R-04-70

Digital elevation models for site investigation programme in Forsmark

Site description version 1.2

Lars Brydsten, Mårten Strömgren
Umeå University

December 2004

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1402-3091
SKB Rapport R-04-70

Digital elevation models for site investigation programme in Forsmark

Site description version 2.1

Lars Brydsten, Mårten Strömgren
Umeå University

December 2004

Keywords: Digital elevation model, Topography, DEM, GIS, Forsmark.

Abstract

A digital elevation model of the Forsmark area has been produced using elevation data from a large number of different sources for elevations of both land and sea. One of the sources of sea levels contains data that is classified for national security reasons. The two versions are:

Version 1 classified model that describes land surface, lake water surface, and sea bottom.
Version 2 classified model that describes land surface, sediment levels at lake bottoms, and sea bottoms.

In cases where the different sources of data were not in point form, such as existing elevation models of land or depth lines from nautical charts, have been converted to point values using GIS software. Several sources of data overlap information provided by other data sources. Because of this, several tests were conducted to determine if both sources of data or only one source would be included in the dataset used for the interpolation procedure. The tests resulted in the decision to use only the source judged to be of highest quality for most areas with overlapping data sources. All data were combined into a database of approximately 1.9 million points unevenly spread over an area of about 900 km^2. The large number of data points made it difficult to construct the model with a single interpolation procedure. Instead, the area was divided into 36 sub-grids that were processed one by one and finally merged together into one single grid.

The software ArcGis 8.3 Geostatistical Analysis and its extension Spatial Analyst were used for interpolation. The Ordinary Kriging method was used for interpolation. This method allows the validation of the elevation model before interpolation is conducted. For this reason, cross validation with different combinations of Kriging parameters was performed for each sub-grid so that standardised mean prediction errors were as low as possible. Since both the quality of the data and the density of the data varied greatly over the model grids, the combined overall elevation model has the significant variations in quality. The best quality comes from models over land and in shallower parts of the sea near Forsmark, the lowest quality comes from the Gräsörännan and the sea east of Gräsö.

The elevation model uses the grid projection RT 90 2.5 Gon W and the height system RH 70, and it has a cell size of 10×10 metres. An analysis of the elevation model confirms existing knowledge of the area that it is extremely flat, with a range in the model of +50 to –57 metres, where the highest point is in the model's south-west section and the lowest point is in the northern part of the Gräsörännan.

Sammanfattning

En digital höjdmodell över Forsmarksområdet har tagits fram med hjälp av punktdata för nivåer över både land och hav från ett stort antal olika datakällor. En av datakällorna över havet innehåller data som är säkerhetsklassad. De två versionerna är:

Version 1 säkerhetsklassad modell som beskriver landyta, sedimentytan för sjöar och havsbotten.

Version 2 säkerhetsklassad modell som beskriver landyta, vattenyta för sjöar och havsbotten.

I de fall där de olika datakällorna inte var i punktform, t ex befintliga höjdmodeller över land eller djuplinjer i det digitala sjökortet, har de konverterats till punktform i GIS-programmet. Flera av datakällorna har data som överlappar utbredningen i andra datakällor varför flera tester utfördes för att avgöra om båda datakällornas data eller bara en av källorna skall ingå i det dataset som utgör ingångsdata till interpoleringsproceduren. Resultaten av testerna medförde att för de flesta områden med överlappande data användes endast den datakälla som bedömdes vara av högre kvalité. Datat slogs ihop till en databas med sammanlagt cirka 1.9 miljoner punkter ojämnt spridda över den cirka 900 km^2 stora området. Det stora antalet punkter i databasen medförde att det var svårt att konstruera modellen med en enda interpoleringsprocedur utan området delades in i 36 delområden där en modell konstruerades för varje delområde och därefter slogs alla delområden ihop till en stor höjdmodell.

Interpoleringen har utförts i programmet ArcGis 8.3 och dess extension Spatial Analyst. Som interpoleringsmetod valdes Ordinary Kriging. Metoden tillåter en validering av höjdmodellen innan interpoleringen genomförs varför det för varje delområde de olika Krigingparametrarna valdes så att medelfelet i predicerade värden blev så lågt som möjligt. Till följd av att både kvaliteten på data och datadensiteten varierar stort över modellarean har den sammanslagna höjdmodellen också stora variationer i kvalitet. Bästa kvaliteten i modellen återfinns över land och i grunda delar av havet nära Forsmark, sämre kvalitet i den s k Gräsörännan och havet öster om Gräsö.

Höjdmodellen har koordinatsystemet RT 90 2.5 Gon W och höjdsystemet RH 70 och har en cellstorlek om 10×10 meter. En analys av höjdmodellen bekräftar vetskapen om att området är mycket flackt. Värdeomfånget i modellen är +50 till –57 meter där den högsta höjden återfinns i modellens sydvästra del och den lägsta punkten ligger i Gräsörännans norra del.

Contents

1 Introduction

Referenced to a common datum, a regular array of z-values allows a digital elevation model (DEM) to represent a continuous variable over a two-dimensional surface. Typically, digital elevation models describe terrain relief.

The aim of this project is to improve an existing DEM /Brydsten, 2004/ buy using new elevation data and a different interpolation technique.

Many types of surface models – such as hydrological models and geomorphometrical models – use DEM as input data. DEM resolution is the size of DEM cells. DEM interpolates irregular spaced elevation data. In this model, we used the Kriging interpolation method. Kriging is a geostatistical interpolation method based on statistical models that include autocorrelation (the statistical relationship among the measured points). 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 sea surface and a constant values for lake surfaces. The DEMs for the Forsmark area has negative values in the sea to represent water depth, but constant positive values for lake surfaces represent the lake elevations or varying values represent lake bottom elevations.

Input data for the interpolation have many different sources, such as existing DEMs, elevation lines from digital topographical maps, paper nautical charts, digital nautical charts, and depth soundings in both lakes and the sea. All data are converted to point values using different techniques. The Kriging interpolation was performed in ArcGis 8 Geostatistical Analysis extension.

2 Methods

2.1 Data catch from land areas

Two sources were used to collect elevation point data for land: the existing DEM from the Swedish national land survey (LMV) with a resolution of 50 metres, and the SKB DEM with a resolution of 10 metres /Wiklund, 2002/.

The existing DEMs were converted to point layers in shape-format using ArcToolbox in ArcGis 8.

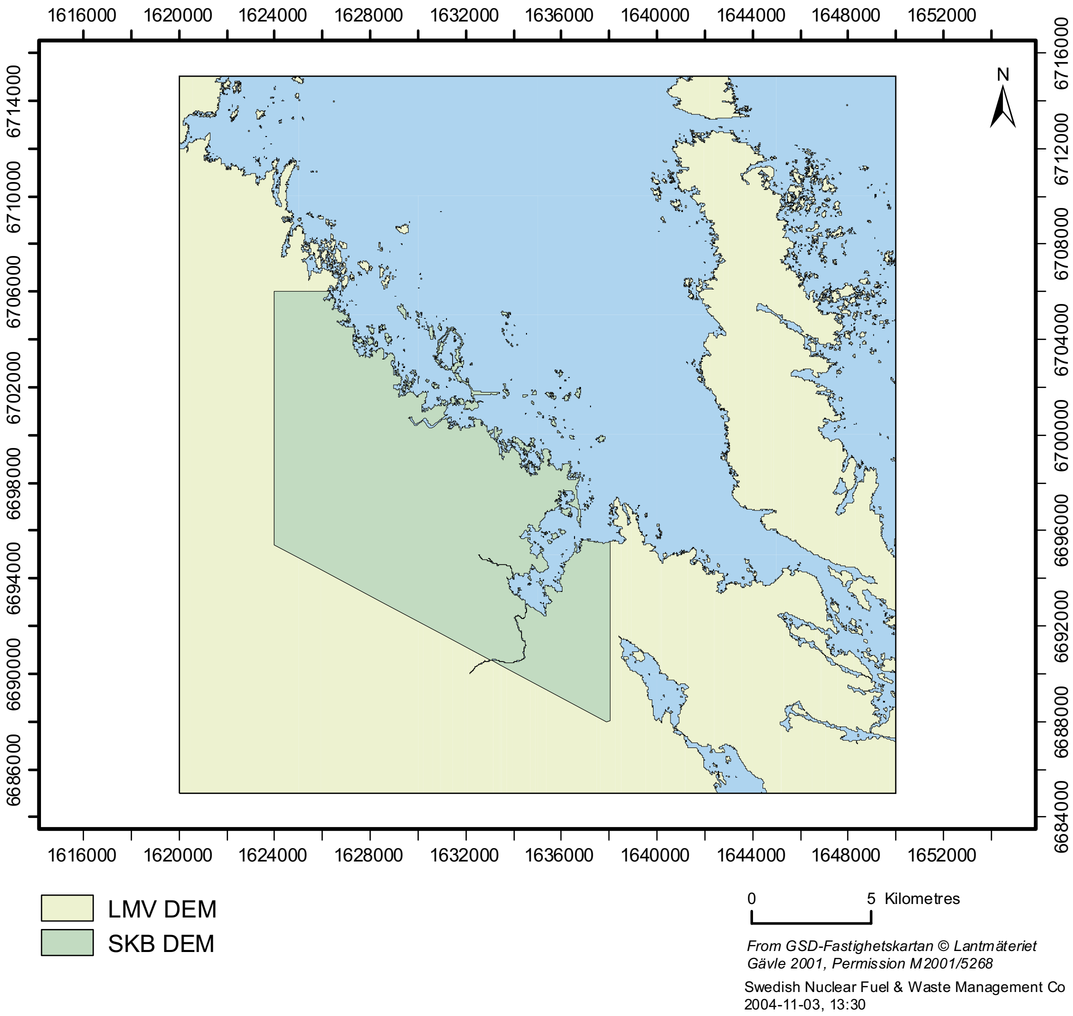

***Figure 2-1.** Extensions of the LMV DEM and SKB DEM, respectively.*

The 10-metre grid values for lake surfaces have errors. In Lake Fiskarfjärden, for points situated at least 25 metres from the shoreline, the Z-value has 16 unique values ranging from 0.589 to 0.755 m.a.s.l. Two values dominate these points, 0.6726 in the western part of the lake and 0.5889 in the eastern part. These areas are separated by a distinct straight north – south line that acts like a threshold in the lake surface at 0.0837 metres. This threshold seems to intersect with the border between two adjacent flying transects.

