Technical Report

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Shore line displacement in Öregrundsgrepen

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SKB

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Keywords: Shore displacement, lake cutting off, SFR, SAFE

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

Abstract

This report is a part the SKB project "SAFE" (Safety Assessment of the Final Repository of Radioactive Operational Waste). The aim of project SAFE is to update the previous safety analysis of SFR-1. The analysis is to be presented to the Swedish authorities not later than the end of 2000. SFR-1 is a facility for disposal of low and intermediate level radioactive waste and is situated in bedrock beneath the Baltic Sea, 1 km off the coast near the Forsmark nuclear power plant in Northern Uppland.

The shore displacement in the Öregrundsgrepen area is at present approximately 60 cm per 100 years (Påsse, 1977) and is slowly decreasing, but will still be substantial for many thousands of years. Since Öregrundsgrepen is a relatively shallow part of the Bothnian Sea, the positive shore displacement will greatly effect the proportions of land and sea in the feature.

Within 2000 years (4000 AD) half of the current water area in Öregrundsgrepen will be land and the water volume will be decreased with two thirds. At 7000 AD, the whole Öregrundsgrepen area will be without brackish water.

The effects on the landscape evolution due to shore displacement in the Öregrunds-grepen area are illustrated in a chronological series of digital maps in PowerPoint format available saved on the supplied CD-rom and entitled "Elevation.ppt".

The bedrock tectonics in the area are in two dominating directions: one northern that can be seen in the west shoreline of the island Gräsö and one in a north-westerly direction seen in the shoreline of the mainland. Many of the large basins that will be established in the area due to the shore displacement will be elongated in one of these directions. Some of the basins are relatively shallow and therefore probably will be totally filled with organic rich sediments and will form peats or bogs. Other basins, especially Gräsörännan (the deep channel on the west side of Gräsö) are deep basins and will form a long chain of deep lakes.

One of the deeper basins will be formed close to the SFR-1. The catchment to this former lake constitutes the inner model area that is studied in more detail. The landscape evolution in this area is also illustrated as a time series of digital maps in PowerPoint format "Elev_inre.ppt".

The sea bottom directly above SFR-1 will start to drain approximately 2400 AD and will be completely dry approximately 3500 AD. The inner model area will be without brackish water approximately 5000 AD and at least 20 new basins (> 10000 m^2) will be formed within this area. Most of them will be shallow basins and will therefore quickly be transformed into pets or bogs. When the inner model area is drained of brackish water approximately 75% of the area will be bedrock or wave washed till and 25% peat, bog or lake.

Sammanfattning

Denna rapport är en del av SKB-projektet ”SAFE” (Safety Assessment of the Final Repository of Radioactive Operational Waste). Syftet med SAFE-projektet är att uppdatera den tidigare utförda säkerhetsanalysen av SFR-1. Analysen skall presenteras för svenska myndigheter senast år 2000. SFR-1 är ett förvar för låg- eller medelaktivt radioaktivt avfall beläget i berggrunden under Bottenhavet ca 1 km utanför kusten nära Forsmarks kärnkraftverk i Norra Uppland.

Strandförskjutning i området kring Öregrundsgrepen är idag ca 60 cm per hundra år (Påsse, 1997). Strandförskjutningshastigheten sjunker sakta men kommer likväl att vara betydande i flera tusen år framöver. Eftersom stora delar av undersökningsområdet idag har ringa vattendjup kommer strandförskjutningen få stora effekter på fördelningen land/hav.

Om knappt 2000 år (4000 AD) har vattenarealen i Öregrundsgrepen halverats och vattenvolymen minskat till en tredjedel. År 7000 AD är området helt fritt från brackvatten.

Strandförskjutningens effekter på landskapsutvecklingen i Öregrundsgrepen finns illustrerade i en tidsserie digitala kartor i PowerPoint-format på bifogade CD-rom samt SKB:s hemsida.

Berggrunden i området har en tektonik efter två tydliga riktningar; en nordlig som bl.a. visas i Gräsöns västliga strandlinje och en nordvästlig som visas i fastlandsstranden. De stora bassänger som p.g.a. strandförskjutningen kommer att bildas i området kommer att få en utsträckning som följer dessa tektoniska riktningar. Flera av bassängerna är tämligen grunda och kommer därför att växa igen och bilda myr eller kärr, medan speciellt längs den s.k. Gräsörännan kommer att bildas djupa bassänger som kommer att utvecklas till en lång kedja av djupa sjöar.

En av de större bassängerna kommer att bildas i närområdet till SFR-1. Tillrinningsområdet till denna blivande bassäng utgör det inre modellområdet. Strandförskjutningsutvecklingen i det inre modellområdet illustreras i en serie digitala kartor i PowerPoint-format under namnet ”Elev_inre.ppt”. Området direkt ovanför förvaret kommer att börja torrläggas ungefär 2400 AD och vara helt torrt ungefär 3500 AD. Hela det inre modellområdet kommer att vara fritt från brackvatten ca 5000 AD. Inom detta område kommer det att bildas minst 20 ytterligare bassänger (> 10000 m^2). De flesta av dessa kommer att bli grunda och därför tämligen snabbt ombildas till myr eller kärr. Vid tidpunkten för total avsaknad av brackvatten kommer ca 75% av arean att bestå av kalt berg eller svallad morän och resterande 25% av myr, kärr eller sjö.

Content

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Introduction

This report is a part of the SKB project "SAFE" (Safety Assessment of the Final Repository of Radioactive Operational Waste). The aim of project SAFE is to update the previous safety analysis of SFR-1. The analysis should be presented to the Swedish authorities no later than the end of 2000. SFR-1 is a facility for disposal of low and intermediate level radioactive waste and is situated in bedrock beneath the Baltic Sea, 1 km off the coast near the Forsmark nuclear power plant in Northern Uppland.

Some of the radioisotopes that are stored in SFR-1 have long half-life, e.g. ^{129}I with a halftime of $1.57*10^7$ years or ^{14}C with half-life of 5730 years. This means that the safety assessment that will be performed within SAFE must be done for a long time period, and the directive to the SAFE project states that the forthcoming 10000 years should be studied in greater detail. The present shore displacement rate in the area is approximately 60 cm per 100 years (Påsse, 1997), and even if the decrease over time in the rate is taken into account, the Öregrundsgrepen will be completely drained during the period of the safety assessment.

