation of the marine part of the model

The accuracy of the DEM varies within the marine area, due to the variation in quality of depth data and spacing between and density of depth data. To help validate and evaluate the model, the marine area was divided into five sub-areas 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 4-2. Almost 1 000 depth measurements were used for the validation of these five areas (Table 4-2.). A statistical analysis of the differences between measured and modelled depths is shown in Table 4-2.

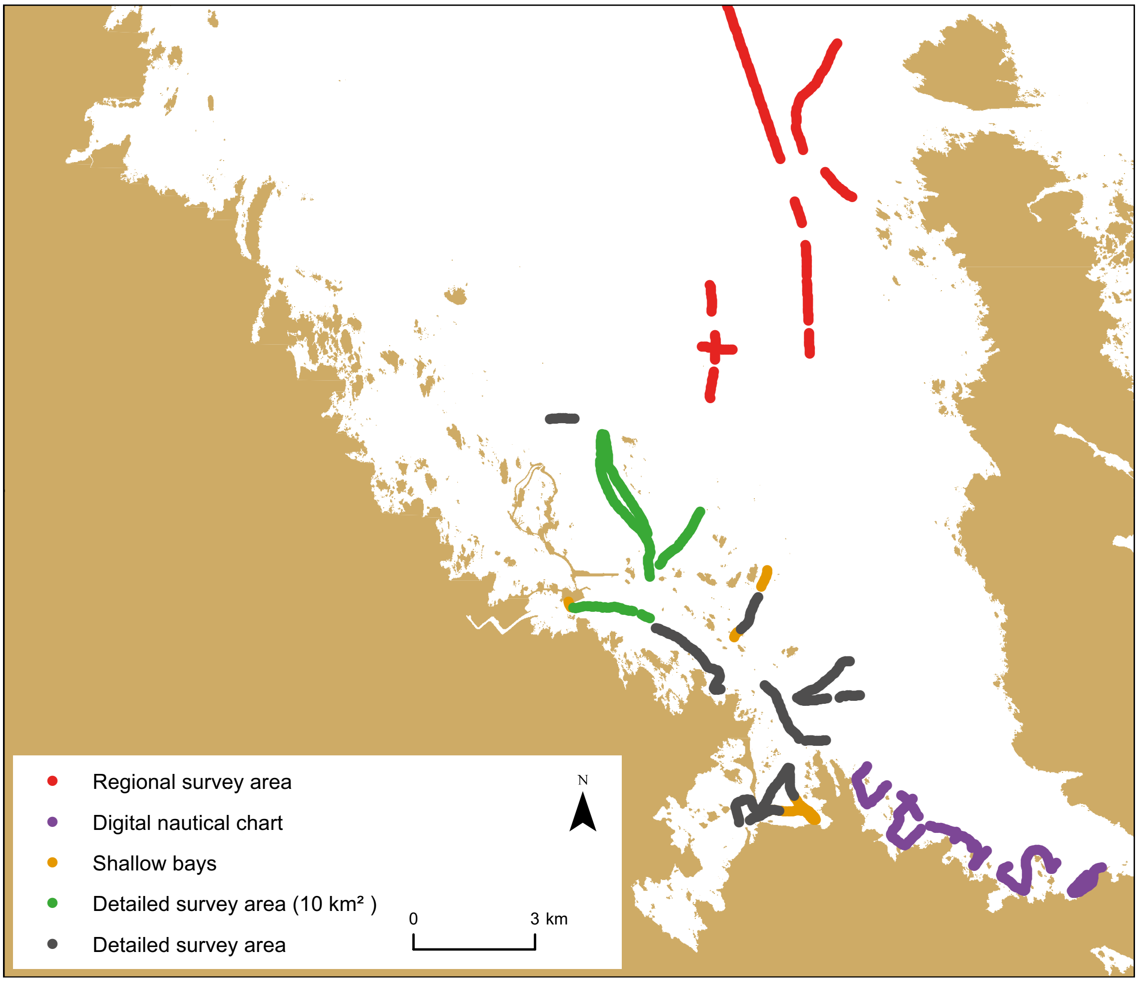

***Figure 4-2.** Data points in different parts of the sea area used in the validation of the marine model.*

In the detailed survey area, the detailed survey area (10 km^2) and the shallow bays, 395 depth measurements from the SKB sounding carried out in 2015 (Table 2-1) were selected. These 395 points were not used in the production of the DEM; they were used in the validation only. For the validation of the regional survey area, 266 points were extracted from the data set used to produce the marine model. An interpolation of the remaining points in the data set was performed with the kriging parameters used for the marine model. The measured depth in these 266 points were then compared to the bathymetry produced without these points.

To perform a validation of the part of the DEM where only data from the digital nautical chart shallower than 10 m were available, a different approach was taken. First, a surface which could be representative of this part of the DEM was identified (the white area in Figure 4-3a). Then depth data in this area were modified to be representative of the part of the marine model where only data from the digital nautical chart shallower than 10 m were available (Figure 4-3b). For this area, depths measured during the SKB sounding in 2015 were also available. These measured depths were removed from the shoreline and within 300 m from depth data used for validation (orange points in Figure 4-3c).

Depth data from the digital nautical chart not used in the data set for the marine model were also added within the white area (Figure 4-3b). An interpolation was performed with a data set consisting of the modified depth data in this area and the depth data outside this area used for the marine model. The kriging parameters used for the marine model were also used in this interpolation. Finally, depth values from the SKB sounding within the 10 m depth lines from the digital nautical chart (orange points in Figure 4-3c) were compared to the modelled depths produced without these depth values, but with all data from the digital nautical chart used instead.