The same phenomenon exists in most of the lakes within the 10-metre grid extension. All points placed within lakes with levelling instruments were leveled (see Figure 2-2 and Table 2-1) and were replaced by the measured values. It should be noted that these levels are not the mean lake levels but the levels at each measuring occasion.

These two point-layers were merged into one single point layer, and all points placed on the sea surface polygon from the digital localities maps were deleted from the datasets. The final layer is in the Swedish national grid projection (RT 90 2.5 Gon W) and in the Swedish national height system 1970 (RH 70).

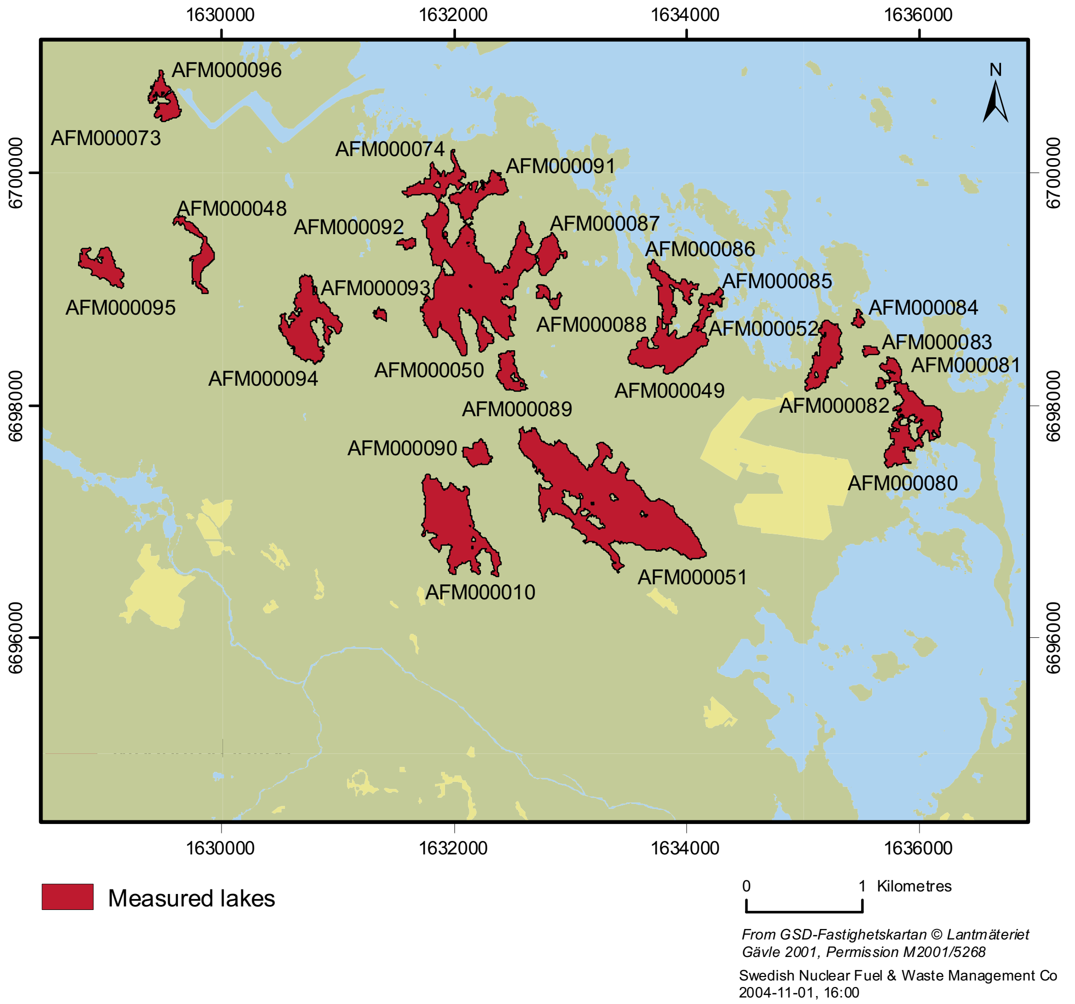

***Figure 2-2.** Lakes where the SKB DEM points were replaced by measured values.*

Table 2-1. Lake surface elevations for the 26 lakes shown in Figure 2-2. The unit is metre above RH70.

Lake	ma RH 70 (m)	Date
AFM000010	5.280	020820
AFM000048	3.660	020226
AFM000049	0.485	020209
AFM000050	0.665	020822
AFM000051	0.555	020826
AFM000052	0.413	020207
AFM000073	1.625	020226
AFM000074	0.450	030116
AFM000080	0.060	030115
AFM000081	0.374	020206
AFM000082	0.305	020206
AFM000083	0.489	020206
AFM000084	0.413	020207
AFM000085	0.365	020208
AFM000086	0.389	020209
AFM000087	0.675	020829
AFM000088	1.352	020208
AFM000089	1.190	020207
AFM000090	3.015	020225
AFM000091	0.730	020208
AFM000092	1.860	020205
AFM000093	2.745	020207
AFM000094	2.235	020225
AFM000095	5.820	020830
AFM000096	1.725	020226

2.2 Data catch from sea areas in Forsmark

Figure 2-3 shows the extensions for elevation data for the sea area. The elevations have been obtained from the following sources:

(i) the digital nautical chart (the Swedish National Administration of Shipping and Navigation), area B in Figure 2-3,
(ii) the base map to the nautical chart, area E in Figure 2-3,
(iii) the paper nautical chart (number 535 Öregrund – Grundkallen – Björn), area B in Figure 2-3,
(iv) depth soundings performed by the Geological Survey of Sweden, SGU /Elhammer and Sandkvist, 2004/, area D in Figure 2-3,
(v) depth soundings of shallow bays /Brydsten, 2004/, area F in Figure 2-3,
(vi) with DGPS measured shoreline points,
(vii) digitized shoreline points from IR orthophotos,
(viii) the sea shoreline from the digital localities maps from Lantmäteriet, and
(ix) constructional drawings for the inlet channel to the nuclear power plant /Vattenfall, 1977/, area H in Figure 2-4.

The digital nautical chart has depth lines for 3, 6, 10, 15, 25, and 50 metres. These line objects have been transformed into point objects in ArcView using the Avenue script LineToPoints.avx. The maximum distances between adjacent points were set to 10 metres.

Because the digital nautical chart lacks the point depths that are present in the paper nautical chart, these points were manually digitized from the paper nautical chart. The paper nautical chart was scanned and rectified to WGS-84 with ArcGis 8, and the point depths were manually digitized on screen. The point depths (single water depth values) and symbols for "Stone in water surface" (a plus sign with dots in each corner) and "Stone beneath water surface" (a plus sign) were digitized as points. The water depth for "Stone in water surface" was set to –0.1 metre and for "Stone beneath water surface" to –0.3 metre.

For the area E in Figure 2-3, the base map for the nautical chart was used to digitize point depths. Because these depth soundings were performed as early as 1898, it was necessary to convert these values from foot to metre and at the same time adjust the values for shore displacement since 1898. The adjustment for shore displacement (1898–1970) was calculated to +0.45 metre using equations presented in /Påsse, 1997/ with the following parameters:

As = 300, Bs = 7250, Af = 95 and Bf = 1,000.

The base map was scanned and rectified to WGS-84 using the point depths from the paper nautical chart. The point depths on the base map were then manually digitized on screen.