At a possibly leakage of radioisotopes *today*, the transport will be by groundwater flows from the SFR-1 to the sea bottom and further to the seawater. At a possibly leakage of radioisotopes *in two or three thousand years*, it is most likely that the transport by groundwater flow will discharge an outflow area on land or in a lake. It is therefore most important to study the effects of shore displacement on the landscape evolution in order to do probable estimations on transport paths for radioisotopes depending on when the leakage occurs, on where the radioisotopes accumulate and if these radioisotopes with time move to completely different chemical environments, i.e. due to shore displacement move from an aquatic to a terrestial environment.

There are two study areas within the SAFE project. Some simulations are performed for a more extensive area that includes the whole Öregrundsgrepen, while other studies only model processes in a small area close to SFR-1. In this study, the shore displacement effects are first presented for the outer area and then in more detail for the inner model area. Figure 1 shows the extensions for the two study areas. The outer model area consists of all sea areas in the figure, while the extension of the inner model area is shown with a red line in the figure. The delimitation of the inner model area is based on hydrological conditions. A new lake north of SFR-1 will develop and part of the lake catchment has been defined as the inner model area.

2 Method

The method is based on a digital elevation model (DEM) over the area with a Geographical Information System (GIS) modelling the effects of shore displacement on the landscape evolution. The DEM has been created from elevation point data collected from different sources.

Two sources has been used for collecting elevation point data for land areas, partly the existing DEM from the Swedish national land survey with a resolution of 50 meters and partly elevation lines from the digital map with a scale of 1:10000 also from Swedish national land survey. The lines were transformed to points with an Avenue script in the GIS software ArcView version 3.1.

Elevation data for the sea area has been obtained partly from the digital chart (the Swedish National Administration of Shipping and Navigation) and partly from the basemap to the chart. The digital chart has depth lines for 3, 6, 10, 15, 25 and 50 meters. These line objects have been transformed into point objects in the same way as for elevations lines in the digital map. The digital chart lacks the point depths that are present in the paper chart, so these points where manually digitised from the paper chart. For the inner model area (see figure 1), the basemap to the chart was used for digitising point depths. These depth soundings were already performed in 1898 so it was necessary to convert these values from foot to meter and at the same time adjust the values for shore displacement since 1898.

Elevation data from different sources was in different co-ordinate systems and therefore the data that was not in the Swedish national Cartesian system (RT90) was transformed to RT90. This transformation was performed with the GIS software ArcInfo.

All elevation point values were collected in a database and with this database new digital elevation models was created. The DEM for the outer model area was created with a resolution of 50 meters while the DEM for the inner model area that has higher point density was created with a resolution of 25 meters. The interpolation from irregularly spaced point values to a regularly spaced DEM was done with the software Surfer (Keckler, 1995). Kringing was chosen as the interpolation method (Davis, 1986). The choosing of theoretical semivariogram model and the parameters scale, length and nugget effect was done with the software VarioWin (Pannatier, 1996). Finally, the DEM was transformed from Surfer format to ArcInfo ASCII Grid format, a data format that most GIS software can read.

The simulation of the shore displacement is performed with a data program written in C++. The program reads the ASCII format DEM, the user chooses a time which will be simulated, the time is transformed to elevation difference compared to the present level by using the shore displacement equation (Påsse, 1996). The program adds or subtracts this elevation difference from the original DEM and writes the new DEM in ASCII Grid format. The new model is imported to the GIS software where it can be displayed and additional analysis, such as area and volume calculations, can be performed.

A DEM covering land areas normally has water surfaces as elevation levels, i.e. not the lake or sea bottom. The DEM over Öregrundsgrepen has water surfaces as elevation level for areas that today are land but the soil surface for areas that today are sea. With a view to predict where new lakes will be formed and to predict the direction of new streams, a new method has been developed with the GIS software ArcView. The method requires the extensions "Spatial analyst" and "Hydrologic modelling".

The DEM is imported to ArcView and saved in Grid format. With the function "Basin fill" in the drop-down menu "Hydro", the DEM is manipulated so that each basin in the model is filled to the basin threshold value, i.e. a DEM value within a basin is replaced by the basin threshold value (water surface level). The original DEM is then subtracted by the "Basin filled DEM", which the new DEM only has values for areas manipulated by the basin fill function. With the function "Map query" all basins are selected (value <> 0) and the model is converted to Shape format. The lake areas are then calculated in the attribute table of the shape file.

By using the new future lake map (shape format), the filled DEM and the information tool, it is possible to detect the threshold level for each future lake. The values in the original DEM that are situated within each future lake are selected by using the Avenue script "Grid_clip_to_poly". Descriptive statistics are calculated for the selected values and the average depth for the future lake by subtracting the statistical average value with the threshold value. The maximum depth is calculated in the same way and the future lake volume is calculated by multiplying the average depth with the area. Finally, the point in time when each future lake is "born" is calculated with the shore displacement equation.

The further extension of existing streams in the future formed landscape is modelled with the ArcView function "Trace flow path" and the inner model area extension is modelled with the function "Watershed".

3 Results

3.1 Modelling shore displacement in the outer model area

The modelling of shore displacement is, as mentioned earlier, based on an equation from Påsse (1996). In the PowerPoint presentation, the time series of maps starts at the time for the first islands to appear in the area, approximately 4,000 years ago. The inland ice had melted off the area approximately 9,000 years ago, so the area was covered with seawater during 5,000 years before the oldest map in the PowerPoint presentation. The series of maps is in intervals of 500 years and ends 5000 AD. The area distribution (land/lake/sea) and water depths in the sea are also presented for some significant occasions (see figures 2-5).

The overall depth conditions can be seen for example in figure 2. A deep channel runs from the deep-sea south facing along the west side of the island Gräsö and through the Öregrund strait. The northern part of the channel runs in a north-south direction, while the southern part is directed in a north-westerly direction. These two directions are the major tectonic directions in the area and can be found in a large number of phenomena. The north-westerly direction is found for example as the present mainland shoreline and a chain of lakes approximately 2 kilometres south-west of the shoreline. The northern direction is not so apparent as the north-westerly but can be found as the deep channel that runs against SFR-1.