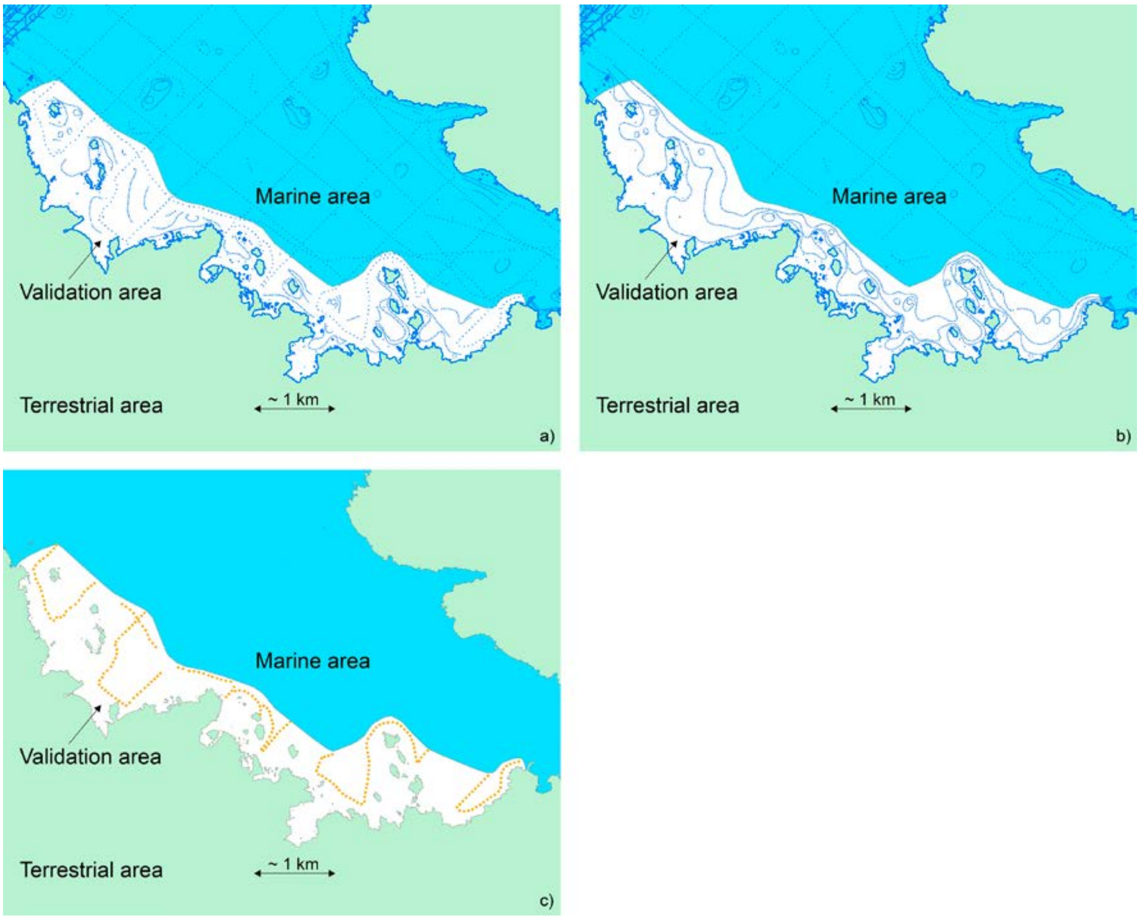

Figure 4-3. *The white area was used for the validation of the part of the marine model where only data from the digital nautical chart for depths shallower than 10 m were available. In a), the blue points in the white area are all data used to produce the marine model within this area. In b), all data from the digital nautical chart available within the validation area are added. Furthermore, all data from the SKB sounding are removed in this area and within 300 m from the orange points used for validation shown in c).*

The results of the statistical analysis of the difference between measured and modelled depths (Table 4-2) show that the differences in RMS (root mean square) and STDV (standard deviation) are small between the shallow bays, the detailed survey area and the detailed survey area (10 km^2). In these areas, the RMS and STDV are ranging between 0.49 and 0.61 m and between 0.46 and 0.51 m, respectively, with the lowest RMS and STDV in the shallow bays and the highest values in the detailed survey area (10 km^2). The mean values are ranging between −0.16 and 0.34 m, with the lowest mean values in the shallow bays and detailed survey area. The minimum and maximum differences between measured and modelled depths in these three areas range between −1.42 and 2.26 m. The 5 and 95 percentiles show that differences larger than 1 m between measured and modelled depths are unusual in shallow bays, the detailed survey area and the detailed survey area (10 km^2).

The statistical parameters in Table 4-2 show that the RMS (root mean square) and STDV (standard deviation) are considerably higher in the regional survey area and the area with depth data from the digital nautical chart only. In these areas, the RMS are 1.18 and 2.63 m and the STDV 1.77 and 1.43 m. The mean difference between measured and modelled depths in these two areas are −0.55 and −2.21 m, with the smallest mean value in the regional survey area. The minimum and maximum differences range between −6.80 and 3.86 m, which shows that relatively large differences between real and modelled water depth can be expected in these two areas of the DEM. The 5 and 