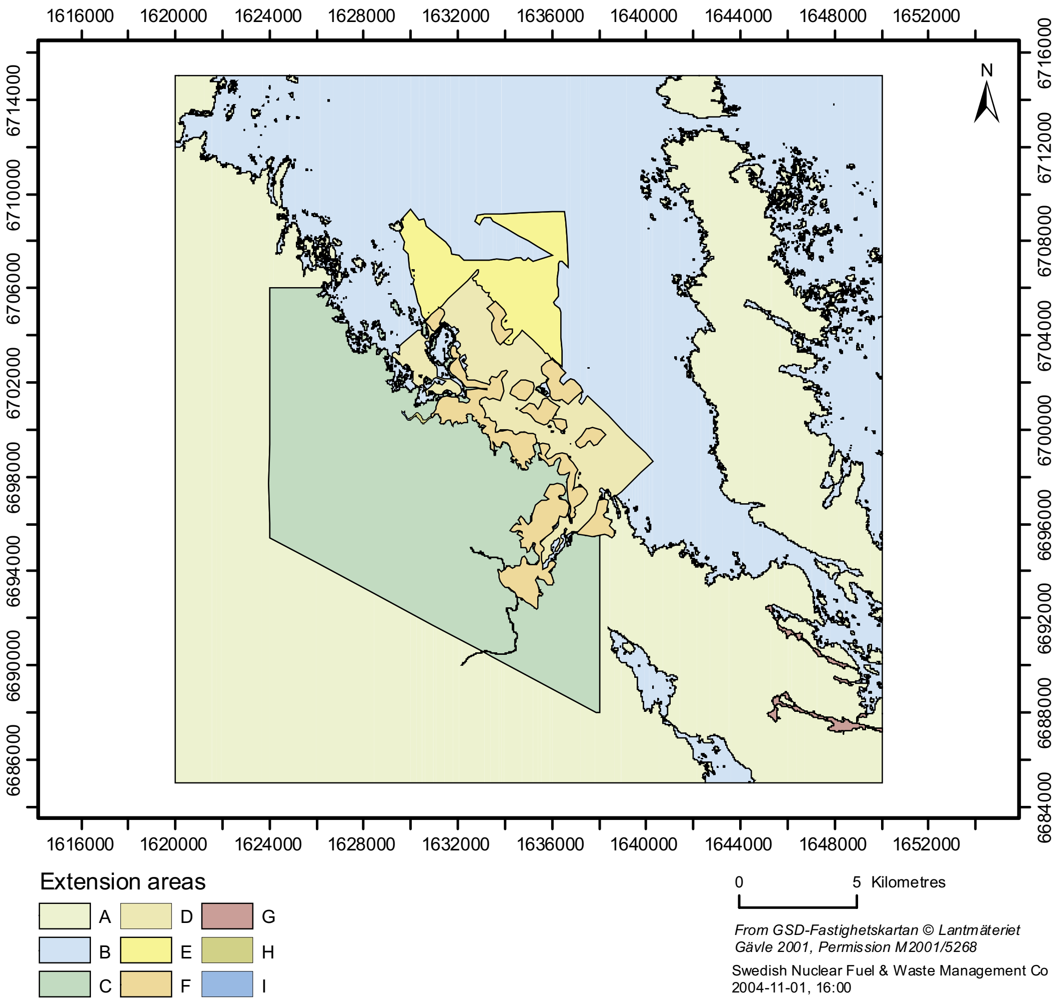

***Figure 2-3.** Extensions for different data sources for the sea areas.*

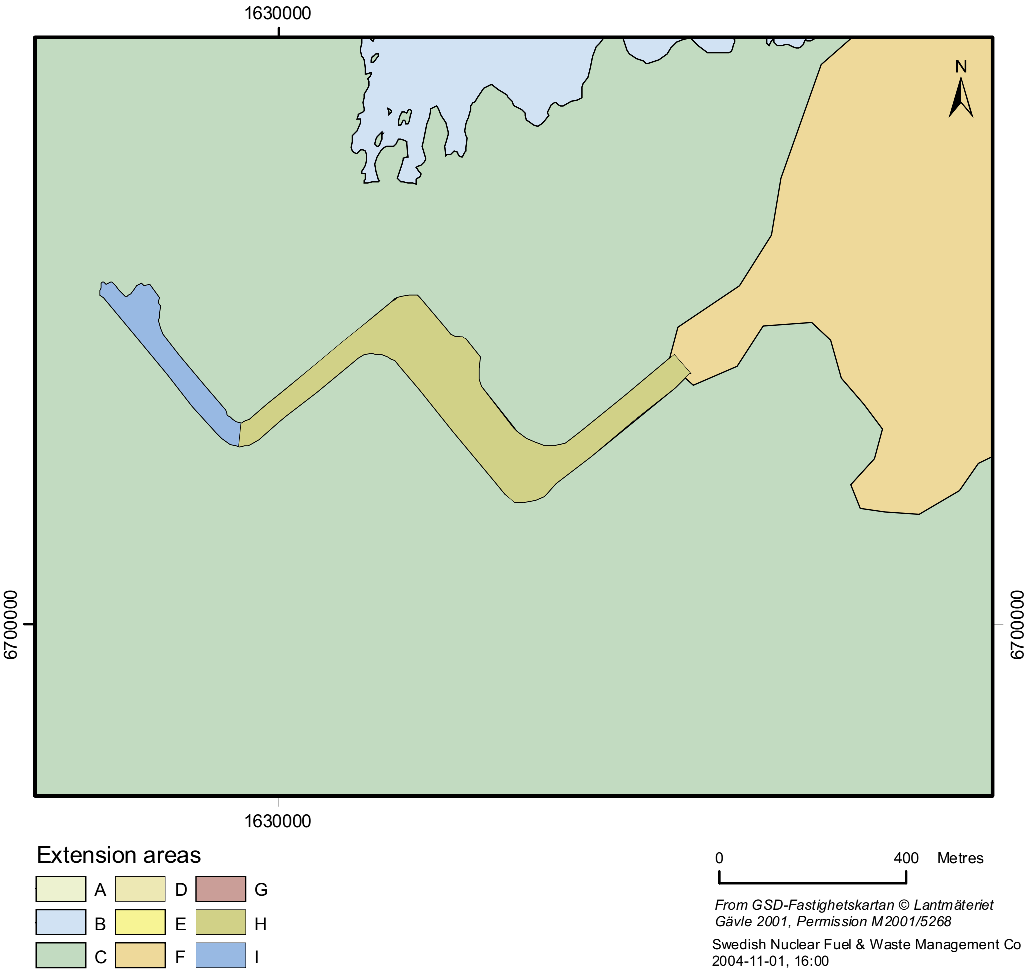

Figure 2-4. *Extension for elevation data from construction drawings for the inlet channel to the nuclear power plant.*

The depth values in both the digital nautical chart and the paper nautical chart refer to mean sea level 1970, so no adjustment is needed for mixing soundings and land elevation data in RH 70. The total number of depth soundings in the base map is 4,300.

The SGU depth soundings were delivered to SKB as 201 files in ascii-format, generally one file for each transect in the survey /Elhammer and Sandkvist, 2004/. The columns in the files consist of X-coordinates and Y-coordinates with a resolution of 4 digits (1/10 of a mm) and a Z-value with a resolution of two digits. The coordinate system is RT 90 and the Z-values are corrected to RH 70. The ascii-files were imported to Excel and exported in dBase4-format to make it possible to import these files to ArcGis 8. All 201 files were merged into one single point layer in ArcGis 8. The total number of measurements are approximately 180,000.

The SGU depth soundings were not performed in the shallow bays due to size of the vessel. Therefore, a completing depth sounding using a small boat was performed /Brydsten, 2004/. To map water depths a digital echo sounder was used (Simrad EQ32 Mk 11) as well as a DGPS (Trimble Pro XR) connected to a field computer (Itronix GoBook) using ESRI ArcPad real time GIS software. For each update of the GPS position (every second), the X and Y coordinates were recorded from the GPS. The Z values (water depth) were recorded from the digital echo sounder. Approximately 2,000 depth values per hour were recorded. The coordinates were measured in RT 90 coordinate system with an accuracy of one centimetre.

An orthophoto (1 metre resolution) was used as background imaging in the field computer. Each recorded depth point was displayed on top of the orthophoto. It was possible to observe which parts of the area had already been mapped, and this was used as a navigational aid. The depth values were adjusted because of different water levels in the sea over time. Using sea level records from Forsmark with hourly accuracy, the water depth values were adjusted to zero sea level in the RH 70 height system. The total number of depth soundings in shallow bays are approximately 84,000 points.

Although a small boat was used in the shallow bay depth soundings, depth values are absent between the shoreline and approximately 0.7 water depth. When using the final DEM in modelling of the modern hydro-geological properties, the DEM of the sea shoreline must be very accurate. A measurement of elevation points close to the present shoreline was therefore performed.

There are four opportunities to catch elevation points close to the sea shoreline by:

(i) using the sea shoreline from the digital localities maps,
(ii) using the 0-line from the digital nautical chart,
(iii) manually digitizing the shoreline with the IR orthophoto as background, and
(iv) measuring the sea shoreline by walking the line with a DGPS.

The accuracy of the sea shoreline from the digital localities maps and the 0-line from the digital chart was tested using GIS and the IR orthophoto. Figure 2-5 shows the result from this test.

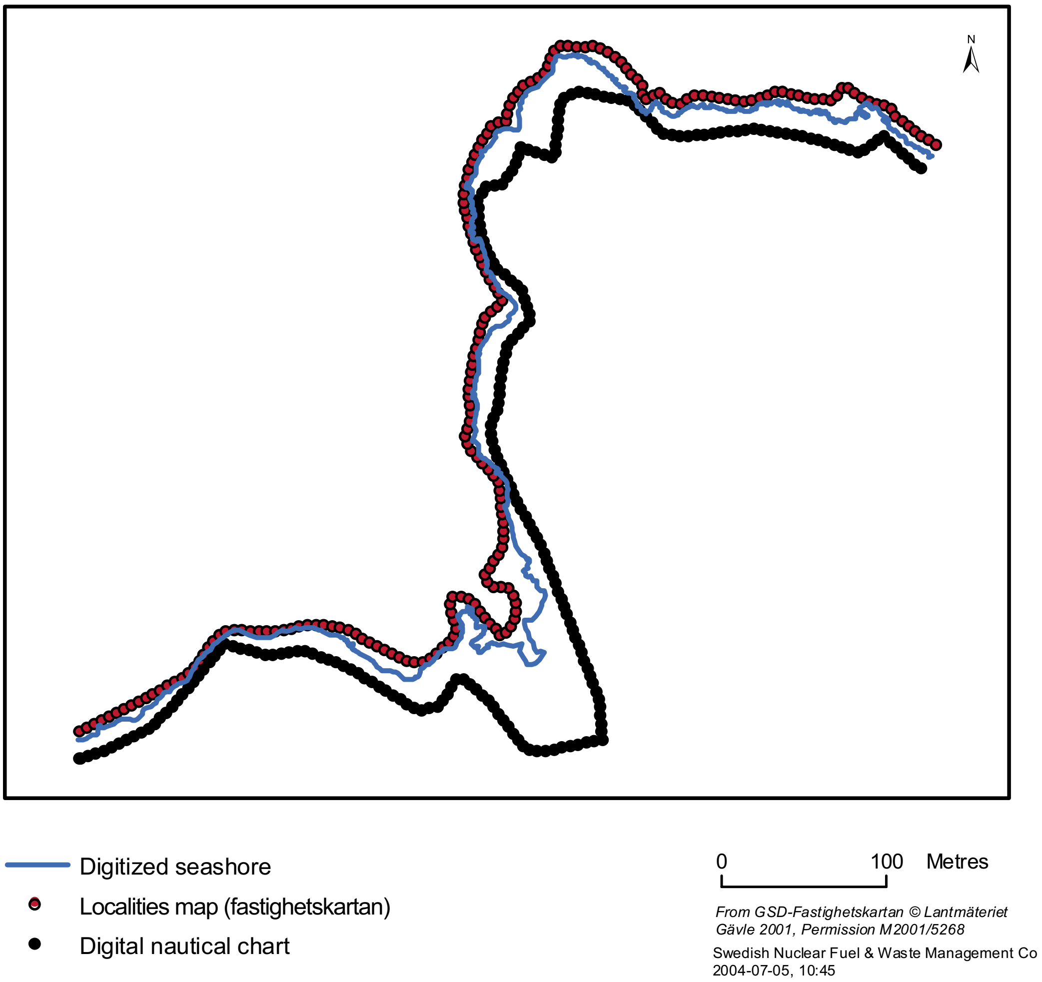

Figure 2-5. *Comparison between shorelines from the digital localities map (Fastighetskartan), the digital nautical chart, and manually digitizing the shoreline with the IR orthophoto as background.*