The island Gräsö appeared for the first time approximately 1,000 BC. Its further development is undramatic; a few islands that grow successively and later grow together and form one large island. An archipelago with a large number of small islands is formed during the period 0 to 1,000 AD in the area south of the village Forsmark. The Öregrundsgrepen is establish about 1500 AD, i.e. one single narrow strait between the Bothnian Sea and Åland Sea on the west side of Gräsö.

From today (see figure 2) to 4,000 AD the major change in landscape evolution will occur close to the mainland and on the east side of Gräsö. The Öregrund strait will successively narrow and close approximately 3,000 AD, i.e. the island Gräsö will become a part of the mainland. Öregrundsgrepen is transformed from a strait to a bay and possibly an estuary if the discharge from Forsmarksån and Olandsån is large enough to generate an estuarine environment.

The greater part of the inner model area will be drained about 4,500 AD, and the remaining sea will be sheltered against the open sea by an archipelago (see figure 4). A relatively large lake will be established in the inner model area about 5,000 AD and at the same time a systems of lakes will be formed along the north-westerly fault fissure. During the following thousand years a narrowing of the former Öregrundsgrepen will occur and about 6,500 AD the first lake in the Gräsö channel will be established, which will soon be followed by further lake formations along the channel. The former Öregrundsgrepen is totally drain on brackish water about 7,500 AD.

The change over time in distribution of land (see elevation.ppt) is more rapid in the beginning of the studied period and decays against the end of the period. Figure 6 shows the change in brackish water area in the outer model area from today to 7,000 AD. Almost half of the water area has been changed to land in 1,500 years. Figure 7 shows the change in brackish water volume over the same period and the change in water volume is decreased even more.

A large number of lakes will be formed in Öregrundsgrepen during the period 2,000 AD to 7,000 AD. The fourteen largest are presented in figure 8 and table 1.

Large and deep lakes will be situated along the deep channel on the west side of Gräsö. The future lakes will form a long chain of lakes along the northern faulty fissure. Similar existing lake systems can be found in the vicinity, from Forsmark toward the north-west (Bruksdammen, N. and S. Åsjön and Skälsjön) and the lake system Utålskedjan. Both these lake systems are elongated along the north-westerly faulty direction. The deepest of the future lakes is "Finnbådasjön" (code = 12) with a maximum depth of approximately 35 meters.

Table 1. Characteristic values for future lakes in Öregrundsgrepen. See figure 8 for the location of the lakes

Code	Elevation (m)	Area (km²)	Volume (m3*10^6)	Average depth (m)	Max depth (m)	Born (AD)
1	-3.60	3.08	8.3	2.7	6.0	2600
2	-6.00	1.82	0.9	0.5	2.4	3000
3	-9.30	1.04	1.7	1.6	4.2	3600
4	-15.20	1.06	1.8	1.7	4.1	4900
5	-15.20	0.74	1.0	1.3	4.2	4900
6	-15.20	0.73	1.7	2.3	5.2	4900
7	-15.20	0.31	0.3	0.9	2.0	4900
8	-15.20	0.79	0.9	1.1	3.1	4900
9	-15.70	7.11	25.0	3.5	7.2	4900
10	-16.20	1.83	3.3	1.8	6.6	5000
11	-21.40	8.14	33.3	4.1	19.3	5400
12	-22.90	3.33	23.7	7.1	34.6	6800
13	-22.90	7.12	36.4	5.1	22.3	6800
14	-26.40	7.61	31.5	4.2	19.9	7700

Many of the future lakes are shallow and will probably be totally filled with organic rich sediments. The basin fill process is most dependent on the basin depth, but other factors include nutrient status and water turnover. Four of the lakes will be small lakes with average depths lower than 1.5 meter (code = 2, 5, 7 and 8) have low theoretical turnover time. These lakes are therefore potential future mires. Many of the remaining future lakes will partly have large shallows and will probably becomes lakes surrounded by organic soils.

The only rivers in the area, Forsmarksån and Olandsån, today already have a common outlet to Öregrundsgrepen through Kallrigafjärden. In 6,000 AD this common outlet will discharge the southernmost of the deep future lakes west of Gräsö. This means that the water turnover in this future lake system will be relatively high. All other future lakes in the area will have low to extremely low theoretical turnover times, especially the future lake nine, which will be a large lake both in area and volume, but will receive low inflow of water due to a small catchment.

3.2 Modelling shore displacement in the inner model area

As mentioned earlier, the modelling of shore displacement in the inner model area is based on a DEM with higher resolution (25 meters) compared to the outer model area (50 meters). The higher resolution makes it possible to detect future basins with smaller areas compared to the outer area.

The shore displacement from today until 5,000 AD is presented in the PowerPoint file "Elev_inre.ppt". A selection of maps from the PowerPoint presentation is also presented in this paper (figure 9–12).

The change in new land formation during the period from today until 2,400 AD is undramatic. Existing islands grow in size and some new islands emerge from the sea. During the period 2,500 AD until 3,500 AD the area directly above SFR-1 is drained gradually and during the same period a large number of small lakes are formed (see figure 10). About 3,400 AD the inner model area is closed from both southern and eastern directions and the only inlet to the area is through the northern channel.

The next significant change occurs approximately 2,900 AD when a lake is established directly downstream from the SFR-1. It is very important to decide if and eventually when this lake will transform to a peat due to sedimentation of organic material, since the dynamics of the radioisotopes differ between these two environments.

About 4,500 AD the sea in the inner model area consists of a long and narrow bay (see figure 11). The inner part of the bay is elongated along the northern fault direction while the outer part is elongated in the north-westerly direction. During this period it is likely that the sea in the model area has an pronounced estuarine environment, i.e. low salinity, a sharp developed halocline, an estuarine water circulation and a sedimentation that is controlled by this water circulation. This means that the transport of particle-bounded radionuclides from the SFR-1 to the open sea is decreased.

The large lake within the inner model area will be formed about 5,000 AD. The lake will be elongated along the north-westerly fault direction, 2 kilometres long and have an area of 1 km^2. The average water depth will be barely 2 meters while the maximum depth will be 4 meters (see code=25 in table 2).

The lake will be one of the lakes with low theoretical water turnover times. The catchment will be 25 km^2 and the specific run off will be 8 $l\ s^{-1}\ km^{-2}$. This gives an average discharge of approximately 0.2 $m^3\ s^{-1}$. The water volume of the lake will be 1.8 million m^3, so the theoretical water turnover time will be approximately 100 days. This falls into the classification of a lake with a long turnover time.