95 percentiles also confirm that 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 4-2. Statistical analysis of differences between measured and modelled depths at selected locations within the marine part of the model area. No test of normal distribution was performed. Figure 4.2 shows the locations of points used in the comparison. The unit is metres (where applicable).

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.

5 Discussion

The goal when constructing a digital elevation model is to describe the topography and bathymetry as accurately as possible, whether it is the land surface, the bottom of a lake or the bottom of the sea. Many different data sources are included to build the final model presented in this report. One major problem is that the density of elevation information varies considerably within the model area. The biggest difference is obviously between land and sea.

The terrestrial part of the model area is ~352 km^2 and more than 150 million elevation points are used in the interpolation performed to produce this part of the DEM. The marine part of the model covers a slightly smaller area, ~322 km^2, but only 1.1 million elevation points are available for the interpolation providing the basis for this part. 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 in both sub-models.

The problem of having an uneven elevation point distribution is also present within the marine part of the model. To map the seafloor, echo-sounding data points collected along survey lines were used. In some cases, there are elevation points every 3 to 5 m along these survey lines. However, the distance between survey lines can be 500 m. 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 model could include interpolation artefacts (linear structures) on the surface in these areas. To minimise this effect, it was decided to modify the modelling procedure as follows:

1. Increase the distance between elevation points along survey lines (decrease number of points).
2. Increase the weight of specific elevation points from the digital nautical chart (increase number of points).
3. Adjust the kriging model parameters to include distant data points.