The selected test area has a fairly steep shore. The sea water level at the time for photographing was –0.01 metres, so the distance between the digitized shoreline and the shoreline in RH 70 height system is small. The test shows that both the shorelines in the localities map and the nautical chart have low accuracies, but some localities have higher accuracy for the localities map. The test also showed that it is difficult to digitize the shoreline from IR orthophotos if the shoreline has a low gradient, because low gradient shorelines are often covered with reeds.

The most appropriate method for catching elevation data close to the zero level is therefore by measuring the sea shoreline by walking along the shoreline with a DGPS. This approach is too expensive to use for the whole area, so this was only performed for vegetated shores within the local model area that are difficult to observe using the IR orthophoto. The rest of the shorelines within the local model area were manually digitized with the IR orthophoto as background, and the sea shoreline from the digital localities maps was used for the rest of the grid (Figure 2-6).

The accuracy of the DGPS measurements was tested by measuring the coordinates of two fixed points for approximately 3 minutes.

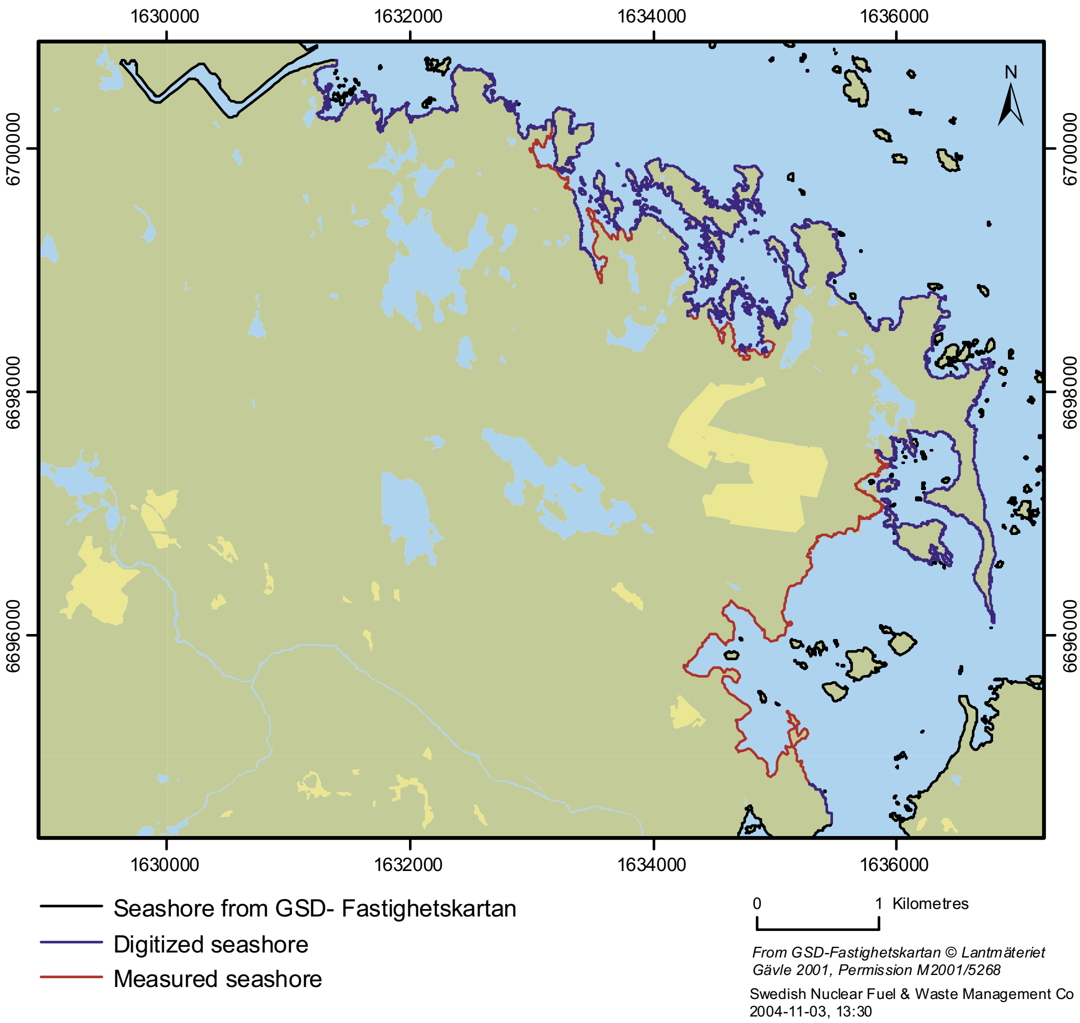

***Figure 2-6.** Extensions for different data sources for the sea shoreline.*

One of the fixed points was measured at two occasions to detect different errors at different times of the day. The DGPS filter was set to a PDOP < 6, SNR > 6 (Signal to Noise Ratio) and a elevation mask < 15 degrees (only satellites situated higher than 15 degrees over the horizon are used in the calculation). These are the same settings as for the usual measurements. PDOP (Positional Dilution Of Precision) is a measure of overall uncertainty in a GPS position. The best PDOP (lowest value) would occur with one satellite directly overhead and three others evenly spaced above the horizon. The results of the tests are shown in Figure 2-7 and Table 2-2. The mean errors for the three tests were 0.28, 0.72, and 0.46 metres, respectively. The maximum error among the approximately 300 measurements is 1.50 metres. Of the approximately 300 measurements, 95% have errors lower than one metre.

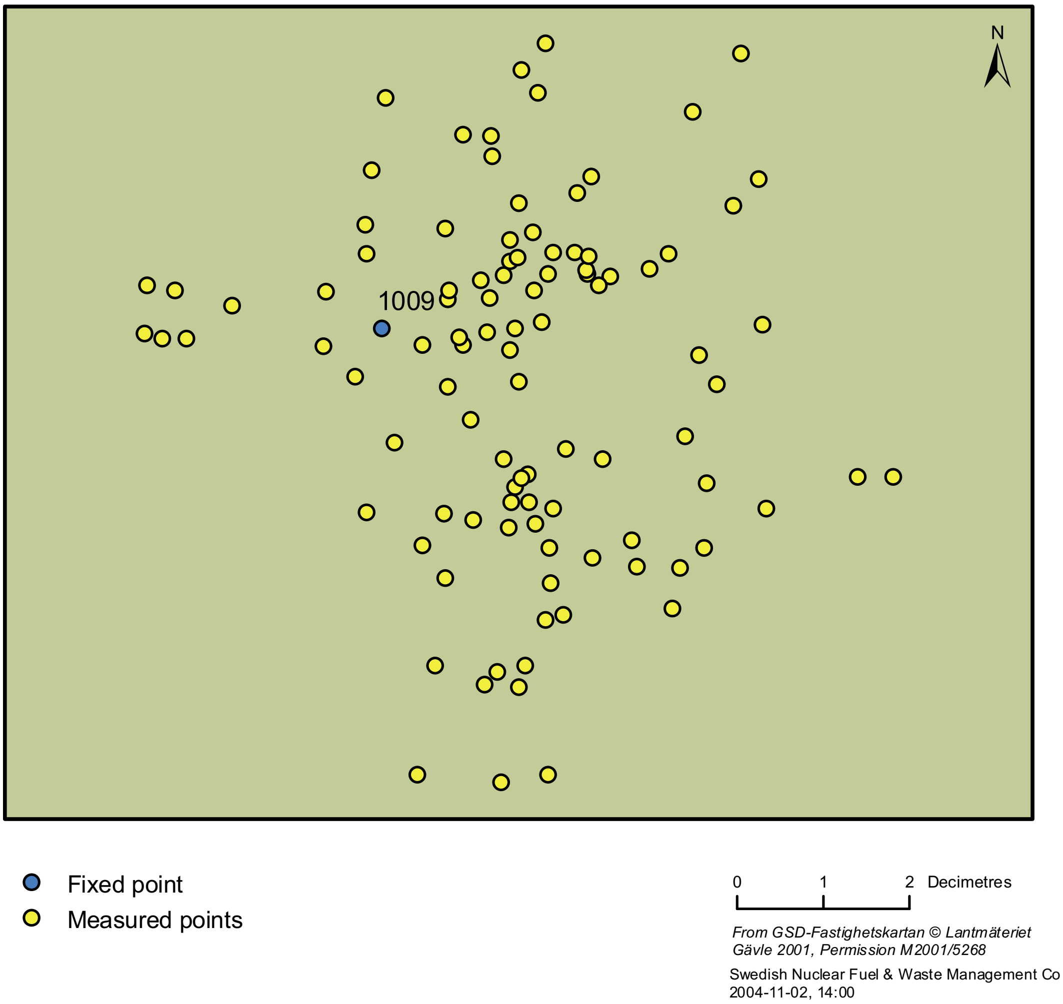

Figure 2-7. *The spread in recorded positions in repeated measurements of the fixed point 1009 at 20040617.*

Table 2-2. Results from tests of DGPS accuracy.