Table 2. Characteristic values for future basins in the inner model area. The locations of the basins are shown in figure 13.

Code	Area (m^2)	Volume (m^3)	Level (m)	Maximum depth (m)	Average depth (m)	Born (AD)
1	45187	8586	-12.93	0.97	0.19	4400
2	20702	1656	-12.93	0.21	0.08	4400
4	69028	80072	-6.77	2.39	1.16	3200
5	205201	102601	-13.90	1.26	0.50	4600
6	12016	6609	-13.54	1.26	0.55	4500
7	123062	153828	-10.97	2.33	1.25	4000
8	65107	31251	-12.96	1.83	0.48	4400
9	144284	157270	-10.05	2.19	1.09	3800
10	69145	93346	-10.34	2.87	1.35	3900
11	15961	10534	-5.95	1.92	0.66	3000
12	16043	5294	-5.01	0.88	0.33	2900
13	39004	15602	-6.45	1.37	0.40	3100
14	166000	370180	-10.87	4.28	2.23	4000
15	162138	220508	-12.11	2.95	1.36	4200
16	21376	17101	-6.90	1.93	0.80	3200
17	34265	13706	-14.52	0.91	0.40	4700
18	15592	12474	-12.68	2.17	0.80	4300
18	41329	16118	-13.55	1.25	0.39	4500
19	26700	25365	-6.40	1.79	0.95	3100
20	159378	219942	-10.20	3.02	1.38	3800
21	83340	60838	-14.77	2.12	0.73	4800
22	16912	15559	-10.59	2.15	0.92	3900
23	41665	14999	-4.46	0.73	0.36	2800
24	1176580	2082547	-14.98	4.34	1.77	4800

4 References

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Appendix 1

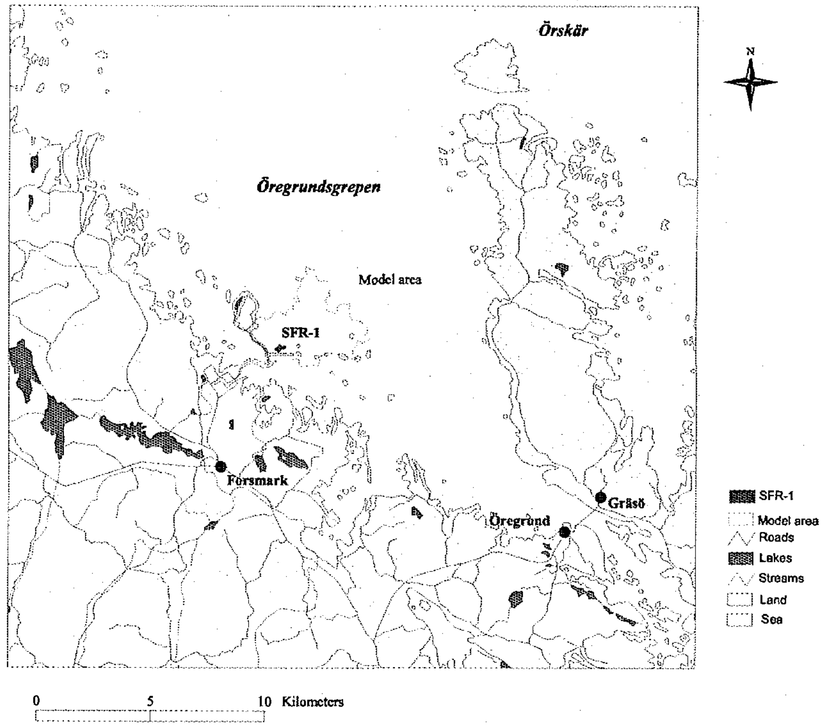

Figure 1. *Öregrundsgrepen with SFR-1 (marked with red symbol within the inner model area) and the inner model area marked with a red line. The outer model area consists of all sea water area in the figure. Permission: The National Land Survey of Sweden. Register number 507-96-1524.*

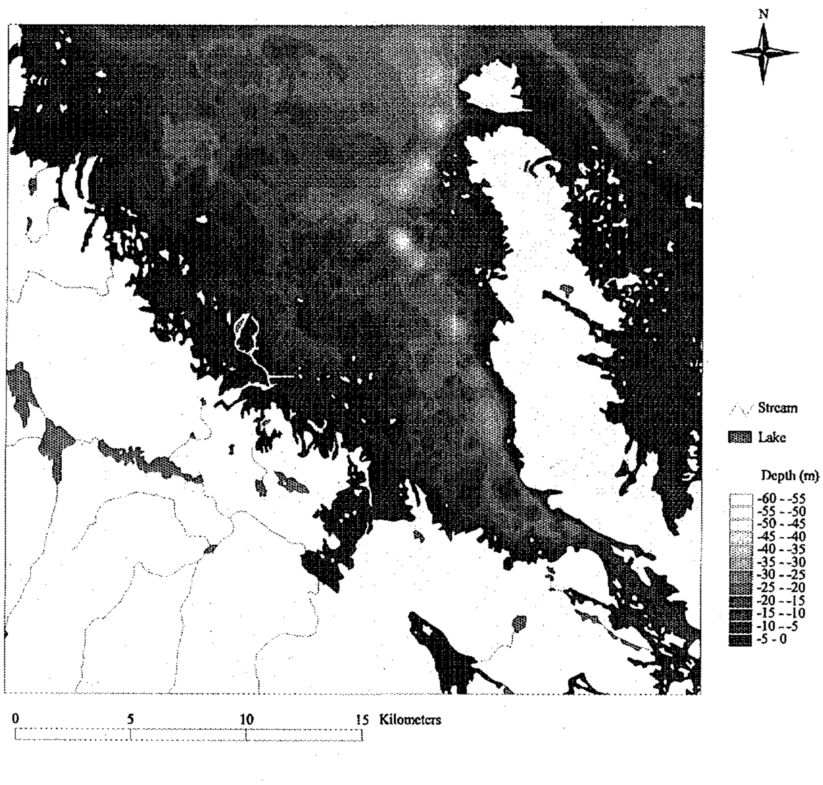

Figure 2. *Öregrundsgrepen with the water depth conditions that prevail today (2000 AD). Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