This led to fewer linear structures in areas with no depth data and along survey lines and in total a smoother surface in the marine sub-model. The downside is that the accuracy along survey lines decreases due to the smoothing since in reality the measurements show a rugged seafloor along these survey lines. However, it is believed that this compromise increases the overall quality of the bathymetry model. The same philosophy and method are applied to most of the data in the marine part of the model; depth data are thinned out to obtain a more even distribution of data points and, if necessary, the weights applied to some specific depth values are increased.

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 the upstream lakes as well as the connected wetland areas, lakes without bathymetry data, lakes studied during the site investigation, the nuclear power plant inlet canal and Lake Biotestsjön. There is a possibility to validate bottom bathymetry for the lakes studied during the site investigation. However, the area defining the lake boundary also includes large areas of wetlands surrounding the lakes. Unfortunately, there are no depth data in these areas and a validation of the lakes would therefore be misleading since it is only possible to validate the open water surface where actual measured depth values exist.

It is recommended that future updates of the Forsmark digital elevation model should be focused mainly on the marine sub-model area and in particular the regional survey area where survey lines could be increased in the northern part of the model area by doing echo-sounding in the SW-NE direction perpendicular to current survey lines. Optimally, new technology such as side-scan sonar could be used to drastically increase the quality of the bathymetry model, as was done here for the detailed survey area (10 km^2). For the parts of the shallow bays where it is difficult to collect depth data even with a boat, it would be possible to mount an echo-sounding device on a kayak or use a drone instead.

Additional echo-sounding data from the Söderviken sea bay could be gathered to further increase the quality of the bathymetry in and around the areas of the planned repositories. In the terrestrial part, the wetland objects often lack or have very little water depth information. This could be improved by a new echo-sounding campaign, either by using a smaller vessel in the summer or by drilling from the ice in the winter.

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Appendix 1

Model parameters

Table A-1. Parameters and models used in ordinary kriging for the interpolation of elevation data in the nine terrestrial sub-areas, Lake Bruksdammen and upstream lakes and the marine area. The lag size/number of lags used in the kriging interpolation were 1/12 for area 1–6 and 8–9, 5/12 for area 7 and 150/12 for the marine area and for Bruksdammen and upstream lakes. The model equation should be read as follows:

Nugget value × Nugget + Partial sill × Theoretical Semi variogram (Major Range)

Area	Modell	Me[1]	N[1]	A[1]
1	0*Nugget+0.12321*Spherical(12)	100 %	5/2	4
2	0*Nugget+0.11625*Spherical(11.132)	100 %	5/2	4
3	0*Nugget+0.040735*Spherical(12)	100 %	5/2	4
4	0*Nugget+0.12321*Spherical(12)	100 %	5/2	4
5	0*Nugget+0.087808*Spherical(10.745)	100 %	5/2	4
6	0*Nugget+0.099151*Spherical(12)	100 %	5/2	4
7	0*Nugget+0.78418*Spherical(60)	100 %	5/2	4
8	0*Nugget+0.19104*Spherical(12)	100 %	5/2	4
9	0*Nugget+0.13176*Spherical(12)	100 %	5/2	4
Bruksdammen	0.2*Nugget+0.5*Spherical(500)	100 %	8/4	8
Marine area	1.5855*Nugget+17.377*Circular(1 727.3)	100 %	28/20	4

[1] Me = Measurement error, N = Searching Neighbourhood, A = Angular sectors

Appendix 2

Data delivery

Table A-2. Elevation data used for the construction of the terrestrial and marine parts of the digital elevation model and depth data collected 2015.

File name	Format	Description	Size
SKB_deep_echo_sounding_2015.shp	ESRI shape	Echo-sounding measurements from 2015	13 MB
Interpolation_terrestrial.zip	ESRI shape	Interpolation set for terrestrial area 1–9	147 MB
Interpolation_marine.zip	ESRI shape	Interpolation set for marine area	9.11 GB

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