Date	Time	Fix Nr	X	Y	Z	Count	Mean error	Max. error	SD
20040617	081721-082027	1009	1633467.781	6698933.04	7.903	100	0.279	0.618	0.131
20040616	160330-160726	1003	1630743.981	6699758.29	5.943	94	0.722	1.502	0.323
20040617	113149-113459	1003	1630743.981	6699758.29	5.943	96	0.464	0.687	0.082

During a post-processing procedure, each x/y-record was given a z-value using sea level data from a water level gauge situated close to SFR. The time resolution of the gauge was one hour. The DGPS measurements were carried out during the third week of August 2004, and during this period the sea water level varied between -0.046 and 0.091 metres in the RH 70 height system. The water level gauge in Kallrigafjärden, managed by SKB, was not working during this period, so only the gauge close to SFR was used.

During depth soundings of shallow bays, the depths of the inlet channel of the nuclear power plant were also measured. However, we were only permitted to survey from the bay up to the bridge. The depths of the rest of the channel were digitized from a scanned and rectified construction drawing. For the innermost 400 metres of the channel, no depth data is available.

At some small areas within the grid extension, no elevation data are available, e.g. part of the inlet channel mention above and two shallow bays in the southeast part of the model area (area I in Figure 2-3 and area G in Figure 2-3) are missing. For these areas, we have manually placed "false depth values", –5 metres in the channel and –1 metre in the bays. This keeps these areas from being classified as land in the final grid.

Elevation data from different sources were in different coordinate systems. Therefore, the data that was not in the Swedish national Cartesian system (RT90 2.5 Gon W) was transformed to RT 90. This transformation was performed using the GIS software ArcGis 8.

2.3 Handling data from different data sources that are overlapping

Because some of the extensions of different point elevation data overlap, different tests were performed to determine whether both datasets in the overlapping area should be used or only one of the sets (see Figure 2-8).

The tests are based on SGU depth soundings. They are estimated to be the most accurate for sea areas because these tests use modern equipment and the SKB 10-metre grid for land areas. The second most accurate depth measurements are estimated to be depth soundings of shallow bays. The five tests are as follows:

(i) the 10-metre grid against the 50-metre grid,
(ii) the digital nautical chart against SGU depth soundings,
(iii) the base map to the nautical chart against SGU depth soundings,
(iv) the depth soundings of shallow bays against SGU depth soundings, and
(v) the digital nautical chart against the base map.

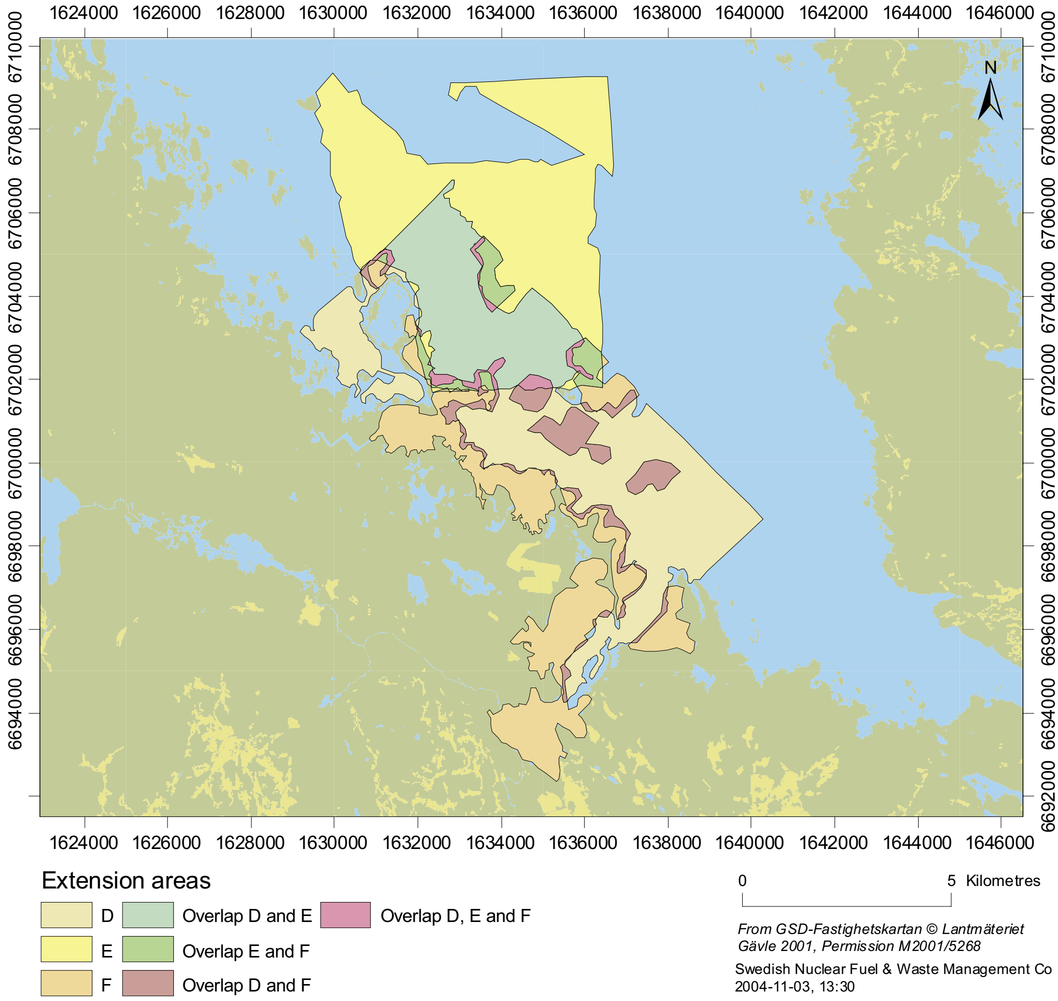

Figure 2-8. *Extensions of overlapping data sets.*

The point elevation data sets were joined against the SGU or SKB 10-metre DEM datasets. This GIS function (point to point join) gives a new attribute with the distance to the closest point in the join to dataset. Points in actual dataset with a distance shorter than 1 metre were selected and the difference in z-value was calculated. Only in an exceptional case, the differences in Z-values larger than one metre are aloud for the dataset to be classified as accurate as the join to dataset (one metre difference in XY-plane and one metre in Z-value means at least a 45 degree slope). A summary of the test results is shown in Table 2-3.

The two existing grids are overlapping within the 10-metre grid extension with approximately 51,000 height values with exactly the same coordinates. If duplicate points are incorporated in the final elevation point data set, the ArcGis program will use the mean value. If there are great differences in Z-values among the duplicates, there is a risk for errors in the final grid. Therefore, a statistical analysis was carried out for the duplicates.

Table 2-3. Summary results from tests for deciding if one or both datasets will be used for the final interpolation when these datasets are overlapping. Total Nb. = total number of points in the "join from" dataset, Nb. < 1 m = number of points within a distance lower than one metre from a point in the "join to" dataset, Nb. Diff. > 1 m = number of points with a difference in elevation value in the "Nb. < 1 m" dataset that are higher than one metre, Max. diff. (m) = the maximum difference in elevation value between two points in "join from" and "join to" datasets that is situated closer than one metre from each other and Mean diff. (m) = the average difference in elevation value between all points in "join from" and "join to" datasets that is situated closer than one metre from each other.

Join from	Join to	Total nb	Nb < 1 m	Nb Diff > 1 m	% error	Max diff (m)	Mean diff (m)
Grid 50 m	Grid 10 m	50,693	50,693	3,1459	62	11.0	1.7
Dig. chart	SGU	32,881	41	29	71	6.4	1.9
Base map	SGU	4,335	8	2	25	2.1	0.7
Shall. bays	SGU	84,122	202	10	5	1.9	0.5
Dig. chart	Base map	4,335	55	55	100	11.0	2.6

The difference in Z-values for the duplicate points was calculated. The results of the comparison are presented in Table 2-3. Only about 38% of the duplicate points have a difference in z-value lower than one metre. That means that it is not appropriate to use the mean values of duplicate points. The 50-metre grid is evaluated from air photos from 4,600 metre level while photos from 2,300 metre level were used for evaluation of the 10-metre grid /Wiklund, 2002/. Therefore, the 10-metre grid will probably be of higher quality. Another reason for using only the 10-metre grid points is the abnormal differences in z-values between adjacent points could occur, i.e. a point from the 50-metre grid surrounded by 8 points from the 10-metre grid. All duplicate points from the 50-metre grid were deleted and not used in the final interpolation.

The tests for the sea depth datasets show that only the depth soundings of shallow bays and the SGU depths soundings have low differences in depth values between points situated within a metres distance. All other comparisons produce significant differences.

Based on the test results, the following datasets were used in the final interpolation procedure:

(i) When the 50-metre grid overlapped the 10-metre grid, only values from the 10-metre grid were used.
(ii) When the digital nautical chart overlapped the SGU depth soundings, only the SGU dataset were used.
(iii) When the base map overlapped the SGU depth soundings, only the SGU dataset were used.
(iv) When the depth soundings of shallow bays overlapped the SGU depth soundings, both datasets were used.
(v) When the digital nautical chart overlapped the base map, only data from the base map were used.

The total number of points in the merged point dataset after deletion of some of the overlapping datasets is approximately 1,890,000.

3 Results

3.1 Construction of the digital elevation models

All elevation point values were collected in two databases, and with these databases new digital elevation models were created. One representing land surface, lake water surface, and sea bottom. And the other one representing land surface, lake bottoms, and sea bottoms.