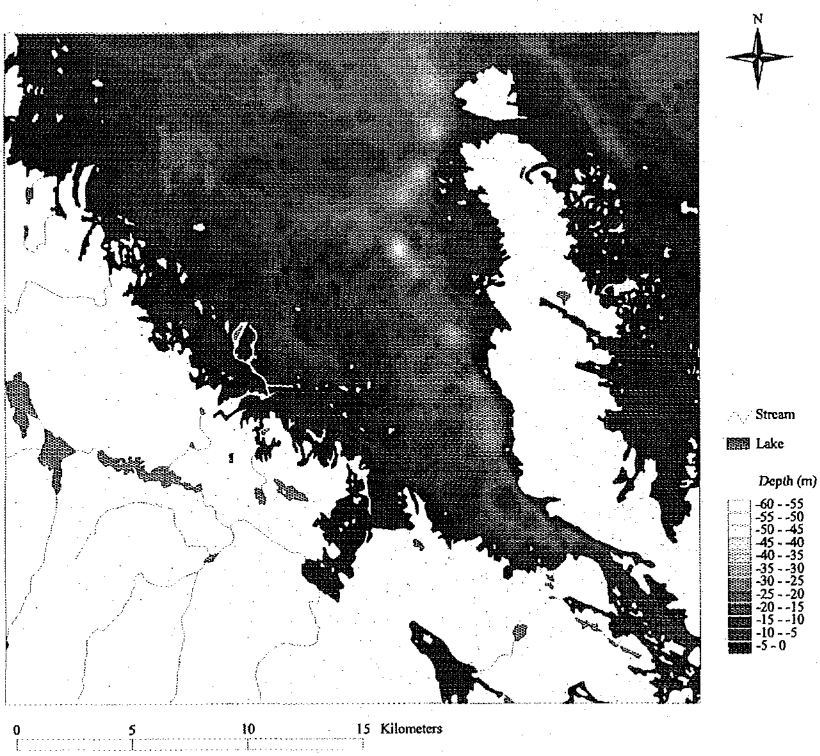

Figure 3. *Öregrundsgrepen with the water depth conditions that will prevail 3500 AD. Today's shoreline is marked to help orient on the map. The larger river and their new extensions and new, larger lakes are also shown. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

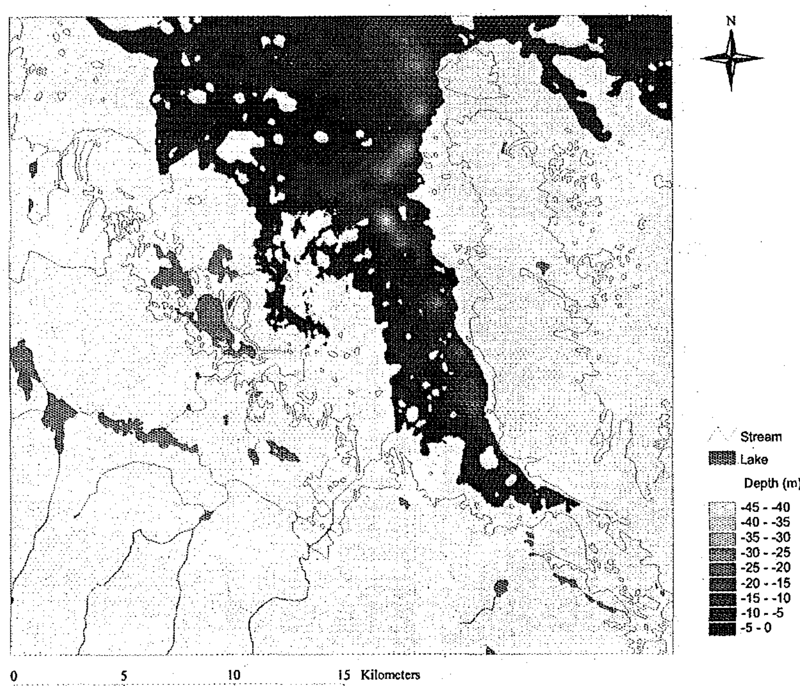

Figure 4. *Öregrundsgrepen with the water depth conditions that will prevail 4500 AD. Today's shoreline is marked to make it easier to orientated in the map. The larger river and there new extensions and new larger lakes are also shown. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

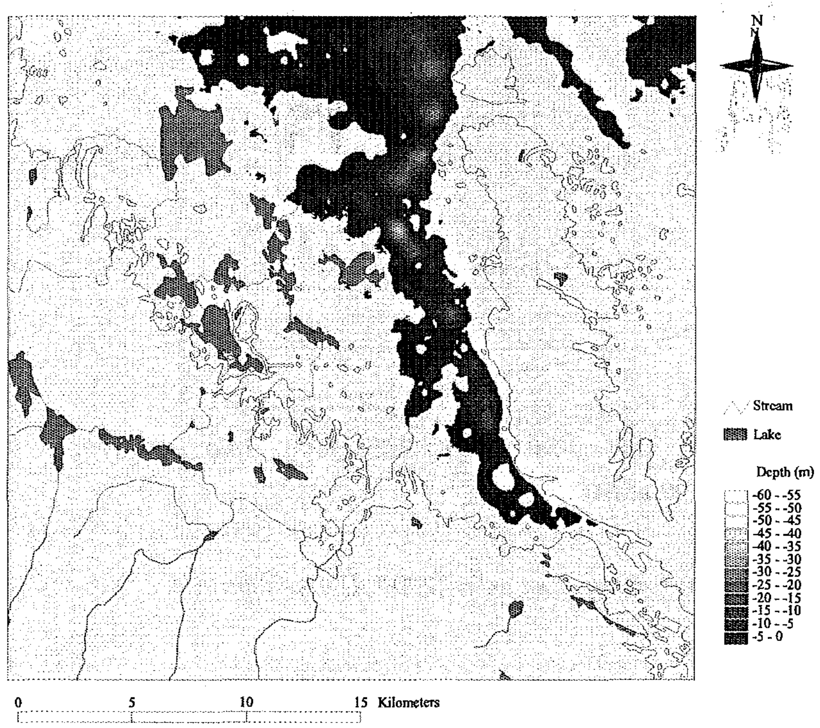

Figure 5. *Öregrundsgrepen with the water depth conditions that will prevail 5000 AD. Today's shoreline is marked to help orient the map. The larger river and their new extensions and new, larger lakes are also shown. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