The DEMs were created with a resolution of 10-metres. The interpolation from irregularly spaced point values to a regularly spaced DEM was done using the software ArcGis 8 Geostatistical Analysis extension. Kriging was chosen as the interpolation method /Davis, 1986; Isaaks and Srivastava, 1989/. The choosing of theoretical semivariogram model and the parameters scale, length, and nugget effect were done with the extension.

Because of the large size of the merged point file, it was impossible to construct the grids by one single interpolation process. Therefore, the grid was divided into 36 sub-grids (see Figure 3-1) that were processed one by one and finally merged together into one single grid. Each sub-grid was treated with regard to its conditions, i.e. different Kriging parameters were set to different sub-grids.

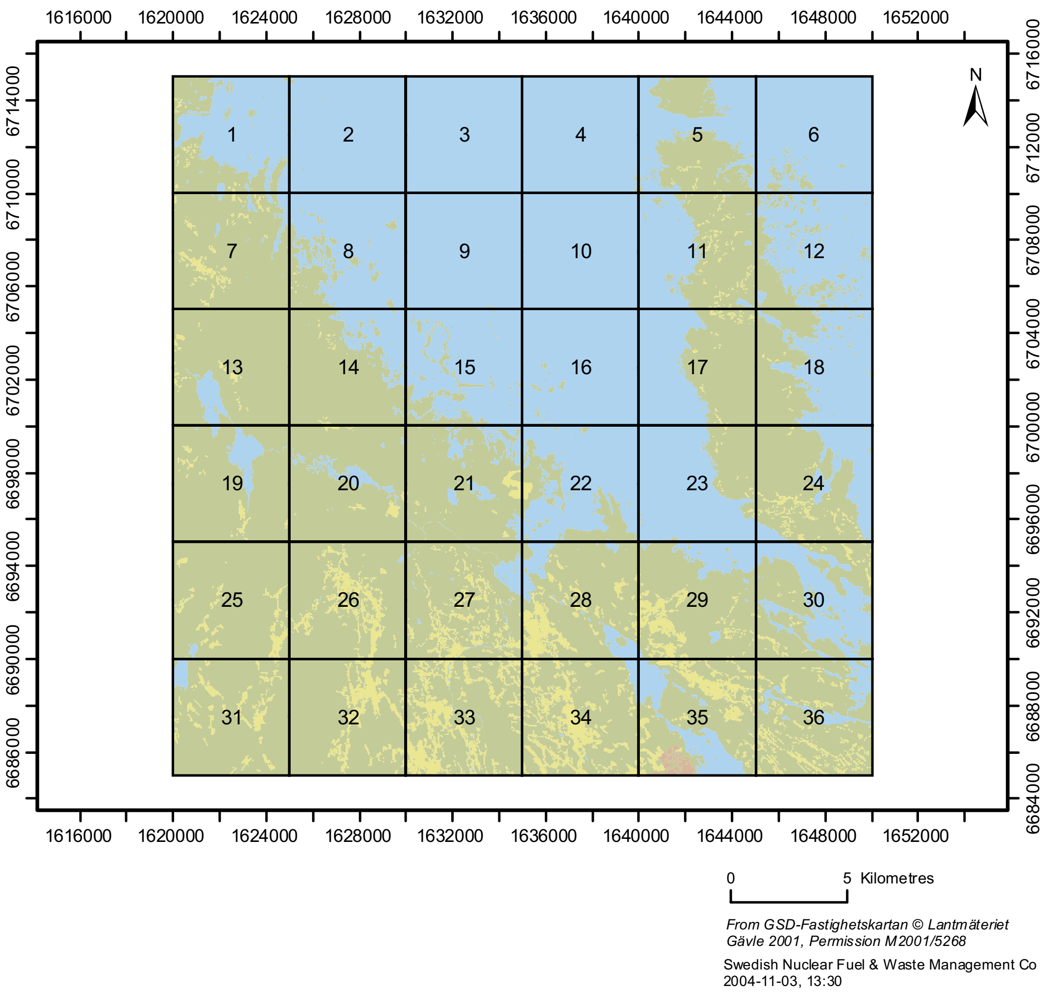

Figure 3-1. *The extensions of the 36 sub-models.*

Common to all sub-grids are an Ordinary Kriging geostatistical method, a spherical theoretical model, and an elliptical search shape. The parameters that differ between different sub-grids are the search size (the length of the major and minor semi-axis of the ellipses), the angle of the major semi-axis, the nugget value, the number of lags, and the lag size. Before the interpolations start, the models are validated both with cross-validation (one data point is removed and the rest of the data is used to predict the removed data point) and ordinary validation (part of the data is removed and the rest of the data is used to predict the removed data). Both the cross-validation and ordinary validation goals produce a standardised mean prediction error near 0, small root-mean-square prediction errors, average standard error near root-mean-square prediction errors, and standardised root-mean-square prediction errors near 1.

Cross validations with different combinations of Kriging parameters were performed until the standardised mean prediction errors were close to zero, but not necessarily the lowest values were always chosen. Because the aim was to determine the most valid model for both measured and unmeasured locations, care was taken to produce low values for the root-mean-square prediction errors and minimise the difference between the root-mean-square prediction errors and the average standard errors. Different models were compared and the ones with the most reasonable statistics were chosen.

Finally, validations were performed with the most appropriate Kriging parameters in order to verify that the models fit unmeasured locations. Unfortunately, the standardised mean prediction errors and the standardised root-mean-square prediction errors were not calculated for all of the models.

3.2 The quality of the digital elevation models

The validation procedure changed the Kriging parameters to minimise the prediction errors. The best combination of Kriging parameters is impossible to find, but the validation procedure was performed until only a minor change was noted by the prediction errors. The final choice of parameters is presented in Appendix 1 (ordinary validation) and Appendix 2 (cross-validation).

Figure 3-2 shows the quality of the sub-grids as the values of root-mean-square prediction errors that should be low for a high quality grid. Sub-grids with low quality are those with only data from the digital nautical chart and those are also the sub-grids with lowest point density.

The coordinates of the starting point (upper left corner) was chosen so that the values from the SKB 10-metre DEM was not changed by the Kriging interpolation process, i.e. the central points in the cells in the new DEM coincide with the central points in the SKB 10-metre DEM. The digital elevation model with lake surface values is illustrated in Figure 3-3.

The final grid had a size of approximately 30×30 kilometres, a cell size of 10-metres, 3,001 rows, and 3,001 columns: a total number of grid cells of 9,006,001 and a file size of approximately 35.3 MB (ESRI Grid format). The extension is 1619995 west, 1650005 east, 6715005 north, and 6684995 south in the RT 90 coordinate system. As mentioned earlier, the height system is RH 70.

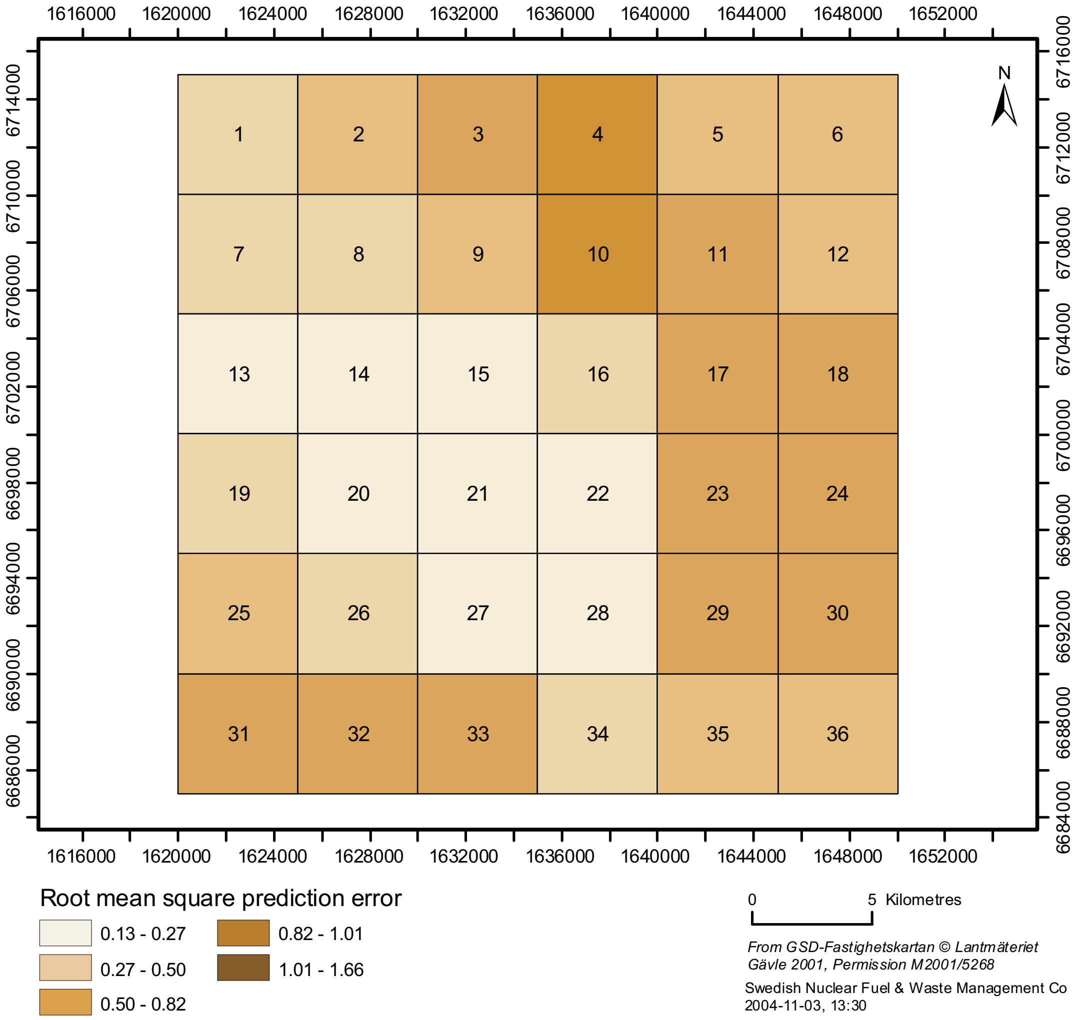

Figure 3-2. *Quality of the sub-grids as the values of root-mean-square prediction errors.*

The area is extremely flat so the range in elevation is only approximately 109 metres with the highest point at 51 metres above sea level at the south-west part of the grid, and the deepest sea point at –58 metres in the northern part of the so called Gräsörännan. The mean elevation in the grid is 2 metres and 58% is land and 42% is sea. The flat landscape is also shown in the statistics of the slope grid where the mean slope is 1.50 degrees, and 97.2% of the cells have slopes lower than 5 degrees and 2.7% have slopes between 5 and 10 degrees. Almost all of the cells with slopes steeper than 10 degrees (0.15%) are man-made such as the inlet channel to the nuclear power plant or piers and wharfs close to SFR.

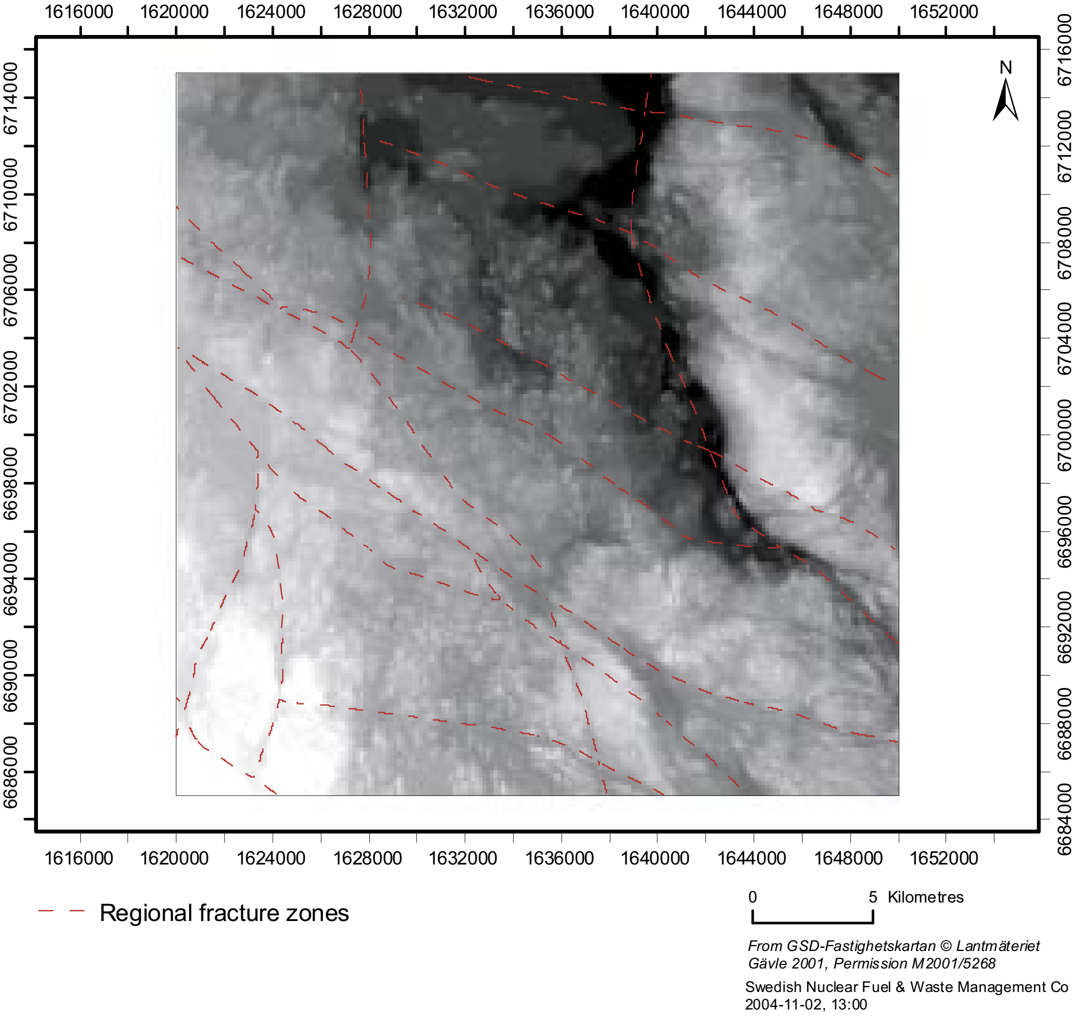

Figure 3-3. *The digital elevation model with lake surfaces.*

3.3 Data files delivered to SKB

Following data files are delivered to SKB:

Forsm_DEM_bot ESRI Grid format, land surface, lake bottoms, and sea bottoms.

Forsm_DEM_yta ESRI Grid format, land surface, lake surface, and sea bottom.

4 References

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

Davis J C, 1986. Statistics and data analysis in geology. John Wiley & sons, New York, p 383–404.

Elhammer A, Sandkvist Å, 2003. In process. Detailed marine geological survey of the sea bottom outside Forsmark. Svensk Kärnbränslehantering AB.

Vattenfall, 1977. Constructional drawing "Forsmarks kraftstation, Block 1, Kylvattenanläggning, Tilloppskanal", Drawings number 1-954511, 1-954512, 1-954513, 1-785661, 1-785662 and 1-797448.

Isaaks E H, Srivastava R M, 1989. An introduction to applied geostatistics, Oxford University Press, NY, Oxford. ISBN 0-19-505013-4.

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

Wiklund S, 2002. Digitala ortofoton och höjdmodeller. Redovisning av metodik för platsundersökningsområdena Oskarshamn och Forsmark samt förstudieområdet Tierp Norra. SKB P-02-02. Svensk Kärnbränslehantering AB.

Appendix 1

Validation of sub-models

Grid	Lag size	Regression function	Mean	RMS	Average SE	Mean stand	RMS stand	Samples
1	70	0.972 * x + 0.026	–0.002801000	0.5010	0.5042	–0.001778000	0.9460	12,011
2	80	0.987 * x + –0.081	0.011960000	0.7986	0.9917	0.006197000	0.7351	2,717
3	40	0.939 * x + –0.881	0.029940000	0.9097	1.6200	0.009443000	0.5883	1,257
4	400	0.998 * x + –0.016	0.051650000	1.2450	1.2180	0.009126000	0.5902	1,585
5	80	0.970 * x + 0.021	0.001515000	0.7045	0.6194	–0.000883800	0.9530	14,992
6	80	0.962 * x + –0.043	0.005131000	0.7198	0.7091	0.003833000	0.9363	8,695
7	50	0.987 * x + 0.080	–0.001510000	0.4981	0.4931	–0.001166000	0.7734	25,894
8	75	0.991 * x + 0.036	0.000499100	0.3366	0.5318	–0.000127000	0.5236	34,196
9	60	0.994 * x + –0.074	0.005548000	0.7653	0.7358	0.000240200	0.9047	17,707
10	100	0.959 * x + –0.547	0.058200000	1.6550	1.5260	0.009468000	1.0050	3,020
11	70	0.980 * x + 0.073	0.005340000	0.8918	0.8348	0.002692000	1.0150	12,291
12	45	0.881 * x + 0.027	–0.000197000	0.6009	0.6016	–0.001794000	0.9080	19,319
13	40	0.999 * x + 0.018	0.000183500	0.2535	0.3188	–0.000195200	0.5530	73,164
14	50	0.999 * x + 0.010	0.001152000	0.1589	0.3569	0.001477000	0.4999	235,832
14_2	50	0.999 * x + 0.010	0.001152000	0.1589	0.3569	0.001477000	0.4999	235,950
15	40	0.999 * x + 0.001	0.001048000	0.2661	0.3587	0.000807000	0.8288	167,235
15_2	40	0.999 * x + 0.001	0.001048000	0.2661	0.3587	0.000807000	0.8288	167,410
16	50	0.999 * x + –0.003	0.000651600	0.3053	0.4334	–0.000857600	0.5651	53,560
17	40	0.989 * x + 0.082	0.005939000	1.0070	1.1140	0.000118400	0.7830	9,114
18	400	0.964 * x + 0.107	–0.000123300	0.9079	1.0840	–0.001340000	0.7898	12,571
19	60	0.995 * x + 0.082	0.000003909	0.3146	0.3306	–0.000078510	0.6441	69,891
20	40	0.999 * x + 0.015	–0.000004232	0.1290	0.3717	–0.000000170	0.3469	291,057
20_2	50	0.999 * x + 0.017	–0.000034130	0.1300	0.3622	–0.000030300	0.3598	290,769
21	50	0.999 * x + 0.009	–0.000542600	0.1488	0.3298	–0.000977700	0.6019	300,482
21_2	30	0.998 * x + 0.012	–0.001188000	0.1542	0.3461	–0.001607000	0.5995	291,803
22	50	1.000 * x + 0.003	–0.001636000	0.1931	0.4008	–0.002119000	0.5856	160,398
22_2	40	1.000 * x + 0.004	–0.001806000	0.1942	0.4006	–0.002263000	0.5862	159,828
23	60	0.995 * x + 0.021	0.014340000	0.9086	1.0040	0.003279000	0.8589	7,952
24	250	0.988 * x + 0.097	–0.010160000	0.9648	1.0080	–0.005978000	0.8757	11,757
25	10	0.988 * x + 0.283	–0.000013130	0.7970	0.7997	0.000067900	0.9465	12,747
26	50	0.996 * x + 0.044	–0.000096280	0.3294	0.5598	0.000009887	0.4632	97,645
27	40	0.996 * x + 0.026	0.000065780	0.1912	0.5676	–0.000012080	0.3071	222,261
28	40	0.999 * x + 0.010	–0.000284300	0.1989	0.4861	–0.000296500	0.3624	167765
29	50	0.985 * x + 0.123	0.000378900	0.8953	1.0150	–0.000157100	0.8144	13,034
30	45	0.959 * x + 0.077	–0.000207100	0.9026	1.0930	–0.000376700	0.7802	16,394
31	55	0.978 * x + 0.682	–0.000200300	0.8489	1.1080	–0.000032570	0.7669	10,710
32	55	0.993 * x + 0.169	0.000207600	0.9473	1.1710	0.000050750	0.8090	11,220
33	30	0.960 * x + 0.279	–0.000870500	0.8545	0.7423	–0.000042230	0.9974	16,433
34	40	0.998 * x + 0.039	–0.000410200	0.4022	0.4354	–0.000041400	0.1559	54,407
35	70	0.976 * x + 0.099	–0.006319000	0.7358	0.8688	–0.004951000	0.7892	11,767
36	70	0.967 * x + 0.177	–0.005251000	0.8205	1.1500	–0.001563000	0.6791	13,961