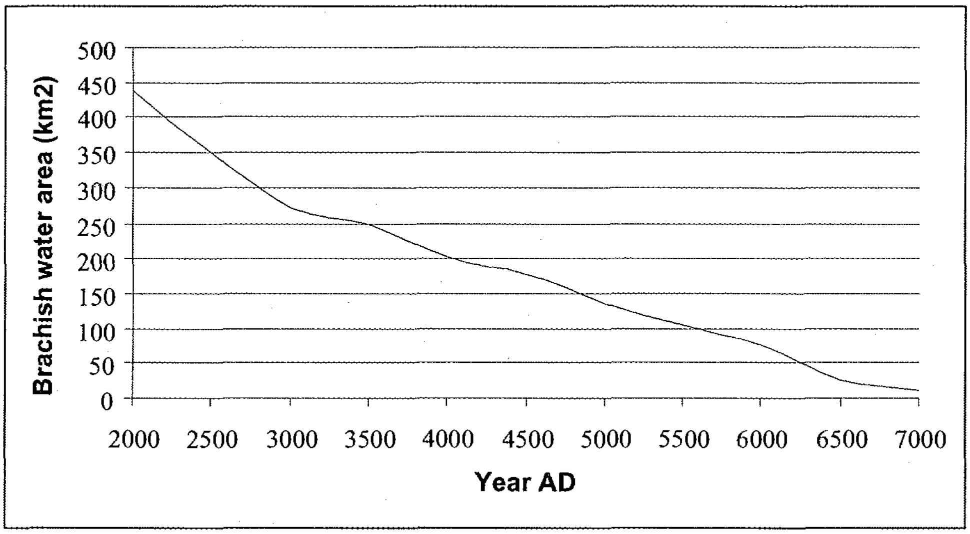

Figure 6. *The decrease in the brackish water area from today (2000 AD) to 7000 AD.*

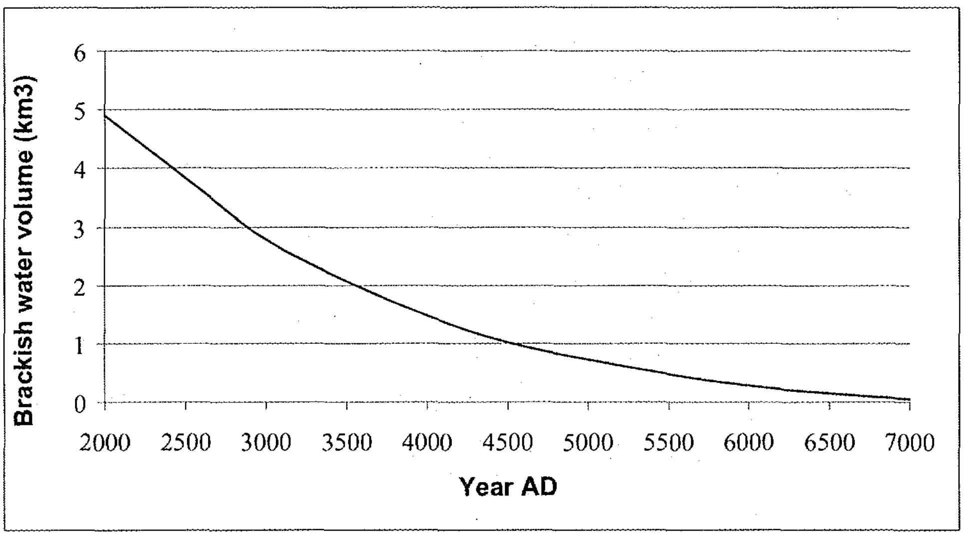

Figure 7. *The decrease in brackish water volume from today (2000 AD) to 7000 AD.*

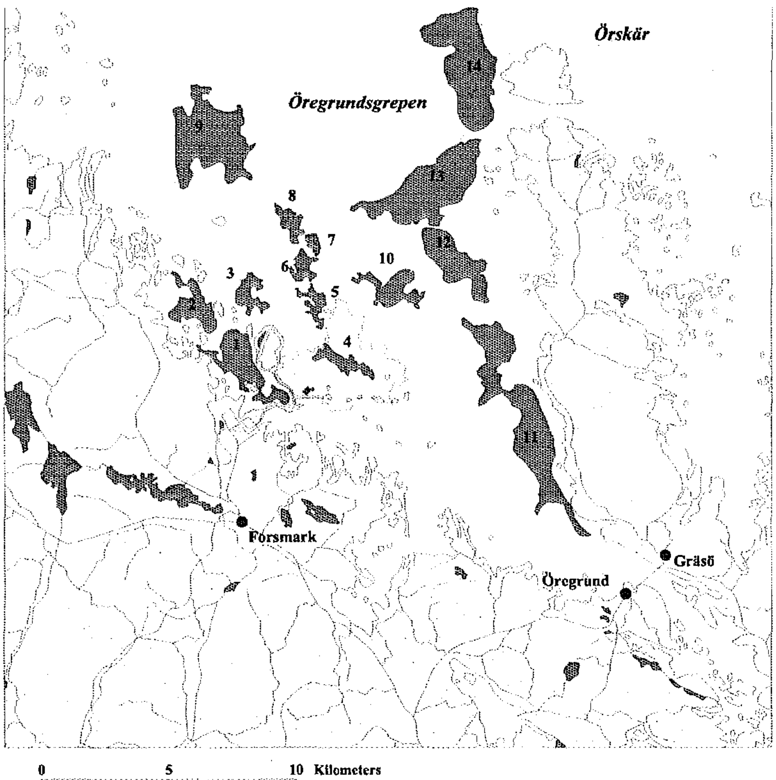

Figure 8. *Future lakes in Öregrundsgrepen numbered according to table 1. SFR-1 is marked with a red symbol and the inner model area with a red line. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

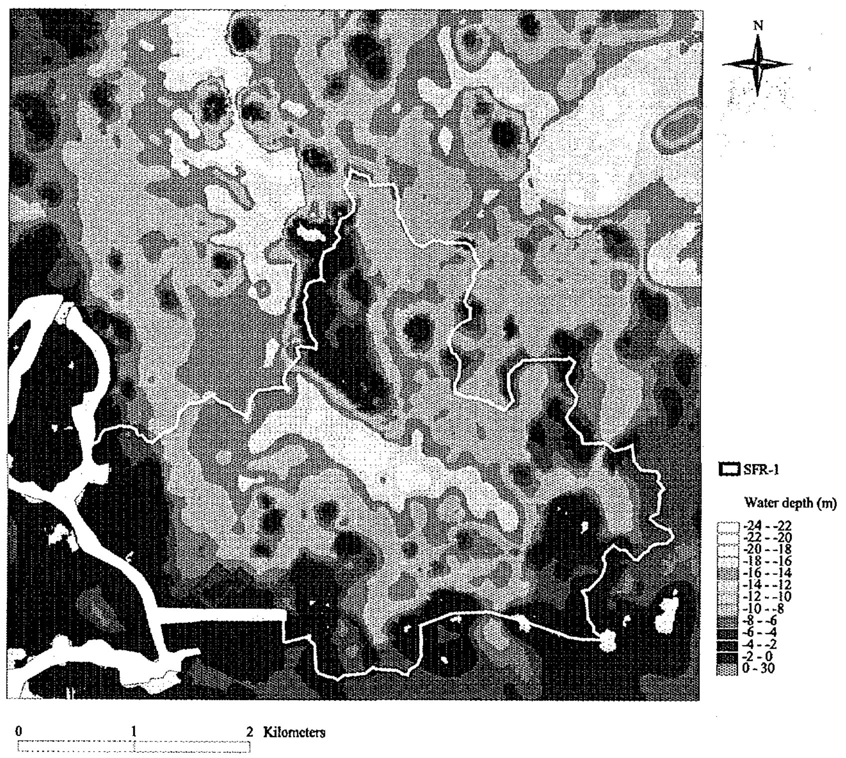

Figure 9. *The water depth conditions in the inner model area. SFR-1 is marked with a red line. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

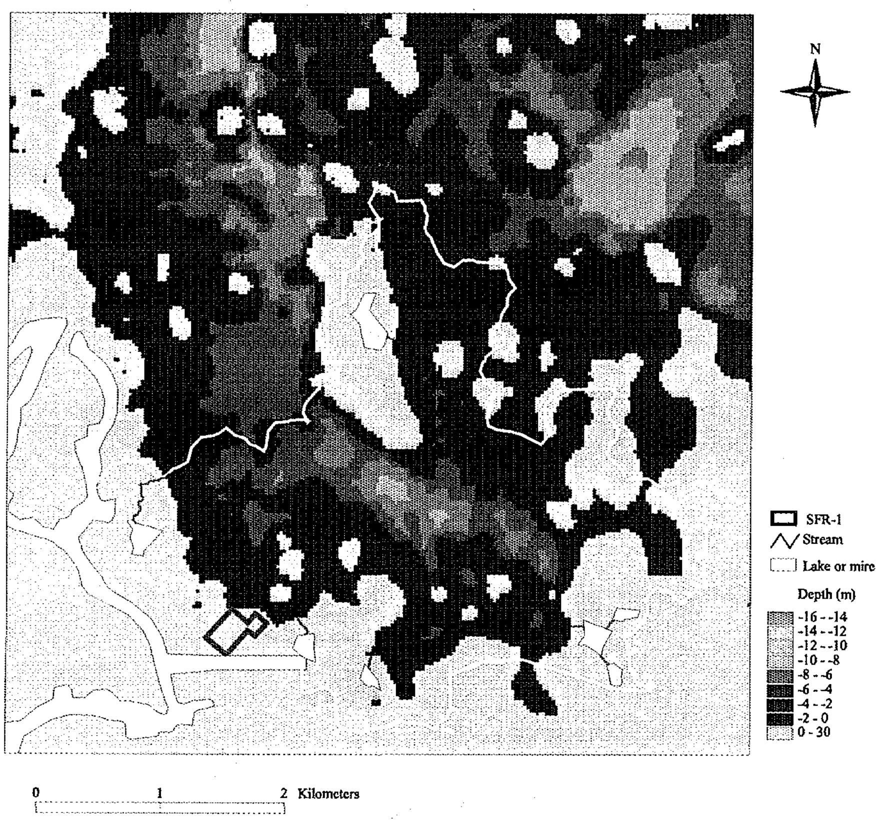

Figure 10. *The water depth conditions in the inner model area 3500 AD. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

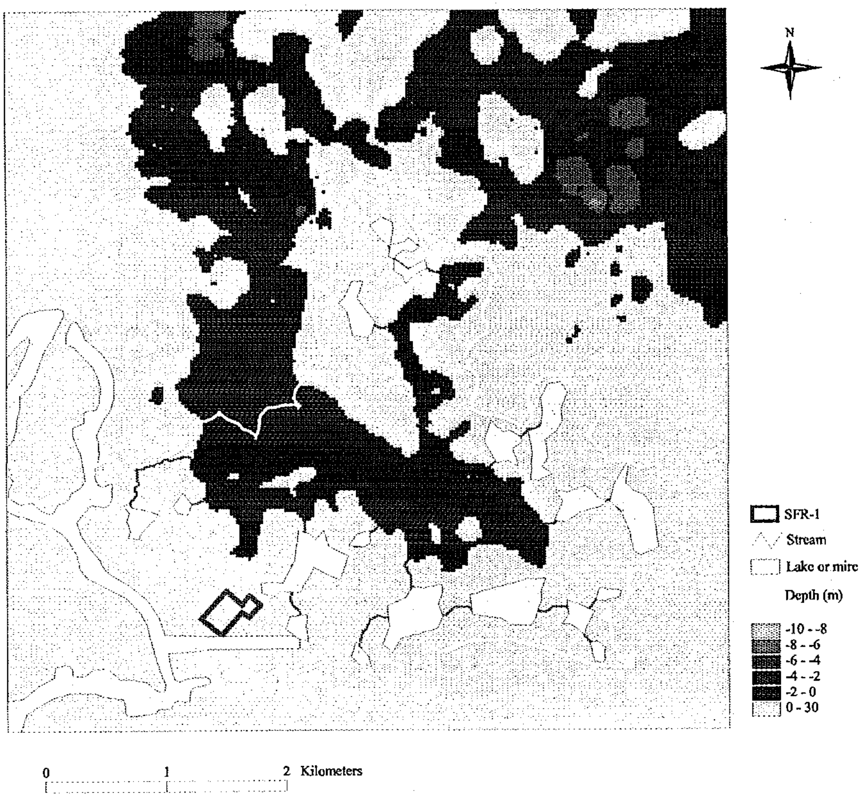

Figure 11. *The water depth conditions in the inner model area 4500 AD. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