Appendix 2

Cross-validation of sub-models

Grid	Lag size	Regression function	Mean	RMS	Average SE	Mean stand	RMS stand	Samples
1	70	0.971 * x + 0.018	–0.013700000	0.5248	0.5290	–0.0174800	0.9085	2,403
2	80	0.978 * x + –0.187	–0.085130000	1.2340	1.0830	–0.0458100	0.9662	545
3	40	0.912 * x + –1.252	0.097990000	0.8810	1.7250	0.0519100	0.5450	252
4	400	0.990 * x + –0.052	0.043830000	0.9164	1.3540	–	–	318
5	80	0.966 * x + 0.020	–0.008901000	0.7539	0.6459	–	–	3,001
6	80	0.956 * x + –0.046	0.032100000	0.7666	0.7172	–	–	1,743
7	50	0.986 * x + 0.085	–0.007772000	0.5370	0.5163	–0.0083170	0.7984	5,179
8	75	0.990 * x + 0.036	–0.000816000	0.3657	0.5504	–	–	6,840
9	60	0.994 * x + –0.073	0.011450000	0.7714	0.7793	–	–	3,543
10	100	0.961 * x + –0.434	0.144200000	1.7550	1.6060	–	–	606
11	70	0.971 * x + 0.090	–0.034170000	0.9670	0.8659	–	–	2,463
12	45	0.860 * x + 0.039	0.001798000	0.7483	0.6078	–	–	3,889
13	40	0.999 * x + 0.016	0.000138800	0.2614	0.3288	–0.0020320	0.5567	14,633
14	50	0.999 * x + 0.010	0.001609000	0.1694	0.3700	0.0036540	0.5022	47,167
14_2	50	0.999 * x + 0.010	0.001609000	0.1694	0.3700	0.0036540	0.5022	47,191
15	40	0.999 * x + 0.000	0.001341000	0.2813	0.3712	–	–	34,483
15_2	40	0.999 * x + 0.000	0.001341000	0.2813	0.3712	–	–	34,483
16	50	0.999 * x + –0.007	0.003783000	0.3403	0.4652	–	–	11,032
17	40	0.986 * x + 0.121	0.045270000	0.9663	1.1460	0.0347500	0.7463	1,823
18	400	0.965 * x + 0.105	–0.013030000	0.9652	1.0980	–	–	2,522
19	60	0.994 * x + 0.090	–0.000059250	0.3225	0.3428	–0.0023300	0.6491	13,979
20	40	0.999 * x + 0.020	–0.000481400	0.1396	0.3850	–0.0011420	0.3605	58,212
20_2	50	0.999 * x + 0.022	0.000650600	0.1395	0.3753	0.0016420	0.3713	58,154
21	50	0.998 * x + 0.011	0.000493000	0.1553	0.3414	–	–	60,202
21_2	30	0.998 * x + 0.012	–0.001421000	0.1664	0.3587	–	–	58,466
22	50	1.000 * x + 0.003	–0.001384000	0.1957	0.4052	–	–	34,332
22_2	40	1.000 * x + 0.002	–0.002583000	0.2006	0.4022	–	–	34,218
23	60	0.990 * x + 0.033	0.028980000	1.0230	1.0560	–	–	1,598
24	250	0.984 * x + 0.127	–0.011700000	1.0420	1.0440	–	–	2,360
25	10	0.982 * x + 0.424	–0.026480000	0.8595	0.8388	–0.0298700	0.9757	2,550
26	50	0.995 * x + 0.050	–0.004533000	0.3525	0.5697	–0.0065240	0.4839	19,529
27	40	0.996 * x + 0.031	0.001544000	0.2053	0.5852	0.0022630	0.3176	44,453
28	40	0.999 * x + 0.012	–0.000008378	0.2107	0.5009	–	–	33,968
29	50	0.978 * x + 0.166	–0.009221000	0.9516	1.0500	–	–	2,612
30	45	0.946 * x + 0.097	0.012780000	0.9770	1.1320	–	–	3,294
31	55	0.974 * x + 0.831	0.017550000	0.9275	1.1510	0.0160400	0.8009	2,142
32	55	0.990 * x + 0.245	0.031160000	0.9765	1.2140	0.0237000	0.8036	2,244
33	30	0.964 * x + 0.270	0.008332000	0.9054	0.7676	0.0101500	1.0200	3,287
34	40	0.996 * x + 0.061	0.000755000	0.4701	0.4535	0.0032580	0.6500	10,882
35	70	0.982 * x + 0.071	–0.000715400	0.7151	0.9032	0.0007314	0.7453	2,354
36	70	0.959 * x + 0.210	0.003311000	0.8952	1.1770	–	–	2,800

Appendix 3

Sub-model parameters

Common to all sub-models are Ordinary Kriging with a spherical model. The model equation should be read as follows:

Partial sill * Theoretical Semivariogram (Major Range, Minor Range, Anisotropy Direction) + (Nugget value * Nugget)

Grid	No of points	Modell
1	12,011	4.9183*Spherical(687, 612.68, 242.2)+0*Nugget
2	2,717	13.128*Spherical(948.26, 691.37, 354.4)+0.029309*Nugget
3	1,257	6.7967*Spherical(474.13, 238.13, 284.0)+0.73316*Nugget
4	1,585	112.38*Spherical(4741.3, 3846.3, 24.3)+0*Nugget
5	14,992	9.1053*Spherical(793.98, 751.44, 336.8)+0*Nugget
6	8,695	2.8934*Spherical(948.26, 779.73, 317.0)+0.33925*Nugget
7	25,894	4.3166*Spherical(592.66, 469.16, 36.6)+0*Nugget
8	34,196	7.1875*Spherical(889, 596.47, 344.2)+0.094884*Nugget
9	17,707	19.018*Spherical(711.2, 484.16, 19.4)+0*Nugget
10	3,020	24.357*Spherical(1185.3, 877.56, 312.9)+0.60284*Nugget
11	12,291	13.264*Spherical(829.73, 772.58, 349.0)+0*Nugget
12	19,319	1.6725*Spherical(450.04, 417.13, 252.4)+0.22402*Nugget
13	73,164	2.818*Spherical(474.13, 474.13, 12.0)+0*Nugget
14	235,832	6.219*Spherical(592.66, 519.53, 328.5)+0*Nugget
14_2	235,950	6.219*Spherical(592.66, 519.53, 328.5)+0*Nugget
15	167,235	9.4038*Spherical(474.13, 435.03, 315.2)+0*Nugget
15_2	167,410	9.4038*Spherical(474.13, 435.03, 315.2)+0*Nugget
16	53,560	13.637*Spherical(515.04, 382.04, 359.7)+0*Nugget
17	9,114	11.152*Spherical(474.13, 409.43, 333.9)+0*Nugget
18	12,571	34.983*Spherical(4741.3, 3378.9, 339.9)+0.72911*Nugget
19	69,891	4.1123*Spherical(711.2, 600.69, 28.2)+0*Nugget
20	291,057	5.5252*Spherical(474.13, 452.81, 303.5)+0*Nugget
20_2	290,767	6.3779*Spherical(592.66, 533.92, 297.5)+0*Nugget
21	300,482	5.4888*Spherical(592.66, 487.79, 303.9)+0*Nugget
21_2	291,803	4.082*Spherical(355.6, 355.6, 10.5)+0*Nugget
22	160,398	14.594*Spherical(592.66, 592.66, 9.5)+0*Nugget
22_2	159,828	11.794*Spherical(474.13, 474.13, 9.3)+0*Nugget
23	7,952	17.078*Spherical(711.2, 636.87, 337.5)+0*Nugget
24	11,757	58.139*Spherical(2963.3, 2295.4, 336.2)+0*Nugget
25	12,747	1.3663*Spherical(118.53, 118.53, 9.0)+0*Nugget
26	97,645	4.2114*Spherical(587.48, 496.43, 36.9)+0.16266*Nugget
27	222,261	7.9007*Spherical(383.94, 322.96, 313.3)+0.041924*Nugget
28	167,765	9.2498*Spherical(474.13, 474.13, 11.8)+0*Nugget
29	13,034	12.003*Spherical(592.66, 530.05, 298.3)+0*Nugget
30	16,394	11.586*Spherical(533.4, 306.56, 309.1)+0.12867*Nugget
31	10,710	12.167*Spherical(651.93, 495.48, 347.8)+0*Nugget
32	11,220	13.897*Spherical(651.93, 521.26, 354.4)+0*Nugget
33	16,433	4.3618*Spherical(355.6, 325.58, 345.1)+0*Nugget
34	54,407	4.3338*Spherical(474.13, 403.74, 349.6)+0*Nugget
35	11,767	10.529*Spherical(829.73, 560.49, 314.6)+0*Nugget
36	13,961	11.335*Spherical(711.2, 402.39, 284.5)+0.31332*Nugget