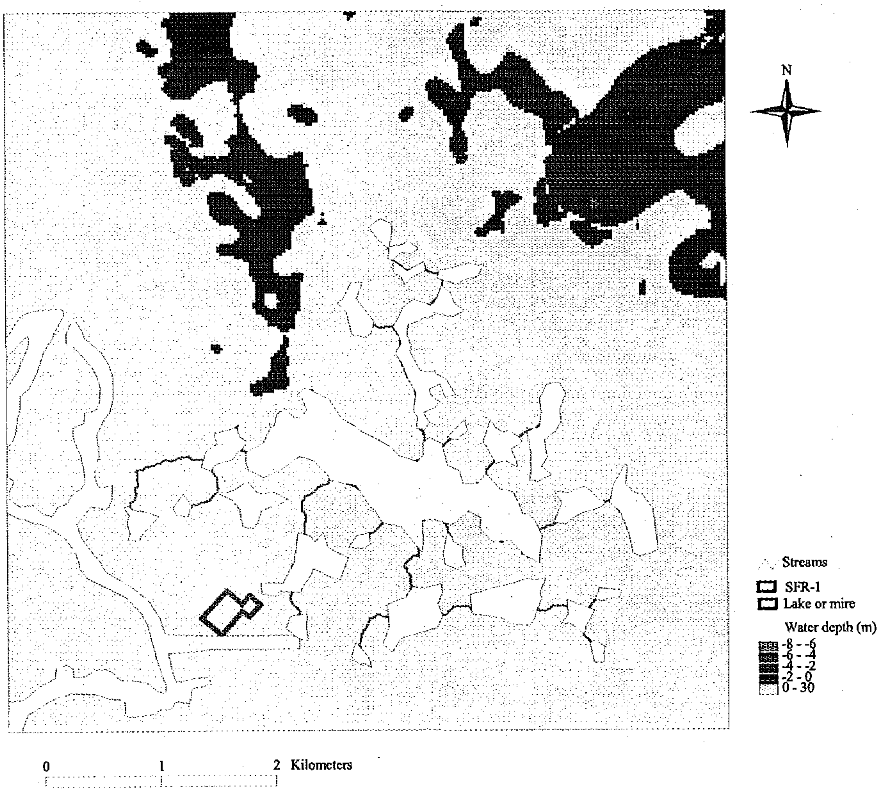

Figure 12. *The water depth conditions in the inner model area 5000 AD. Notice that no brackish water occurs in the inner model area at this time. Permissions: The National Land Survey of Sweden, register number 507-96-1524 and the Swedish national administration of shipping and navigation, permission number 9709388.*

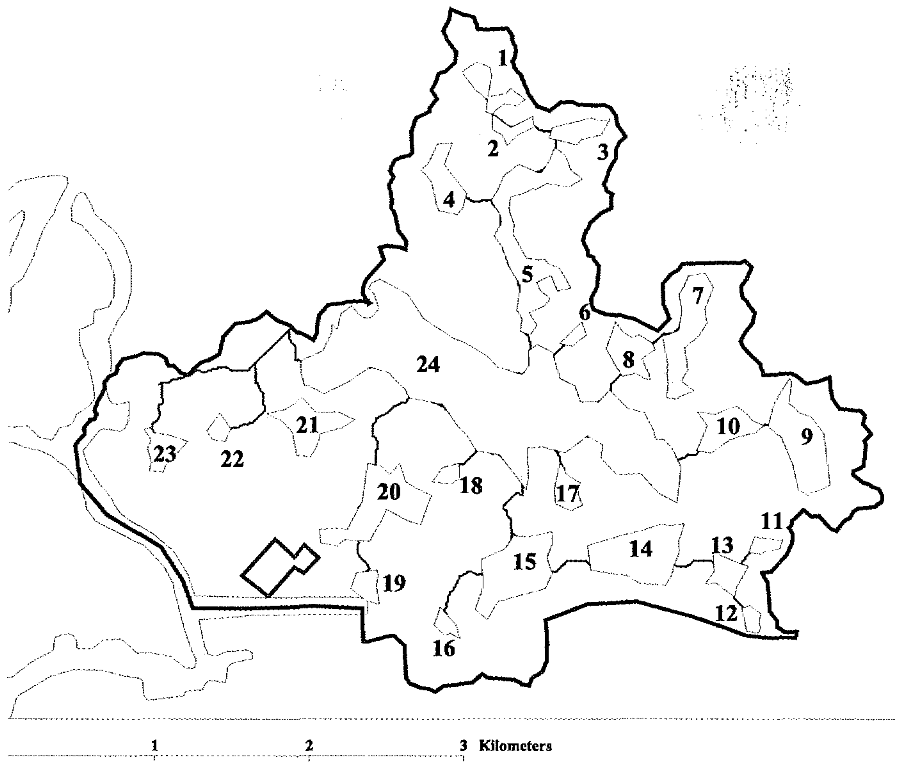

Figure 13. *Closed basins in the inner model area that will form lakes and later eventually peats or bogs. These are numbered according to the column "Code" in table 2.*

Appendix 2

Instructions how to load files from CD-ROM

The files on the CD-ROM are stored on formats that can be used by Windows and Macintosh. The animations are Powerpoint files.

To run the animations double click on the files elevation.ppt or elev_inre.ppt.

When the files are loaded, select the slide show viewing mode ("visa bildspel"), then the landrise process will be animated. It will take about 10 seconds for the first map until the following maps are stepped forward. Stop the animation by pressing <esc>.

If you don't have Microsoft Powerpoint installed there is a viewer for Window on the CD-rom. Double click on the program to install the viewer.

The viewer can also be downloaded from http://www.microsoft.com/downloads/

An electronic version of the report is also supplied as a .PDF file on the CD-ROM. A viewer for this file format is also available on the CD-ROM for Windows.

The following files are on the CD-ROM

Readme.txt	This text
Elevation.ppt	The shore line displacement of the entire area
Elev_inre.ppt	The shore line displacement of the inner area
TR-99-16.pdf	An electronic version of the report
Folder Viewers	If necessary viewer for the file formats can be installed for Windows